TSAT4: A Modular 3U CubeSat Characterizing Anabaena Cylindrica in Low Earth Orbit

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Abstract

TSAT4 is the fourth iteration of the University of Manitoba Space Applications and Technology Society's 3U nanosatellite design with a decentralized modular systems architecture that supports a biological payload. The payload tests the effects of exposure to a low earth orbit (LEO) environment on the growth cycle of *Anabaena cylindrica* bacteria. In addition to providing a potential base tropic layer for more advanced biological experiments, *Anabaena cylindrica* has shown potential for use in bioreactors for spacecraft life support and food production. As such, detailed characterization of how their lifecycle is affected by the LEO environment will be an important factor for future missions. This paper provides details about this scientific payload as well as the overall systems design, including: attitude determination and control, command and data handling, communications, power, structure, and thermal subsystems.

INTRODUCTION

TSAT4 is the fourth design iteration of the University of Manitoba Space Applications and Technology Society's (UMSATS') 3U nanosatellite. This iteration continues the development of the modular system architecture initialized in TSAT3 which includes separate electro-mechanical modules for command and data handling (CDH) and communications, attitude determination and control (ADC), power, and payload.[1]

Founded in 2009, UMSATS is a student driven technical society at the University of Manitoba which designs, builds, and tests 3U cubesats to compete in the Canadian Satellite Design Challenge (CSDC). The CSDC is an inter-university design competition with a two-year development cycle and USMATS is presently completing its fourth cubesat for the 4th iteration of the CSDC (2016-2018). Previously, UMSATS has placed 2nd at CSDC1, won the UrtheCast Outreach Award for CSDC2, and again won 2nd place at CSDC3.

MISSION GOALS AND CONTRIBUTIONS

The primary goal for TSAT4 is to learn how prolonged exposure to a low Earth Orbit (LEO) environment affects the development of primary producers such as members of Anaebaena spp. By characterizing their growth capabilities in LEO, the groundwork will be laid for future experiments investigating multi-trophic level experiments with *Anabaena cylindrica* as a base capable of oxygen production as well as nitrogen and carbon fixation. The encompassing metabolic capabilities of this microorganism paired with proven hardiness make it a candidate for investigation in applications such as enclosed space-based life support systems.

Secondary objectives of this mission are to assess the performance of the satellite bus architecture, especially the experimental command and data handling (CDH) and power subsystems, including deployable solar arrays.

Both CDH and power subsystems have been developed to utilize COTS components to provide capabilities for a wide range of potential missions. Using the modular TSAT architecture, these subsystems can be easily integrated into future cubesat designs to provide quick development and simplified testing.

PAYLOAD

The TSAT4 payload consists of a biological experiment which will measure the effect of exposure of LEO on the growth cycle of cyanobacterium *Anabaena cylindrica*.

Payload Background

Recently, there has been a renewed interest in human space exploration within both private and public sectors. For example, SpaceX aims to send humans to Mars by 2024. In the pursuit of becoming a spacefaring civilization, no shortage of problems exist. One such challenge is supplying food and oxygen on long-term missions. Cyanobacteria based bioreactors have been proposed for life support and food supply.[2] However, the effects of space environments on cyanobacteria lifecycles are poorly understood.

One such cyanobacterium, *Anabaena cylindrica*, seen in the figure below, is a photosynthetic microorganism with a history of space flight. Primary criteria included ability to form spores or desiccate, aerobic versus anaerobic, diet, pathogenicity, photosynthetic ability, benthic versus planktonic, special considerations such as toxin production and nitrogen fixation, research on the organism, and generation time.[3]

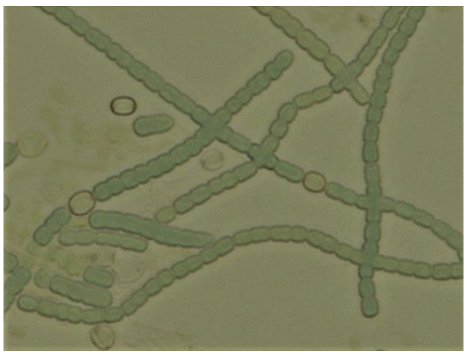

Figure 1: *Anabaena cylindrica* with vegetative cells, heterocysts, and akinetes.

Anabaena cylindrica has a well-documented strong photosynthetic capability and ability to form akinetes. In this resting state cells can remain inactive for years but can be revived to a vegetative state when exposed to optimal light and temperature conditions.[4,5] This long term storage capability is an especially important consideration for CubeSat missions as these satellites often require long storage periods prior to launch.

Additionally, *Anabaena cylindrica* forms a special cell called a heterocyst that fixes nitrogen for the carbon fixing cells.[6] Oxygen poisons nitrogen-fixing enzymes, and a heterocyst isolates the enzymes. While not the focus of this experiment, this nitrogen fixing ability has utility in future microecosystem experiments.[7] This microbe is also well characterized and its genome was sequenced in 2012.[8] *Anabaena cylindrica* is known to possess a resilient protein and DNA repair system and this, combined with its history of space exposure, made for an ideal experimental candidate in which to monitor the effect of growth in LEO.[9,10]

Previous research has demonstrated that *Anabaena cylindrica* can tolerate certain extreme environmental conditions including exposure to LEO environments while in its akinete (resting) cell state.[11] However, previous research has not tested *Anabaena cylindrica* while it is in its growth state. Despite their limitations, the results of these studies suggest that *Anabaena cylindrica* can be used as a model organism for experiments in LEO.[12] Additionally, *Anabaena cylindrica* may be suitable for more complex studies of multi-trophic level interactions involving bacterial producers and other model organisms for space experimentation such as tardigrades.

Payload Methodology

This experiment aims to evaluate the re-germination and growth rates of while still being exposed to LEO conditions. Necessary apparatus will provide required nutrients, growth conditions, and mechanisms for re-germination as well as varying degrees of shielding from solar radiation. The payload module will carry an array of identical growth chambers to increase the statistical significance of these tests and to allow for multiple exposure durations.

Following various durations of exposure to solar radiation and microgravity, akinetes will be provided growth-stimulating conditions: heat and light.

Detection will occur by measuring light absorbance at the maximum absorption wavelength of chlorophyll using a photodiode positioned on the side of the well opposite the light source (See Figure 2). This wavelength is 660 nm for the specific strain *Anabaena cylindrica* selected. The photodiode measurements will monitor levels of chlorophyll autofluorescence within each chamber as an approximation of growth. In addition, specific wavelength absorption measurements (known to relate to cell health) will assess cell quality.

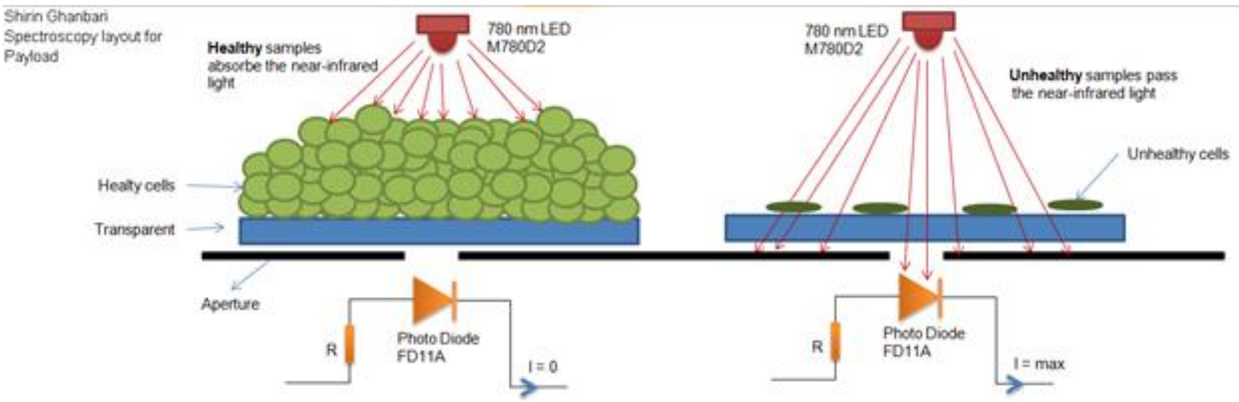

Figure 2: Design of custom spectroscopic detection system. Photodiodes sensitive to the absorption maxima of the *Anabaena cylindrica* in lab culture is used. Light supplied via near-infrared LEDs.

The control for this experiment will be an identical sister payload module housed in a laboratory on the University of Manitoba campus. As wells are activated and experiments are run in orbit, they will also be run on the ground. Comparison of growth in LEO and on ground can be made.

Our hypothesis is that exposure of vegetative cells to LEO will result in a significant decline in growth rate as the exposure time increases.

Payload Apparatus

The TSAT4 payload module provides approximately 1U (10x10x10 cm) of volume in which to house the payload. This space holds the light source, thermal control, light-detection system, and the microorganism enclosure. The enclosure itself was developed by microfluidics experts from the University of Manitoba physics department and consists of etched Polydimethylsiloxane (PDMS) with a fused to glass lid.

Test wells in the enclosure will be filled with BG-11 growth media and *Anabaena cylindrica* akinete samples which have been isolated using Percoll density separation. The enclosure will then be sealed and inserted into the payload module of the UMSATS satellite.

Microfluidics enables a much greater number of replicates than would otherwise be possible, increasing the reliability of results. Also of importance is the detection system. Again, the small scale posed an issue when looking into commercial solutions for the 3U CubeSat. University of Manitoba specialists in spectroscopy designed a custom system consisting of photodiodes sensitive to the maximum absorption wavelength of chlorophyll from the strain of *Anabaena cylindrica* being used in our experiment with light supplied by fiber optics.

Due to how close experimental assays are, and that light is used to stimulate organism growth, it is necessary for light to be confined to one area. LEDs supply light to fiber optic cables which focus light on specifically targeted wells. This ensures that non-tested wells remain dark. An exploded view of the payload apparatus can be seen in Figure 3 below.

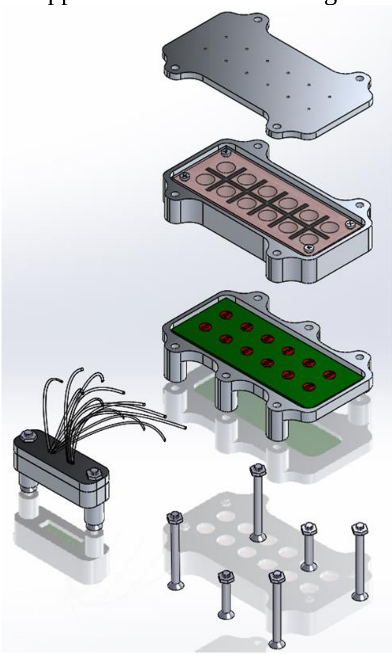

Figure 3: Exploded view of payload housing. Visible are the fiber optics, microfluidics wells, and aluminum chassis.

Heterogeneous growth of *Anabaena cylindrica* in the experiment wells presents a challenge for the precise measurement of growth. This microorganism is filamentous with growth occurring in long chains of cells. These chains elongate in the wells and when they reach a length equal to the diameter of the well they bend. The result is a greater association of cells with the perimeter of the wells than elsewhere – referred to as heterogeneous growth. Because light is supplied from above the wells and the photodiode is below, a lens is placed between the photodiode and the well so that after light passes through the sample it is focused onto the photodiode. This addresses the issue of non-uniform growth.

A further challenge is maintaining the temperature of the microbes between 25°C+/-3°C, a temperature range observed to be ideal for the growth of the strain which is being used in the payload. Again, due to the special constraints of the 3U CubeSat, specialists were required to supply a custom solution. Mechanical engineering students designed an array of thin heating elements capable of supplying heat to a set of two wells at a time. Since each exposure will be grown in duplicate, this solution fulfills the needs of the payload.

Radiation Shielding

A final consideration is radiation shielding. Physics specialists and biology specialists worked together to investigate the radiation profile likely to be encountered in LEO, and then to expose *Anabaena cylindrica* to simulated conditions on earth to ascertain the required shielding.

Radiation Tolerance of Anabaena

Our preliminary on-earth experiments resulted in a sub 50 percent growth of *Anabaena cylindrica* in 48 hours under UV-B radiation (wavelength 296 nm). Our laboratory tests found that higher levels of UV radiation exposure cause a decrease in anabaena cell-division, and eventually death of the organism.

The energy of X-ray photon radiation is 30,000 times UV-B. It is therefore likely that X-radiation would kill our payload samples within a few minutes. As such, X-ray photons must be minimized through shielding. Based on our laboratory tests, a maximum in-orbit dosage rate of 100 rad/year was proposed.

SPENVIS Simulation

To quantify the radiation protection effect of the satellite structure on the payload, a SPENVIS analysis was conducted for the assumed ISS-orbit.

The shielding power of the aluminum structure was tested on (i) dose in animal tissue (ii) dose in H2O and (iii) dose in general. The analysis revealed that in one year the total radiation dose for an unprotected payload will be 10^5 rad. But, using 2 mm aluminum, the most energetic bremsstrahlung is decreased by 98%. This reduction implies 2 of the 100 bremsstrahlung comes in using the Al shielding. For the total incoming radiation dose of 10^5 rad, 2 mm of aluminum shielding reduces it to 10^3 rad. The same results were observed in all three cases as shown below:

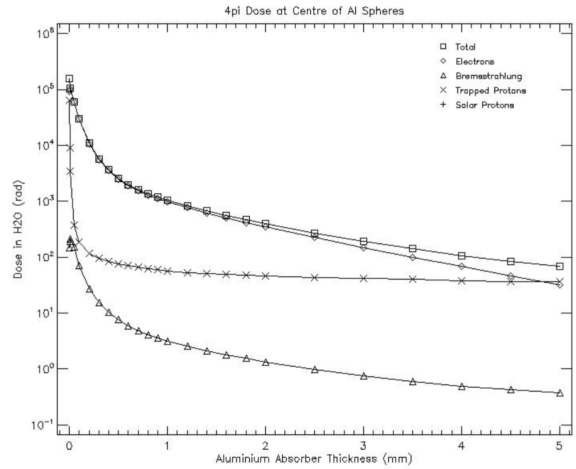

Figure 4: Radiation dose in water.

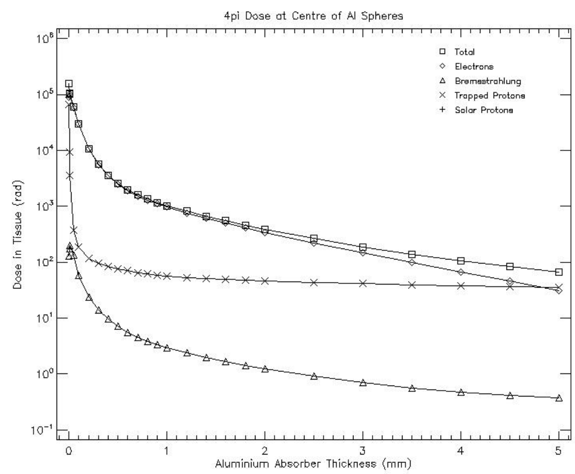

Figure 5: Radiation dose in water.

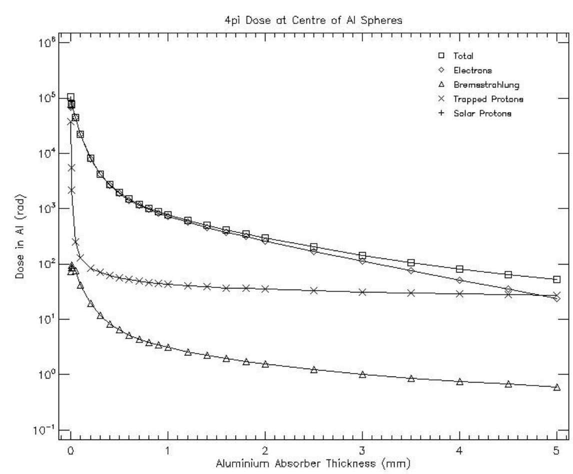

Figure 6: Radiation dose in general.

Proposed Shielding

To reduce the expected yearly radiation dosage from 1000 rad to 100 rad, a simple shield was developed consisting of 1mm of polyethylene within the 2mm aluminum structure. This shield provides graded Z shielding by ordering the materials from lower to higher Z materials.

The inner layer of polyethylene is required as, if high energy photons hit outer aluminum structure, they may produce harmful bremsstrahlung photons. In order to address this, a high-Z material such as polyethylene is required to absorb these energy photons. Nagamatsu et al. address the benefits of polyethylene-based shielding.[13]

CONCEPT OF OPERATIONS (CONOPS)

A 400km 51.6° inclination ISS-inserted orbit was selected for the development and analysis of this CubeSat. This orbit was selected due to its well documented radiation environment and ease of access through commercial launch services.

After the satellite has been deployed, it enters its launch and early orbit phase (LEOP) in ADCS stabilizes the satellite, as seen in figure 7 below. After 45 minutes the antenna is deployed and the satellite begins periodically transmitting telemetry data. On receiving a signal from the ground station, the satellite enters a holding mode. Further ground commands can activate a test trial of the primary *Anabaena cylindrica* payload or deploy the solar panel actuation mechanism (SPAM) which deploys the CubeSat's solar arrays.

In the event that the power system detects or transition the satellite into an over-current or low battery level, the satellite moves to a low-power mode in which non-essential functions are halted. In the event of a major power disruption or very low battery levels, the satellite will enter an ultra low power state in which all functions aside from the power subsystem and communications receiver are disabled. The satellite will only transition back to its holding mode by a ground station command.

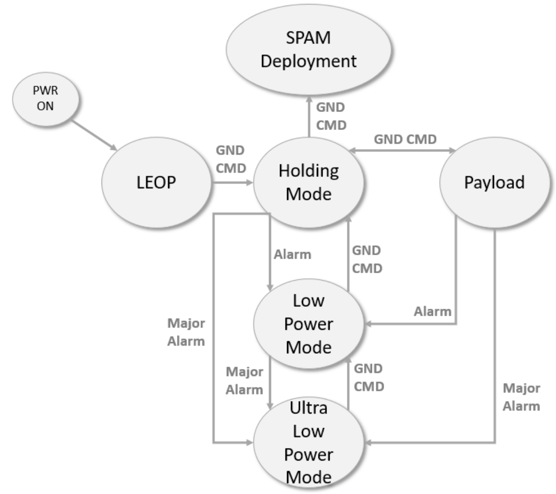

Figure 7: CONOPS

SYSTEMS ARCHITECTURE

TSAT4 employs a continuation of the decentralized modular systems architecture first developed for TSAT3.[1] This architecture is comprised of a set of independent electro-mechanical modules for CDH/Communications, payload, ADCS, and power subsystems. Each module is capable of performing tasks autonomously as prompted by the CDH scheduler.

This modular architecture aids development as well as assembly, integration and testing (AI&T) by: providing a common interface between subsystems, allowing concurrent testing, greatly simplifying systems integration, and increasing cross-mission compatibility. Modules can be used independently for new CubeSat missions or other applications such as weather balloons.

Each module uses a standardized mechanical and electrical interface as shown in below.

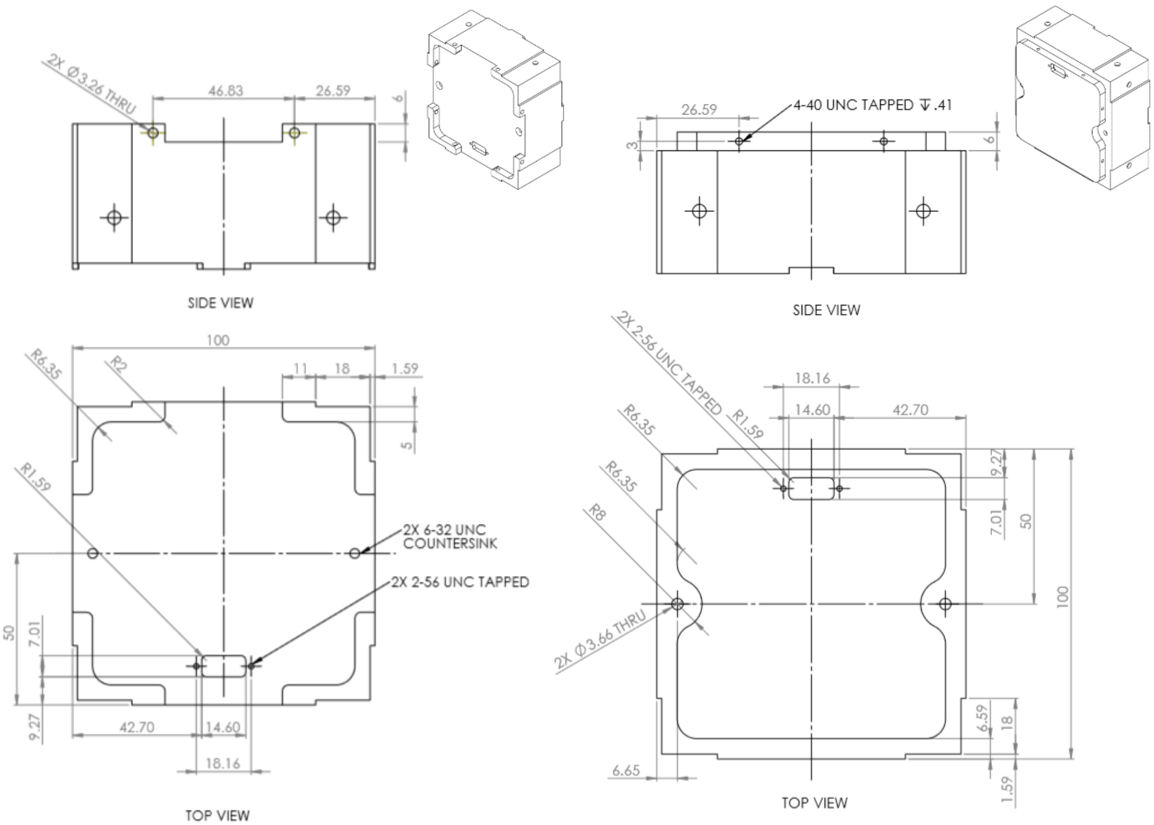

Figure 8: Upper (Left) and Lower (Right) Intermodule Interfaces

As seen in the figure above, the upper and lower segments different intermodule connection are held in place by four pairs of 4-40 machine screws. Additionally, two 6-32 machine screws are used to hold the two segments of each module together.

This common interface includes a 15 pin D-Sub connector for data communications and power distribution. Data communications are performed using the control area network (CAN) bus protocol. A systems diagram of this interface can be seen in figure 9 below.

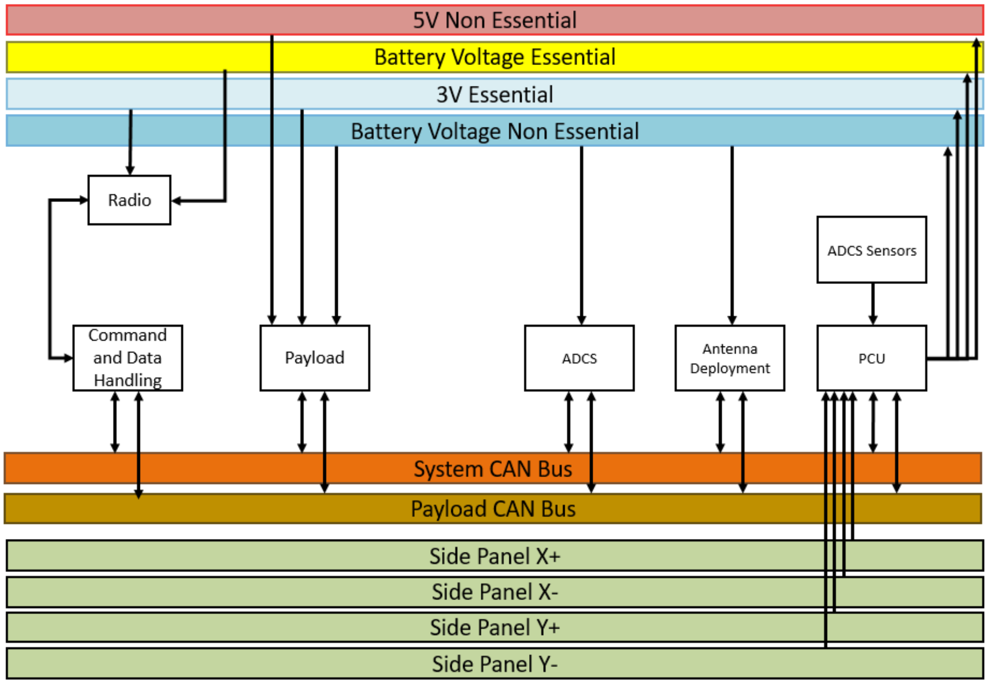

Figure 9: Systems Power and Communication Architecture

A CAN bus was chosen as it allows for a single common communications line for inter-module communications and functions well in high noise environments. Additionally, the CAN bus allows all nodes on the bus to perform error checking and ensures that faulty nodes do not prevent others from sending or receiving data.

SATELLITE BUS SUBSYSTEMS

The following sections provide details on the designs of each individual bus subsystem:

Attitude Determination and Control

As the primary *Anabaena cylindrica* payload does not have a required pointing accuracy, ADCS pointing requirements were driven by the power and communications requirements. This resulted in a comparatively low required pointing accuracy of 30° from the sun-vector.

As seen in Figure 10 below, the satellite uses four COTS sun sensors mounted on the +/-X and +/-Y surfaces and a BNO055 inertial measurement unit (IMU) for orbital determination. Attitude control uses three permalloy torque rods along each of the satellite's primary axis. An AT91SAM3X8E microprocessor-based controller performs ADCS calculations locally. Detumbling control is performed using the B-dot algorithm while PID based control is used for sun vector pointing.

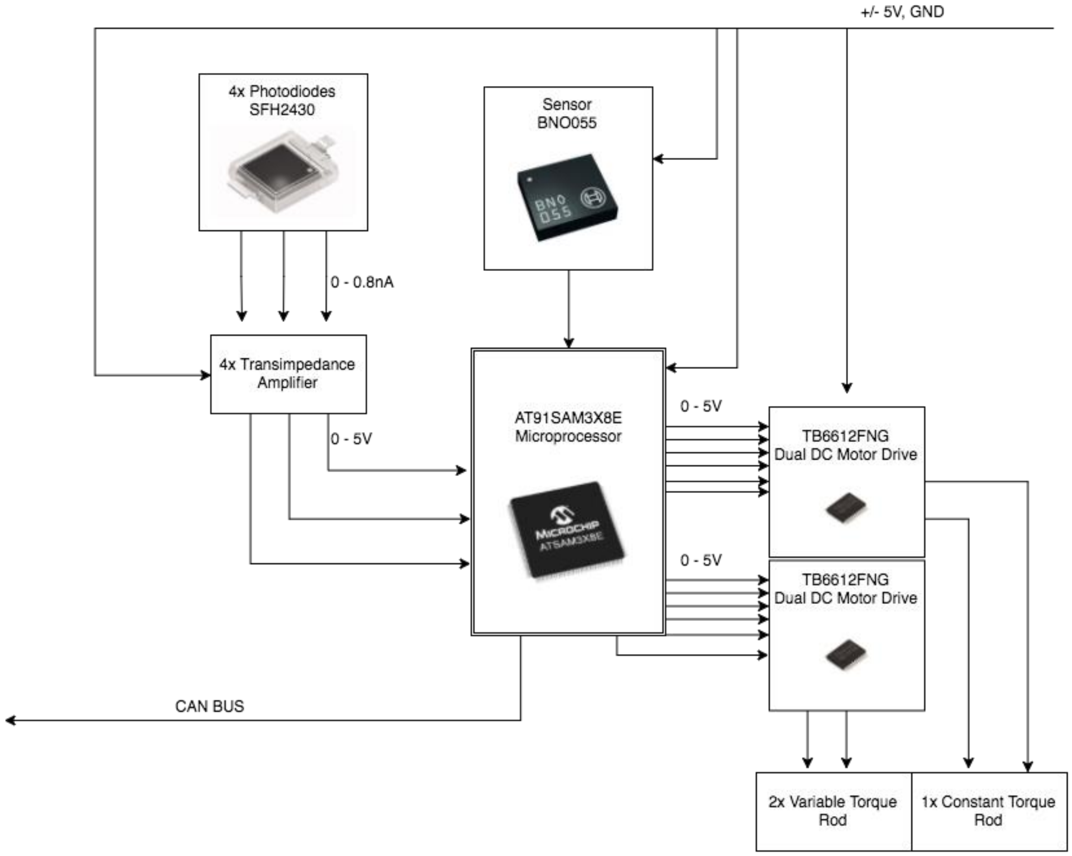

Figure 10: ADCS Hardware Diagram

Command and Data Handling

The command and data handling (CDH) subsystem is responsible for three main tasks: interfacing with the communication system to send and receive ground station commands, scheduling payload experiments and storing payload data, and taking telemetry data from other subsystems.

Interfacing with the communication system is done through serial peripheral interface (SPI), while interfacing with the other all other subsystems use the controller area network (CAN) protocol.

The core of the CDH subsystem is a scheduler that is capable of running pre-programmed and time-tagged tasks received from the ground station. The CAN bus also monitors the satellite's power levels. Certain tasks can be suspended from running based on the current power levels and task prioritization.

The AT32UC3C2512C-A2UT 32-bit AVR microcontroller from Microchip was chosen for this system due to its automotive grade that satisfies temperature requirements and its CAN bus capability. The scheduler is built on top of a pre-existing operating system, Free Real Time Operating System (FreeRTOS), since it offers support for multiple microcontrollers. Figure 11 below shows the CDH system block diagram.

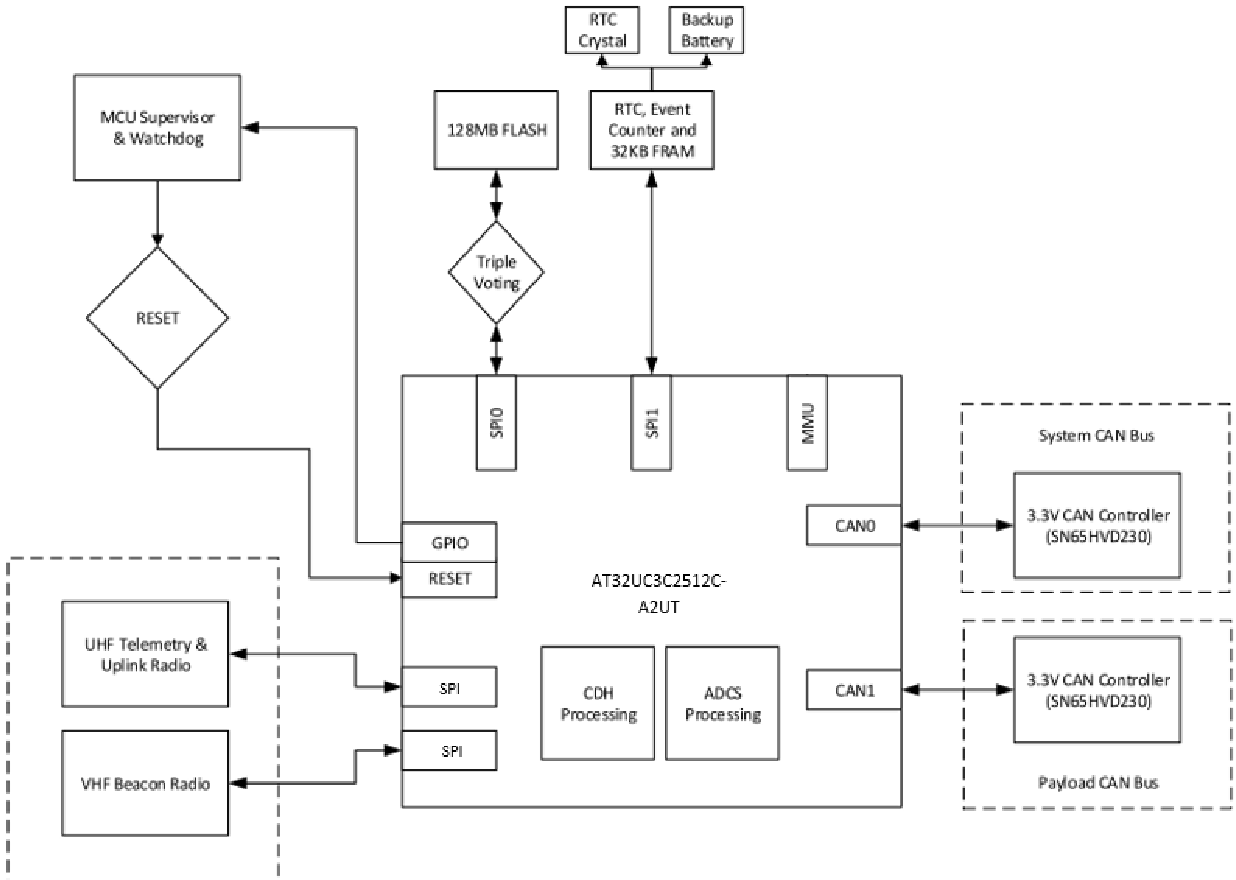

Figure 11: CDH Block Diagram

Communications

The satellite's communication subsystem is comprised of a 70cm ultra high frequency (UHF) monopole antenna, an SI-4463 transceiver, and an RF front end. It is a half-duplex system that uses frequency shift keying (FSK) modulation and the amateur radio protocol AX-25 encoding for a data rate of 9600 bps and a downlink margin of 4.6dB.

The communications system will be able to receive commands from the ground station and request data from the CDH subsystem to be downlinked. The system also has a beacon that transmits the callsign periodically every 10 minutes at the central frequency of 434 MHz.

The front end for the communications system is shown below, in figure 12, which includes a failsafe switch, 1W external amplifier (ADL5611), matching networks, one band pass filter and two low pass filters.

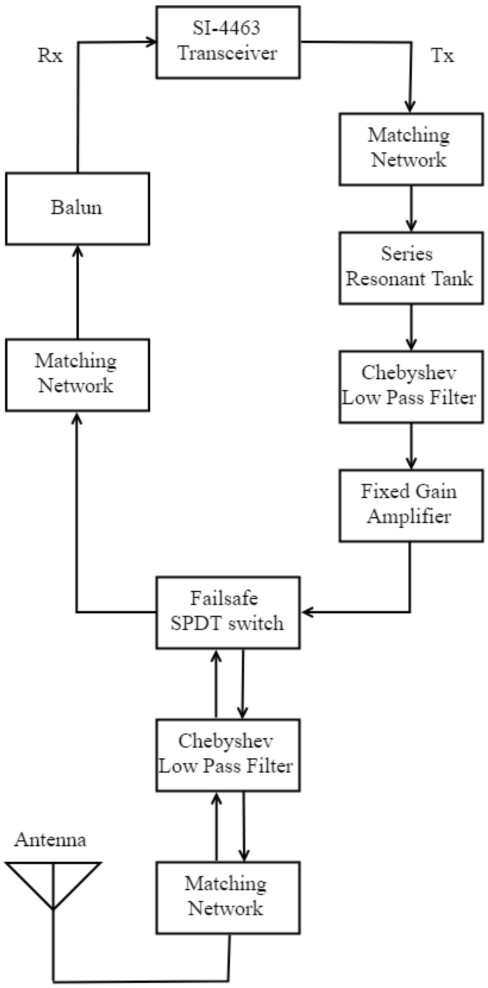

Figure 12: RF Front End

TSAT4 will use the University of Manitoba Amateur Radio Society (UMARS) ground station which is located in Winnipeg Manitoba. This ground station includes a 100W transceiver and a cross polarized UHF Yagi-Uda antenna with an automated tracking system.

This ground station will provide an average of four 6.6 minute passes per day for a maximum average daily data throughput of 1.9MB.

Power

The TSAT4 power subsystem was designed as a general purpose nanosatellite power system. Its performance significantly exceeds requirements for the current primary payload. Based on the TSAT4 mission's power budget (as seen below), orbit and using static solar arrays, the power system will experience a depth of charge of 5.3% and provide a power margin of 1.56. With the addition of deployable solar arrays included as a secondary payload, higher performance is expected.

Table 1: Power Budget

Component:	Budgeted Power	Duty Factor:	Orbital Average Consumption	Units
On-Board Computer:	0.76	30%	0.228	watts
Radio	1.82	30%	0.54	watts
Anabaena Payload:	2.80	30%	0.84	watts
Power Control Unit:	0.18	100%	0.18	watts
ADCS	1.19	50%	0.59	watts
		TOTAL	**2.38**	**watts**
			233.8	**W min**

During regular operations, the satellite receives power from four independent solar arrays with one array on each of the ±X and ±Y faces. All arrays, except for the -X array have six 28.3% efficiency Spectrolab UTJ solar cells in series, where as the -X array contains five cells in series to provide space for the satellite's umbilical connector and remove before flight (RBF) pin. The ±Y arrays are a part of the satellite's experimental deployable solar array, to be deployed after the primary biological experiment has been completed to gather valuable data to support future payloads that require more power.

Each solar array has its own independent maximum point power tracker (MPPT) circuit to maximize solar charging efficiency to near 98% before connecting to the main power bus in parallel, each capable of being monitored/controlled independently. The power to and from the batteries are monitored, along with all spacecraft loads. There are two DC-DC converters that operate at a nominal 97% efficiency each, and with an absolute maximum de-rated power output of 10W on the 3.3V essential bus and 15W on the 5V non-essential bus. The power control unit also includes three independent high side driven bus voltage switches for the essential/ non-essential battery voltage buses and the battery heater. This power is distributed to the satellite through one 15 pin D-Sub connection which runs through the satellite's structure, each with separate returns. The energy storage system consists of six Lithium Iron Phosphate (LiFePO) 18650 batteries in a 2-Series, 3-Parallel (2S3P) configuration for a total capacity of 4500mAh.

Deployable Solar Arrays

As previously mentioned, the power system includes a pair of deployable solar arrays, referred to as the Solar Panel Actuation Mechanism (SPAM), arranged along the Z/Y faces as shown in the figure below.

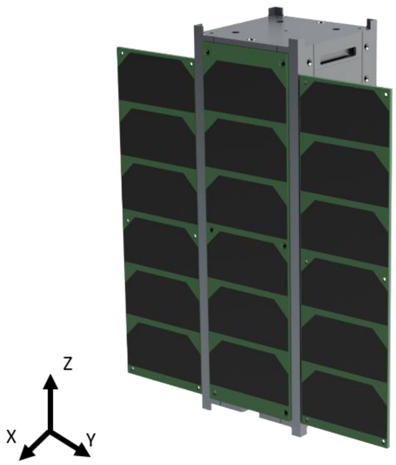

Figure 13: TSAT4 with Deployed SPAM

These solar arrays are included as a technological demonstration payload. However, as TSAT4's ADC system is not capable of controlling the satellite's rotation about the Z axis, these arrays are to be deployed at the end of the satellite's operational life.

Each array is connected to the primary structure through two spring-torsion hinges and is held in place using a spring-loaded latch. During launch and normal operations, the latch is held in balance by a spring and UHMWPE cord. When the array is to be deployed, the cord is cut using a burn-wire. This allows the tension-spring to pull the latch out of position which in turn allows the array to deploy.

Structure

The TSAT4 structure is an iteration on the modular system developed for TSAT3 and is comprised of four modules which contain the satellite's CDH and communication systems, payload, ADCS, and power systems respectively.

Each module is comprised of two alodined half shells, machined from 6061-T6 aluminum, with minimum wall thicknesses of 2mm and integrated supports for internal components. Four anodized rails provide continuous contact between the modules and the deployment chamber.

Based on quasi-static acceleration and random vibration testing, the structure has a factor of safety of 3.8 and the first three fundamental frequencies are 119 Hz, 524 Hz, and 1245 Hz. The satellite has a total mass of 3.01kg, well below the 4kg maximum mass specified by the CSDC competition requirements.[14] The structure comprises 2.06kg of this total mass.

Thermal

Based on thermal analyses, the satellite's minimum and maximum nodal temperatures are 2°C and 26°C when the solar arrays have not been deployed. This is well within the -20°C and +60°C upper and lower temperature of the satellite bus' hardware. Thermal control for the bus was performed using passive thermal control via surface coatings. Heaters are included for the satellite's batteries, which must be held between 0°C and 45°C.

Active thermal control, utilizing thermoelectric coolers and resistive heaters, is required to provide fine thermal control for the *Anabaena cylindrica* payload chamber which must be maintained at 26°C +/-3°C while the experiment is active.

CONCLUSIONS

The UMSATS team has developed a 3U CubeSat, utilizing the modular architecture established by TSAT3, to develop a new iteration of the cubestat design which includes robust COTS-based CDH and power subsystems that can be used for a wide range of future missions.

The primary payload of this new iteration is to determine how the growth cycle of *Anabaena cylindrica* bacteria is affected by exposure to a LEO environment. In this payload, the bacteria will be activated from a spore-state and its growth will be monitored over time to both characterize *Anabaena cylindrica's* growth in LEO and to set the stage for more complex trophic studies that could, one day, enable oxygen and food production during long-duration spaceflight.

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