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A Novel Spacecraft Standard for a Modular Nanosatellite Bus in an Operationally Responsive Space Environment

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A novel spacecraft standard for a modular nanosatellite bus in an operationally responsive space environment

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ABSTRACT

A truly modular satellite design must be approached from a systems perspective in order to meet the Operationally Responsive Space (ORS) community's goal of a rapidly responsive spacecraft. In such a design approach, the modular mechanical bus system must complement a modular data bus system. Through the University Nanosatellite 5 competition, Boston University and Taylor University have built a comprehensive nanosatellite bus where each subsystem has followed a standardized electrical and mechanical interface. This standard is based on the CubeSat concept, but expanded to nanosatellites. It allows for instrument and subsystem designers to know the mechanical and electrical interfaces their instruments or subsystem must conform to prior to a mission, providing for ease of reuse for subsequent missions. Examples from the recently constructed Boston University Student Satellite for Application and Training (BUSAT) are given to illustrate the proposed standard and its capability for a rapid response.

KEYWORDS: BUSAT, Cubesat, Ionosphere, Modular, Magnetosphere, Standard**,** Small Satellite

INTRODUCTION

The goal of the Operationally Responsive Space Office to assemble and launch a satellite in seven days or less requires a streamlined process that draws on standardized interfaces between subsystems, instruments, the primary bus, and interfaces to the launch vehicle. The success of being able to launch a satellite in this timeframe is dictated by the part requiring the most time to bring to flight-readiness level, independent of whether it is an instrument or spacecraft bus feature. This dependence on low priority items that may hold up the integration of a spacecraft requires a modular systems design that encompasses both the mechanical and electrical aspects of the satellite. Significant effort has gone into the design of mission planning, software modules, and electrical interfaces that provide for a capable plug-and-play concept; however, a plug-and-play concept for the mechanical design has not kept pace with its spacecraft counterparts. The "Boston University Student Satellite for Application and Training" (BUSAT) provides this capability to plug subsystems and instruments in a truly modular manner while surviving the harsh requirements of launch and space.

The BUSAT nanosatellite was a collaboration between Boston University and Taylor University and was funded through the Air Force's University Nanosatellite 5 Program (UNP). The UNP is a contest between 11 universities with each school provided with limited funds to construct a working nanosatellite. At the end of two years the school with the most completed satellite, and applicability to the Air Force objectives, is selected to be launched. Throughout the process the Air Force provides opportunities for feedback to the universities through a set of design reviews, expert area teleconferences, and hands-on training workshops. Through this educational arm of the Air Force, BUSAT's modular bus was first developed at Taylor on the Thunderstorm and Effects Science and Technology (TEST) nanosatellite that was part of the UNP 3 competition[1]. Based on the CubeSat concept, BUSAT defines subsystems and instrument housings that are able to be rapidly assembled. In addition to a novel bus design, BUSAT had a strong science mission to better understand the coupling between energetic particles in the magnetosphere and their subsequent effect on the ionosphere. In order to meet this objective a suite of 5 scientific instruments was chosen and are described below:

- **Imaging Electron Spectrometer (IES)** – measured energetic particles between 50keV and 500keV. Comprised of nine solid state detectors centered on the zenith direction, each pixel observed different regions of the sky allowing the IES to resolve the pitch angle of incident particles in addition to the particle energy.

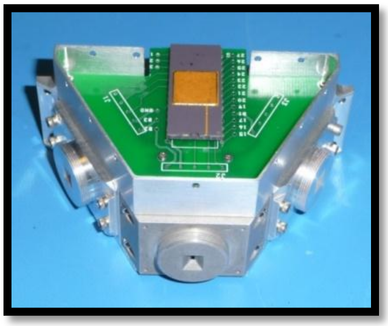

Figure 1 - Imaging Electron Spectrometer sensor head is capable of measuring particles in the 30keV to 1 MeV range.

- **Auroral Imager** – the Auroral Imager instrument's purpose was to observe several key light emissions from the N_2 and O optical range. This was accomplished through an optical filter, a grating, and several focusing lenses before it was captured by a CCD camera.
- **Langmuir Plasma Probe** – the Plasma Probe's purpose was to measure low energy electrons and ions. This was achieved by placing a conducting sphere with a varying voltage in the ram direction of the satellite.

Figure 2 - Fixed boom holding the Langmuir Plasma probe and the Very Low Frequency Receiver antenna in the background.

- **Very Low Frequency (VLF) Receiver** – the VLF receiver measured the integrated RF energy in six VLF bands, and was used to determine the presence of electromagnetic phenomenon such as Whistler waves.
- **Magnetometer** – The magnetometer instrument was a Commercial Off The Shelf (COTS) component purchased from Honeywell.

Each of these five instruments played a significant role in the mission objective to better understand the dynamic processes that are involved in the coupling between the magnetosphere and the ionosphere. Although BUSAT was brought to a significant level of completion, it was not selected as the winner of the UNP 5 competition. However, its modular design offers a number of features to the space community as varying methods are being examined as how best to lower the cost of spacecraft construction.

SPACECRAFT BUS DESIGN

BUSAT has implemented a modular spacecraft bus that allows the designer to know the interfaces required prior to a specified mission. Unique in its implementation, BUSAT requires the engineer to rethink some of the traditional aspects of spacecraft design and assembly.

The need for a unified mechanical bus design

As spacecraft budgets are stretched by the growing assets that need to be maintained in space, the need to reduce the cost of spacecraft design and fabrication has increased. Because flying simpler satellites is not an option for operational or scientific satellites, the arena remaining to be simplified is the interfaces between these complex systems. Standardizing interfaces allows for complex systems to be connected together in a straightforward method, thus reducing the significant costs of systems engineering, custom designs and analysis. Although one spacecraft bus may not work for the nanosatellite to the full commercial communication satellite, an effort needs to be made to utilize similar standards within similar spacecraft categories. While recently attending a small satellite workshop it was mentioned that no one bus would be able to meet the needs of everyone. Although this may be true, a well designed bus that accounts for both the mechanical and electrical considerations in a spacecraft could serve a large percentage of the operational and scientific missions in a single weight category, thus reducing the cost of spacecraft design in the long run. If the space community continues to use different mechanical buses, instrument and subsystem designers will not be able to create hardware that is easily able to be integrated into other bus designs, thus requiring a redesign which drives up cost and lengthens the delivery schedule.

BUSAT is one option to be considered as a mechanical bus design for the 10kg to 100kg Small Satellite category as it allows a method to rapidly integrate payloads together; it allows instruments of varying sizes; it allows full knowledge of the payload volume prior to a specified mission which allows for early research and development, as well as a number of other benefits.

Mechanical Bus Design

The BUSAT mechanical design builds off of the cubesat concept by defining the housings of the subsystems and instruments in a pre-defined manner. The basic unit of the satellite is a 1U cube of 4in by 4in by 4in. Subsystems are able to be any size as long as the subsystems are a multiple of the 1U plus some additional spacing between the cubes. Each subsystem wall can then be defined in terms of length as shown in the equation 1:

$$x = 4 * n + 0.5 * (n - 1), \qquad (1)$$

where the length x is the length in inches and n is the number of the basic 1U lengths on the side. For example the subsystem shown in Figure 3 is a 3U cube as it is 4” x 4” x 13”.

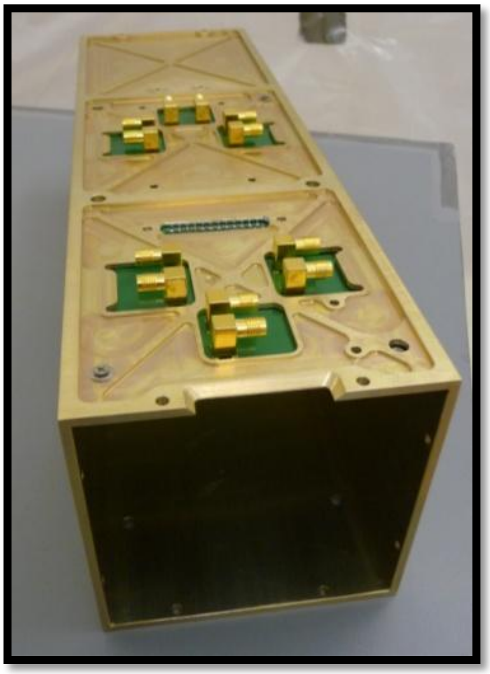

Figure 3 - Triple cube housing the Attitude Determination and Control subsystem

Subsystems and instrument designers initially determine what size box they will need, and are immediately able to know the interfaces their instrument will have. The advantages to this are significant as circuit designers know how to break up components earlier, which allows for a reduced development cycle.

In the BUSAT design, subsystems and instruments are able to be stacked together in a rapid fashion as shown in Figure 4. The first step is to start with the primary structure which is shown in Figure 4. The next step is to start stacking subsystems and instruments using spacers to maintain the separation between the cubes and exoskeleton. Subsystems are able to be placed in any orientation convenient to the spacecraft systems engineer, and do not compromise the instruments or subsystems requirements (i.e. a magnetometer instrument may require a certain orientation to the spacecraft axis). This can be an advantage to the systems engineer that needs to maintain a particular center of gravity and moment of inertia.

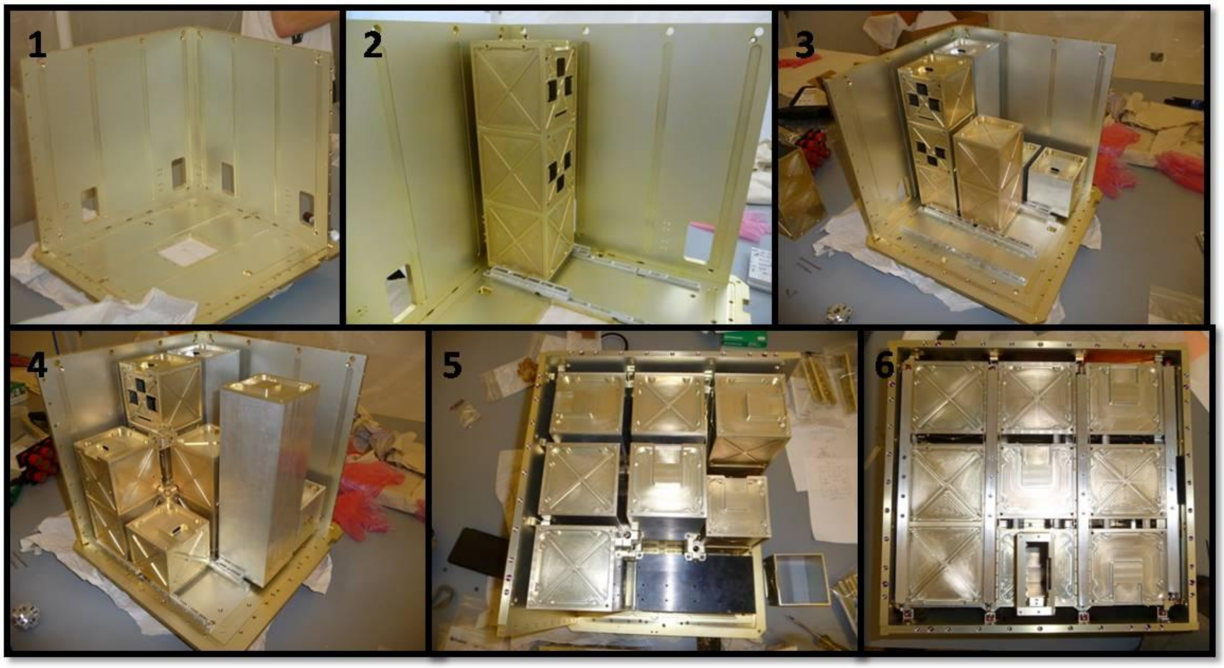

Figure 4 – Assembly of the BUSAT spacecraft starting with the primary structure and then the filling of the subsystem cubes.

Once all of the subsystems are placed in the structure a spacecraft-proven mechanism called a Wedge-Lok, is used to hold all of the subsystems in compression. The Wedge-Lok, built by Birtcher Inc.,[2] has traditionally been used to hold circuit boards in place while providing the capability for easy assembly.

Figure 5 - Shown is a typical Wedge-Lok produced by Birtcher Inc.[2]

In the BUSAT design, a threaded rod passes through five wedges and is held in place inside of a U-channel. As the rod is turned, it pushes three of the wedges away from the U-channel and provides an equal force on each of the wedges. One of the primary advantages of the Wedge-Lok is it allows for slight misalignments due to tolerance creep as boxes are stacked on top of each other. The result is designers are not required to maintain a high degree of precision in their designs, which can be costly. The overall error between cubes must be less than 60 mils or 1.5mm in the BUSAT design. This was accomplished on BUSAT by requiring cubes to be within ± 5 mils or about 0.12 mm, a very reasonable tolerance that is able to be maintained at most machine shops. Once all of the cubes are placed, the remaining sides of the primary structure are attached and the Wedge-Loks are torqued to the proper specification. It is important to note that the BUSAT modular design is not a friction-based design because Wedge-Loks are placed in all three axis.

One of the concerns expressed in this design has been that it is inherently a heavy system that wastes a lot of mass. Although there is a significant amount of mass to the BUSAT design (not all bad when considering the self shielding nature of the design), it is surprising at how competitive the design is to current spacecraft bus designs in its payload to dry mass weight. The BUSAT design is an efficient design that utilizes the entire volume of the spacecraft. Different than the traditional design where there is a primary structure and subsystems and instruments act as parasitic weights to the primary without adding much strength, BUSAT utilized the housings of the subsystems and instruments to strengthen the primary structure. Stress is translated three dimensionally in the structure providing for a strong design resulting in a modeled high first vibration mode of around 200Hz in the worst axis. At the time of this article the BUSAT design has not undergone vibrational testing; however, a previous version of the spacecraft was vibrated. In this version of the satellite the subsystem cubes were bolted to the primary structure rather held in place by Wedge-Loks. Figure 6 is the output of an accelerometer attached to the TEST Satellite as a 0.25G sine wave was applied to the vibration table. As can be seen from this test the first mode was around 320 Hz. .

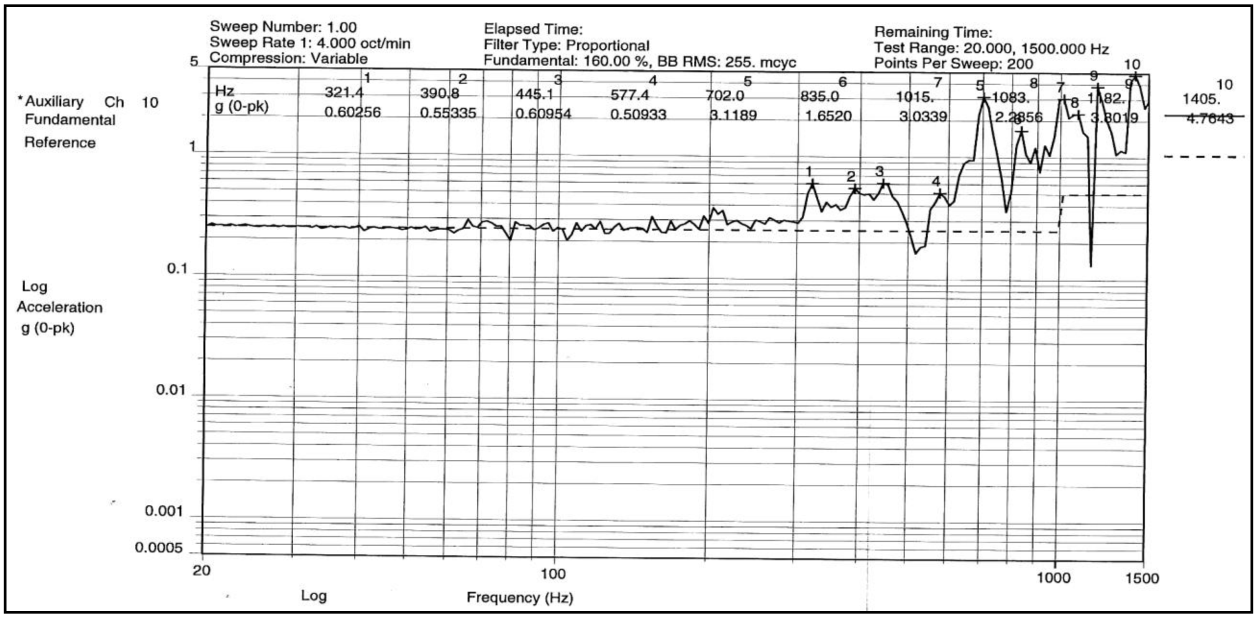

Figure 6 - The sin sweep of the TEST satellite where the first mode was at 320 Hz. Similar in design as far as the cubed subsystems, TEST required subsystems to be bolted to the primary structure rather than using the Wedge-Loks.

As with any satellite the greater the number of payloads flown, the better the payload-to-dry-mass relationship will be as long as the primary structure is not increased. In Figure 7 the relationship between payload mass to dry mass is depicted. The plot utilizes the IES experiment as a representative weight and uses its 1U mass as a represented mass for payloads. The dry mass is the entire weight of the spacecraft. This last number varied inversely to the number of payload cubes.

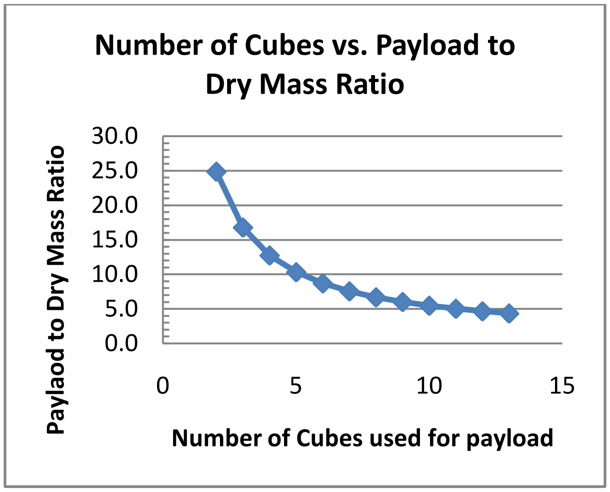

Figure 7 - The above figure illustrates the relationship between the Payload to Dry Mass Ratio as the number of empty cubes are used for instruments.

In the BUSAT design there were a total of 13 1U cubes that were allocated to payload use and the five instruments ended up using nine of them. This resulted in a payload-to-dry-mass of six. An improvement in this ratio would have been achieved by designing the primary structure out of honeycomb panels; however, this was not allowed in the UNP competition, so heavier weight-reduced aluminum panels were used, and are the numbers reflected in the above graph. It is estimated that honeycomb panels would have brought the payload-to-dry-mass ratio for BUSAT to 5.2. It should also be noted the BUSAT weight numbers reflect an extremely heavy battery pack design that used a NiCd batteries with 13 cells as well as six magnetic coils that each take up a side of the spacecraft.

Although on the heavy side, BUSAT is similar to many other earth orbiting satellites as was demonstrated by a JPL study[3] of 46 Earth-orbiting satellites shown in Figure 8. The average for these satellites payload mass to On Orbit Dry Mass was around 4.8, only slightly lower than the BUSAT ratio[4].   .

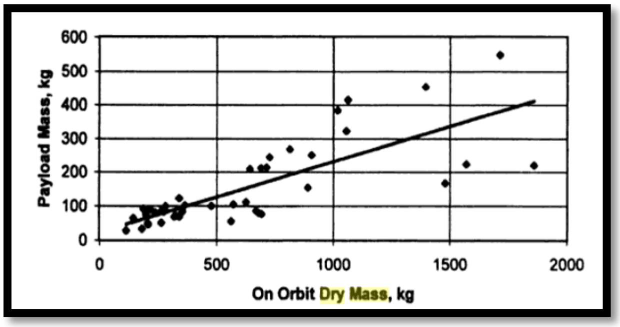

Figure 8 – A study illustrating the relationship between Payload Mass to On Orbit Dry Mass

The BUSAT design however has not been optimized for mass reduction because the design limit for the UNP competition was 50 kg. Lower mass levels could be achieved with additional mass reduction of subsystem cubes, primary structure material, cubes spacers, and cabling. Using the BUSAT design as an example, the below table demonstrates the breakdown between the various spacecraft sections.

Table 1 - Mass breakdown for BUSAT

Spacecraft System	Percent Dry Mass
Primary Structure	28%
Internal Compression Pieces	15%
Subsystem Mass	40%
Empty Cubes	3%
Payload Mass	14%

It should also be noted that although the BUSAT design is a 3U by 3U by 3U primary structure, allowing for a total of 27 1U cubes, the design is able to be scaled up or down depending on the spacecraft's operational needs. The modular subsystem cube design does not place any requirement that mandates each side of the spacecraft be an equal number of cubes. Spacecraft designers could construct a 2U by 5U by 3U, illustrated in Figure 9, and all are accommodated by the Wedge-Lok and subsystem housing design.

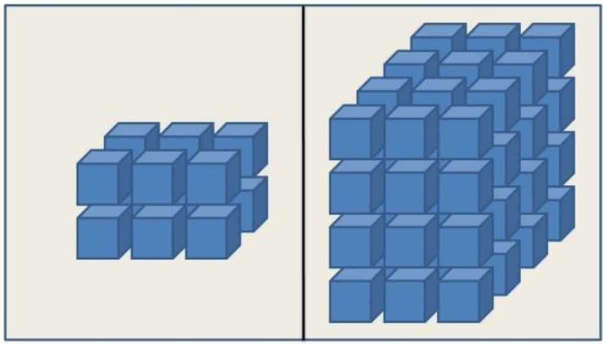

Figure 9 - The BUSAT design is able to accommodate multiple cube configurations

The upper bound on the number of cubes that are able to be supported is dictated by the stiffness capability of the primary structure and the size of Wedge-Lok available. As the number of cubes is increased, the flexing of the primary structure in the middle of the wall may be larger than the Wedge-Loks ability to accommodate the tolerance misalignment. The obvious example to adding cubes is the capability to integrate additional payloads with little impact to other subsystem and instrument designs providing the power and data handling systems are able to accommodate additional interfaces.

Electrical Bus Design

BUSAT's data bus design is built off of a simple modular concept that standardizes the interfaces between the data processing system, the power system, and the instruments and subsystems. The standardization applied to the wire harness, the power distribution, the physical data protocol, and the packet structure.

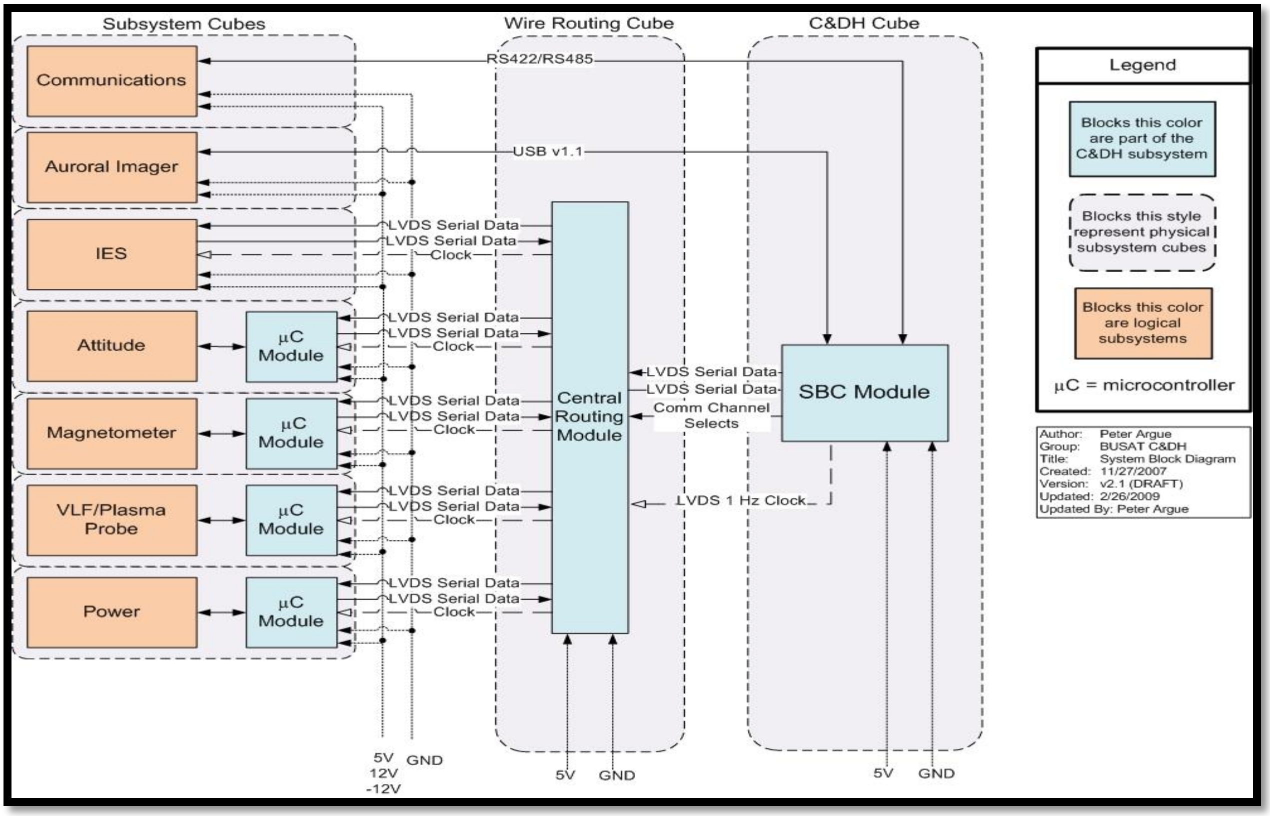

Figure 10 - The data handling system for BUSAT. Each subsystem and instrument communicated with the Single Board Computer through an FPGA that acted as a MUX.

Due to the high packing volume of the spacecraft, a new method was needed for cable routing in order to avoid a highly complex wire harness. BUSAT continued the design of the TEST satellite by using a single interface box as a Central Routing Cube or CRC. The CRC housed the power supply for the spacecraft and acted as a router for all of the signals within the spacecraft as shown in Figure 10 made by BUSAT student Peter Argue.

The CRC allowed for a single cable to be run from an instrument directly to the CRC. These predefined cables could be mass produced in-house or purchased from a vendor as the connectors were standard 21 pin micro-D connectors. Within each cable, pins were allocated for data handling, power, and spacecraft clock, with some left over for instrument of subsystem defined needs. With the CRC, complicated circuit routing could then be done on a single multilayer PCB rather than in a cable harness. The simplification in the harness design allowed for the high packing volume of the spacecraft.

The power distribution supplied a regulated and fused 12 V supply, minus 12 V supply, 5 V supply, and their respective grounds to each subsystem. This allows instrument and subsystem designers to be able to limit the regulation needs within their subsystem and provides for a more efficient system power design. Fuses are able to be swapped out depending on the subsystems current draw. Each subsystem's current and voltage for each power line was monitored and stored in a housekeeping packet in the power subsystem.

The physical data link between the instruments and subsystems was a Low Voltage Differential Signaling (LVDS) protocol. LVDS uses a 3 mA bi-directional current to signal either a logic 0 or a logic 1. At the receiving end a resistor is used to create a voltage drop. One of the advantages of LVDS is its low power consumption while still providing a high degree of resilience in electrically noisy environments. However, due to the LVDS design it is typically used for point to point communication. Rather than having a Data Processing Unit (DPU) that is required to have a large number of UART ports, a Field Programmable Gate Array (FPGA) with built in LVDS termination was used in the CRC to act as a router. This allows for a large number of subsystem to be connected to any DPU that has a single UART port. The DPU communicates to the CRC via a single LVDS data pair and four LVDS address pairs. This provides up to 16 subsystems and instruments to be connected to the DPU. The number of address lines coming from the DPU is scalable to accommodate an even larger number of subsystems and instruments if desired.

In addition to the data lines an LVDS clock is distributed from the DPU to each instrument and subsystem via the FPGA. This provides for synchronization between all instruments and subsystems with the DPU.

It should be noted that although a serial LVDS physical protocol was selected for the BUSAT spacecraft the same data distribution system could just as easily have been implemented with an Spacewire, I^2C, RS422, optical, or wireless protocol. Current research at Boston University is examining the capability of optical and wireless communication in the cavity between cubes. This cavity provides an ideal medium for both RF and optical solutions as it is both RF and optically isolated from the instruments and subsystems by the subsystem housings, and from the outside environment by the primary structure.

Although beyond the scope of BUSAT, future CRC's should be designed with the capability to speak a variety of spacecraft standards in order to rapidly integrate various COTS instruments and subsystems. A limited implementation of this was demonstrated in BUSAT by the use of LVDS for most instruments and subsystems, USB in communication with the Auroral Imager, and RS422 in communication with the Communication Subsystem. An example of this design philosophy is the basic computer with its various ports assessable to the user. A basic laptop for example is equipped with 4 USB ports, a Secure Digital card port, Firewire, and a VGA port. CRC's with similar capability could accommodate a wide variety of spacecraft needs and could easily be designed into the CRC design.

The packet structure was custom designed to meet the needs of the BUSAT spacecraft. Although the packet was standardized there are other packet structures that may better meet the needs of a truly responsive satellite. Due to the two year design life of the University Nanosatellite program the BUSAT team was not able to integrate any of the industry spacecraft standards, such as the Consultative Committee for Space Data Systems (CCSDS) formats.

In the BUSAT spacecraft a data packet and a command packet was defined and all instruments and subsystems were required to follow the protocol. An example of the data packet can be seen in Figure 11 drawn by BUSAT team member Peter Argue.

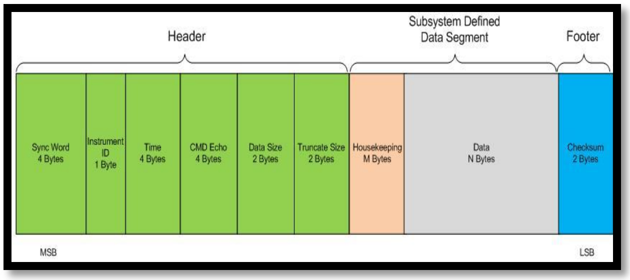

Figure 11 - A standardized data packet with a common header and footer to all instruments and subsystems.

A four byte sync word was used to identify the start of a data packet and was shared by all subsystems. Each instrument had a unique one byte instrument ID that was used to verify the packets origin as well as in data parsing in the Ground Support Equipment (GSE). A four byte spacecraft time is included in the header representing when the packet was sent. Following the time, a four byte command echo is embedded in the header echoing back the most recent command that was sent to the subsystem or instrument. The Data Size bytes and the Truncated Size Bytes are used to determine the housekeeping bytes size, and the data size. In BUSAT each Data Packet is a defined length and subsystems that only utilized a portion of the packet size filled the rest of the packet with zeros. This feature was unique to the student environment and could be optimized for larger scaled missions. The data packet ended with a 2byte checksum that was used to verify the proper transmission of the packet.

BUSAT Communications

BUSAT's communication system combines the traditional point to point data uplink and downlink with a novel system to provide for ad hoc communication with ground, air, or other space based systems. The mesh network capability provides for extended touch time with the ground, real time communication between satellites and balloons. In the traditional communication design nanosatellites within a constellation would need to communicate with the ground station directly to receive commands and downlink data. With the ad hoc network capability only one of the nanosatellites need be in range of a ground station allowing the other nanosatellites in the orbiting mesh to route their data through the nanosatellite in range of the ground station. The BUSAT design implements a MESH networking plan using the TDMA (Time Division Multiple Access) format to route the data through a possible network of nanosatellites to the ground. This protocol automatically allows for various routes within the mesh to transfer the data.

The MESH setup has been used successfully on the Taylor high-altitude balloon program with good results using six lofted communication units at 25 km altitude and separated, on average, by about 100 km in the HALO 1 experiment. The Spread Spectrum (900MHz) communications OEM RF module is manufactured by Freewave Technology. Freeway Technology has reported to have successfully flown their module in space on a picosat from the shuttle with changes to the Doppler shift software algorithm. The top illustration in Figure 12 shows the capability of Mesh networks to pass data through various members of the network providing for a more robust system. The bottom illustration of Figure 12 shows the proposed launch of high attitude balloons in the 2008 HALO experiment. Taylor and its partners were able to successfully launch and make connection with eight balloons in as many states.

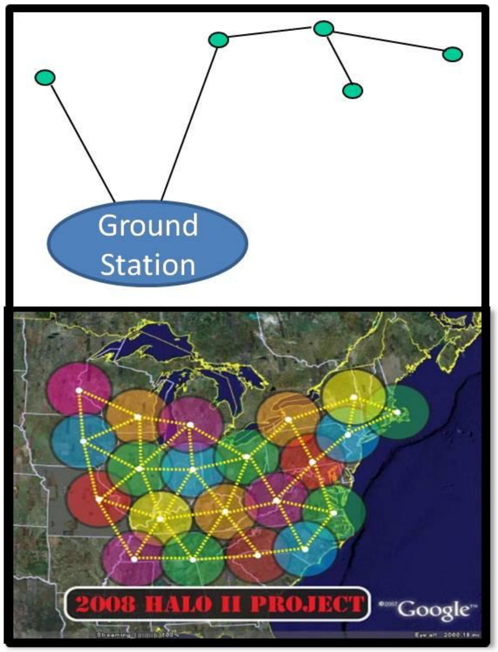

Figure 12 - The top figure illustrates the capability of passing data from point to point. The bottom figure was the attempted launch of HALO II launch. The actual number of points was eight balloons in as many states.

BUSAT Thermal Design

BUSAT's modular design provides an isothermal structure for the payloads and subsystems. This allows for a simple and reliable thermal control with minimal use of active thermal elements. With each component enclosed in its own thermally conductive case all of the cases are heat sunk to each other via the spacing braces. If one of the payloads in the satellite needs to be maintained at a different temperature than the rest of the systems a material with a lower thermal conductivity is substituted for that cube's spacing braces. For modules which require a higher temperature than the primary structure the spacers will act as an insulating blanket with the module's own internal power acting as part or all of the heat source. For payloads that require colder temperatures than the primary structure a conduction path leading to an exterior radiator can be configured. On BUSAT the batteries have a preferred operating temperature range above the preferred operating temperature range of the IES with its solid state detectors. Since all of the other payloads and subsystems can operate in the temperature range of either the batteries or the solid state detectors the decision to maintain the primary structure within the temperature limits of the IES and insulate the batteries was made. Since the IES is partially exposed to outer space the option to maintain its temperature lower than that of the primary structure is also viable. Also, the use of other thermal control technologies can be used. An example of this is the Variable Thermal Layers (VTL)[5] designed by InfoSciTex and Enerdyne Solutions that acts as a heat pump between a temperature sensitive cube and the remaining cubes. This thermal technology could allow individual cubes to have a limited temperature range while the rest of the structure swings over a much larger range.

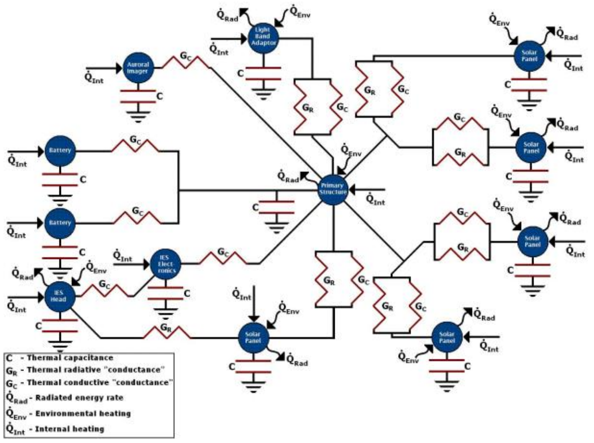

Figure 13 - Thermal network diagram of BUSAT

A MATLAB script is used to determine the temperature profile of the spacecraft over a variety of different orbits and orientations. Given the highly isothermal behavior of this satellite's internal structure, a thermal model with a limited number of nodes was developed to streamline the simulation time. Figure 13 is an electrical circuit analogy of BUSAT's thermal network. Once the spacecraft's design maintains the temperature requirements of all its components a more complex finite element software package will be used to analyze BUSAT's temperature profile.

Launch Vehicle Interface

The BUSAT design was built to interface with the Lightband adapter from Planetary Systems Corporation[6]. The Lightband is designed to provide for a secure, yet rapid deployment of small spacecrafts from a launch vehicle. BUSAT was designed for the 15 inch Lightband and was intended to be integrated onto a single port of an EELV Secondary Payload Adapter (ESPA).

COMPLIANCE WITH CURRENT STANDARDS

The BUSAT design was not built around any single commercial or space standard; however, the design complements several current standards.

Compliance with Space Plug and Play Avionics

The Space Plug and Play Avionics (SPA) is a standard for spacecraft design that is being proposed by a large number of organizations. SPA meets many of the objectives of the rapid response community by providing a design framework for the mechanical, electrical and software interfaces. SPA provides the mission designer the tools to rapidly formulate a mission, select payloads and subsystems based on rapidly determined requirements, and to ensure that the payload and instruments talk together. Although in the current version[7] of the SPA guidelines there is not a significant amount of detail concerning the actual physical implementation for SPA packages, the SPA concept is, in principle, able to integrate different packages that follow the SPA guidelines. The data system of BUSAT was not designed to follow the SPA handshaking arrangement through the sharing of device driver information with each other. However, the BUSAT mechanical concept strongly aligns with the SPA objective of rapidly integrating hardware together and fills the lack of specification concerning mechanical structures in the current document. The LVDS signaling protocol also meets the SPA guidelines as a space rugged data handling system. Were BUSAT to be compliant with the SPA guidelines the software of the instruments, subsystems, and C&DH would have to be rewritten to allow for self organization.

Compliance with PC104 Standard

The form factor for the BUSAT cubes allows for the use of PC104 size boards to be stacked inside the subsystems. The PC104 standard is a commercial embedded systems protocol that defines the physical size of boards and the signals that are passed between them. In the BUSAT design a PC104 Single Board Computer (SBC), a PC104 MILSPEC power supply, and a PC104 Xilinx FPGA are used. The ability to use ruggedized COTS components for short duration missions opens up a large number of commercial products to the space community. In the case of BUSAT and its Low Earth Orbit (LEO) mission it was determined that many of the commercial components were able to handle the low radiation environment.

Compliance with the CubeSat Standard

Although based off of the CubeSat concept BUSAT varies slightly from the volume specifications of the CubeSat design. The 1U cube of CubeSat is based on a 10 cm by 10 cm by 10 cm cube[8] whereas the BUSAT cube is based on a 4 in by 4 in by 4 in cube. Also the spacing between stacked cubes is different. BUSAT increased the spacing between cubes in comparison to the CubeSat spacing to allow for cable routing between the cubes and for thermal isolation capability. However, despite the difference payloads are able to be designed for both the CubeSat and the BUSAT standard by the addition of small spacers in the corners to the CubeSat size payload.

FUTURE WORK

The BUSAT design provides spacecraft engineers the ability to rapidly assemble a satellite; however, there are a number of ways to improve upon the design. As mentioned the data bus system could be designed to meet the SPA standard for network discovery and self organization. Compliance with the SPA software standard would provide a strong option for mission designers attempting to meet the ORS communities seven day objective of mission definition to launch. Work is also being done to investigate the capability of using the cavity between the subsystem and instrument cubes as a transmission medium for RF or optical communication. Finally, BUSAT's structure would require a vibration test to verify the analytical analysis that has been completed.

CONCLUSION

BUSAT is a comprehensive data bus standard originally constructed for the University Nanosatellite Program. The innovative mechanical bus design provides for rapid assembly of subsystems and instruments that are able to be built and tested prior to a specified mission. Coupled with the Space Plug and Play Avionics standard the BUSAT bus design provides a bus standard that is able to meet the needs of spacecrafts in the 10kg to 100kg mass category.

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