BAMMsat-on-BEXUS: A technology and operation demonstration of a bioCubeSat platform on a stratospheric balloon flight educational program

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ABSTRACT

This paper reports the current use of the REXUS/BEXUS educational program. The program allows university students across Europe to carry out scientific and technology experiments on research sounding rockets and balloons. BAMMsat-on-BEXUS (BoB) is an experiment from Cranfield University and University of Exeter performing a technology and operation demonstration of a bioCubeSat on a stratospheric balloon at an altitude of ~30km above the ground. BEXUS stands for Balloon Experiments for University Students and is realized under an agreement between the German Aerospace Centre (DLR), Swedish National Space Agency (SNSA), European Space Agency (ESA), and EuroLaunch. The term bioCubeSat could be used to refer to a nanosatellite in a CubeSat format with a biological experiment on-board. Over the last decade, a series of six bioCubeSats have been launched into orbit by NASA and a private company, SpacePharma, i.e., GeneSat, PharmaSat, O/OREOS, SporeSat, Dido-2, and EcAMSat. The BAMMsat concept (Bioscience, Astrobiology, Medicine and Material science on CubeSat) is a bioscience hardware platform which aims to advance the current state of the art technology, under development at Cranfield University, for application in LEO and beyond LEO. This generic platform can be flown as a free-flying CubeSat or hosted as a payload on a larger spacecraft. BAMMsat utilizes COTS sensors, actuators, and fluidic components to enable bioscience experiments by reproducing the features in a traditional laboratory into a miniaturized "laboratory." It is designed to be compatible with the mass, volume, and power budget of a CubeSat payload and flexible for a broad range of applications and biological systems such as microorganisms, nematode worms, and mammalian cells cultures, including human cell cultures. The core features of BAMMsat are the ability to (i) house multiple samples, (ii) maintain samples in an appropriate local environment (ii) perturb sample fluidically, and (iv) monitor samples.

BoB aims to perform a technology and operation demonstration of the BAMMsat bioCubeSat payload in an extreme environment such as the stratosphere. The experiment is to be flown on the BEXUS30 flight campaign in October 2020 from ESRANGE Space Centre, Sweden. The stratosphere can be used as an analog of some aspect of a relevant spaceflight physical environment such as reduced pressure (near-vacuum; ~11 mbar), and temperature (-50°C). The BEXUS flight campaign could also be used as an analog of pre-flight, flight and post-flight operation similar to orbital launch campaign. For bioscience experiments, the biological samples often imposed additional requirement during pre-flight to ensure its viability. BoB will house *C. elegans* in a 2U pressure vessel to demonstrate its functionality to provide a controlled thermal and fluidic environment with appropriate housekeeping control. This functionality reflects the hardware capability to maintain a viable biological sample. BoB has a 3U CubeSat form factor with 2U allocated for the BAMMsat hardware and 1U allocated as the BAMMsat-on-BEXUS bus. This paper reports progress at four months before flight campaign. The paper also discusses an overview of the experiment objectives and systems design, to build a representative CubeSat that is translatable into a free-flying orbital CubeSat.

ABBREVIATIONS

AIV	Assembly, integration and verification
ATM	Atmosphere
BAMMsat	Bioscience, Astrobiology, Medicine, Material on Satellite
BEXUS	Balloon Experiment for University Students
BoB	BAMMsat-on-BEXUS
CAD	Computer-aided design
COTS	Commercial off the shelf
DC	Direct current
EcAMSat	E. coli AntiMicrobial Satellite
EPS	Electrical Power System
FEA	Finite Element Analysis
ISS	International Space Station
LEO	Low Earth Orbit
LCL	Latching Current Limiter
MCSD	Multi-chamber sample disc
NSTP	National Space Technology Programme
O/OREOS	Organism/Organic Exposure to Orbital Stresses
PID	Proportional–Integral–Derivative
P-POD	Poly-Picosatellite Orbital Deployer
REXUS	Rocket Experiment for University Students
RV	Rotary valve
RPi	Raspberry Pi
RTD	Resistance Temperature Detectors
SEVO	Space Environment Viability of Organics
SLS	Space Launch System
TRL	Technology Readiness Level
UKSA	United Kingdom Space Agency
WT	Wild type

INTRODUCTION

Why bioCubeSats in space?

National space agencies around the globe have manifested interest in travelling beyond LEO with planned long-duration spaceflight to the Moon and Mars. However, our knowledge of long-duration radiation exposure to high energy particles and microgravity effect on Earth's biology is still inadequate to be able to perform these missions safely. There is a knowledge gap concerning the impact of the space environment on Earth's biology, especially for beyond LEO. These biological studies require *frequent access* and *a large number of discrete samples* before it can be understood and accepted by the scientific community. Historically access to the space environment has been limited due to high cost, infrequent flight opportunities, and long-lead-time. CubeSat platforms offer opportunities to improve access with shorter development time, reduced mission cost and an increasing number of flight opportunities. Research in life science can leverage from the CubeSat concept to access space environment compared to the traditional, more prominent space laboratories or satellites. In this paper, the term bioCubeSat refers to a nanosatellite in a CubeSat format with a biological experiment on-board.

The current state of the art in bioCubeSat

The interception of biological experiment and CubeSat has been established in LEO by NASA, and a private company named SpacePharma. To date, six bioCubeSats have successfully launched into orbit. While volume and mass restriction in a CubeSat will be challenging, the success of these bioCubeSats is proven and de-risk the basic concept of bioCubeSat.

The six bioCubeSat are GeneSat [1], PharmaSat[2], O/OREOS [3], SporeSat [4], Dido-2 [5], and EcAMSat [6]. Five of these bioCubeSats shared a common heritage coming from NASA Ames. Except for Dido-2 which was developed by SpacePharma. Due for launch, BioSentinel will likely be the first bioCubeSat experiment to be performed beyond LEO, and hence beyond the protection of the Earth magnetosphere [7].

Microfluidic has been an enabler for bioscience research on CubeSat where volume and mass are limited. Both NASA Ames and SpacePharma leverage from microfluidic concept to have a compact end to end experiment design carrying on-board microliter reagents to run the experiment. NASA Ames fabricated a fluidic card constructed by laminating various layers of materials, often laser-cut polymers, and laminating them with pressure-sensitive adhesive [8]. The fluidic card contained the chamber which houses a single-cell organism such as *E. coli*, *S. cerevisiae, B. subtilis,* and *H. chaoviatoris*.

It should be noted that bioCubeSat application is not limited to microfluidic. The O/OREOS SEVO experiment was designed as an exposure experiment to the space environment. SEVO exposed thin-films of organic molecules that have astrobiological relevance to the outer space environment [3]. BioCubeSat could also perform simulated gravity experiment as demonstrated on SporeSat. The bioCD on-board SporeSat is a lab-on-chip device that measures the Ca^{2+} ion around a single cell fern spores, *C. richardii* [4]. Varying levels of artificial gravity was produced by an integrated rotating centrifuge platform.

What is BAMMsat?

Bioscience, Astrobiology, Material and Medicinal science on CubeSat or BAMMsat is a bioCubeSat concept developed to contribute to the advancement of the field. The concept revolves around the development of a core hardware to cater to a broad range of BAMM related experiment. The applications have common features that have the abilities to (i) house multiple samples, (ii) maintain samples in an appropriate local environment, (iii) perturb sample fluidically, and (iv) monitor samples. To date, a functionally representative breadboard of the final CubeSat design is currently being developed, advancing closer to a CubeSat model as part of the BAMMsat-on-BEXUS experiment.

The objectives of this paper

This paper objective is to update the community with the recent progress of the BAMMsat concept to introduce the mission and overall systems design of the experiment. A 3U flight version for a stratospheric balloon flight is currently in development in conjunction with BAMMsat-on-BEXUS.

BAMMSAT-ON-BEXUS

BAMMsat-on-BEXUS (BoB) is an experiment to demonstrate the technology and operation demonstration of the BAMMsat hardware platform on a large stratospheric balloon. BoB will be using *C. elegans* as a biological sample for the experiment ensuring its viability for the duration of pre-flight and flight. Experiment success will demonstrate the hardware capabilities to perform such an experiment in anticipation for spaceflight by increasing its TRL.

BoB's experiment was accepted on the REXUS/BEXUS program, specifically BEXUS, in December 2019. The program provides opportunities for university students to perform experiments on a sounding rocket or a large stratospheric balloon. BEXUS provided the flight platform to launch BoB to an altitude of ~30 km above the ground. At this altitude, the environment is harsh with reduced pressure of ~11 mbar and temperature of -50 °C. The dynamic environment is not easily replicated on the ground and can be used as an analog to spaceflight.

Another essential aspect of performing technology demonstration with a live biological sample is operation. Additional procedures and handling have to be in place to meet the biological requirements as oppose to other types of experiments to ensure the viability of the samples. The flight enables the team to develop a pre-flight, flight and post-flight operations that could be translatable to spaceflight.

There are limitations with a stratospheric balloon flight. The flight environment does not include microgravity, radiation from high energy particle, and extreme vibration associated with a rocket flight. BoB was designed to demonstrate the features of the hardware, and test the pre-flight, flight and post-flight operation.

Why C. elegans in BAMMsat?

C. elegans is a non-parasitic, multicellular nematode worm commonly found in soil. [9]. It also has flight heritage, previously flown on the Space Shuttle, ISS, Shijian and Shenzhou spacecraft.

C. elegans and humans have highly conserved signaling and molecular pathways as 83% of *C. elegans* genes having human homologues, making it a model organism and a good representative of human physiology. *C. elegans* have been used to study genetics, development, ageing, muscle physiology, radiobiology and a variety of human diseases.

The applicability of *C. elegans* in BAMMsat was identified in 2018 when a full science case was developed for a flight opportunity in LEO. The consortium, which consisted of Cranfield University and University of Exeter developed a science case to study the therapeutic efficacy of existing approved drug compounds against molecular pathway involved in deleterious human response on space radiation and microgravity. Fortunately, humans and *C. elegans* show similar physiological and molecular maladaptation to microgravity. Microgravity elicits reproducible alterations in cytoskeletal and metabolic gene and protein expression in space-flown *Caenorhabditis elegans*. The long-term goal is to develop a future countermeasure for long-duration human spaceflight.

It was identified during the development of this flight opportunity that *C. elegans* has never been flown in a bioCubeSat. However, the concept was proposed in 2004 as NemaSat[10]. Previous bioCubeSats have opted for a single cellular model organism such as *E. coli* and *S. cerevisiae*. Having a complex multicellular organism, *C. elegans*, as another option on-board a compact, and automated bioCubeSat could contribute significantly to the science community

Aim and objectives of the experiment

The experiment aims to perform technology and operation demonstration of a BAMMsat payload using, C. elegans, on the BEXUS stratospheric balloon flight in anticipation for future spaceflight

The experiments objectives are:

1) Develop and demonstrate the ability to handle, integrate and operate BAMMsat in a spaceflight representative context

2) Demonstrate the key BAMMsat ability to provide a controlled environment relevant to maintaining viable biological samples in extreme operational environments (specifically thermal and fluidic control together with appropriate housekeeping sensing).
3) Complete the development of a spaceflight relevant model version of BAMMsat suitable for the flight on BEXUS. BoB is designed to have a 3U form factor. The 2U experiment hardware and the pressure vessel is the spaceflight relevant model while a 1U bus is intended to be an interface to the BEXUS balloon platform.

House multiple samples

One of the core features of BoB is the ability to house multiple samples. BoB achieves this using a custom fluidic disc, see Figure 1. The 87 mm disc holds 32 chambers with each chamber diameter of 3.5 mm and 3 mm depth.

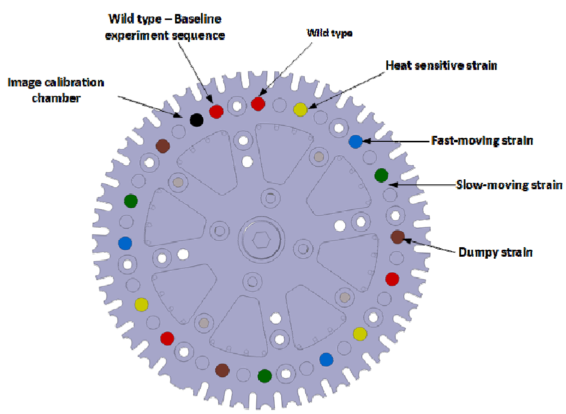

Figure 1: Housing of various *C. elegans* strain inside the MCSD

Various strains of *C. elegans* are employed for the BoB flight to simulate generic strain variety in a bioscience experiment. The strains on BoB were explicitly chosen to help validate the experiment objectives. The different type of strains and its justification are available in Table 1. The WT strain will be used as the primary data or baseline and compared with other strain to validate the objectives. The placement of the strains in Figure 1 may seem scattered. However, the strains were carefully placed to optimize experiment timeline taking account the rotation of the disc.

Table 1: Multiple *C. elegans* strains on-board BoB

Type of strain	Remarks
Wild type (WT)	Primary data for the experiment, the WT behavioral will be confirmed via comparison to the other strains
Cha-1 Heat sensitive	The phenotype will react to temperature changes and can be used to confirm the thermal control system on BoB
Dpy-13 Dumpy	The phenotype will grow shorter than WT. Will be used to proving that BAMMsat can show changes in body size and mobility and motility movement
Unc-54 Slow-moving	The phenotype will be used as a control to show that the WT is moving at the expected rate
Unc-43 Fast-moving	The phenotype will be used as control to show that the WT is moving at the expected rate

Maintain samples in an appropriate local environment

Another core feature of the BoB hardware is the ability to maintain an appropriate local environment. The feature facilitates the sample to ensure its viability for the duration of the experiment. The BoB hardware is designed to meet the *C. elegans* requirements. For instance, the 2U experiment hardware is placed inside a 2U pressure vessel to contain the local ambient atmosphere during assembly. The disc has a layer of gas permeable membrane to allow an exchange of O_2 and CO_2 between the fluidic chambers to the contained local atmosphere fo sample use.

The viability of the biological samples is dependent on the surrounding temperature. Intrinsically, BoB hardware has a combination of active and passive thermal control to maintain a regulated temperature during pre-flight and flight. During pre-flight, to lower the metabolic rate of the *C. elegans*, the temperature will be maintained at +12 °C ±2 °C. During the flight, the temperature will be maintained at +20 °C ±2 °C to resume standard metabolic rate.

Fluidically Perturb samples

The ability to fluidically perturb the sample provides BoB with the ability to change the fluidic compound in the sample chamber and hence the state of the *C. elegans*. It is foreseen that having the ability to administrator three different fluidic compounds enables a high-throughput experiment. The type of fluidic compound and its justification is included in Table 2. It is designed to demonstrate generic operational procedures.

Table 2: Fluidic compounds on board BoB

Fluidic compounds	Remarks
Growth media + OP50 *E. coli*	A liquid solution designed to support/feed the growth of *C. elegans*
Growth media + drugs (sodium azide)	Low concentration of anesthetic and administration will inhibit movement providing a visual biological outcome simulating drug administration
Fixative (glutaraldehyde/ paraformaldehyde)	A chemical substance used to preserve or stabilize *C. elegans* for post-flight analysis. More relevant towards spaceflight with sample return capability such as ISS

Monitor samples

The fourth feature of BoB is the ability to monitor the samples. After exposing the samples to the environmental stressors or experiment in question, the information and results have to be obtained for analysis. BoB has an imaging system which captures static images and video for assessing sample health and activity.

The feature on BoB is a pared-down version of spaceflight. The hardware on BEXUS was simplified due to budgetary constraint and quick project turnaround. Bright-field microscopy was seen as sufficient to meet the objectives. In the final flight version, the hardware can include fluorescence microscope, visible spectrometer, pH sensors and O_2 sensor. The selection can be catered to the experiment requirements.

SYSTEMS OVERVIEW

The section will discuss a systems overview of the BAMMsat concept currently in development. At four months before the launch campaign, the system is presently being manufactured and tested at Cranfield University. The section of the paper will include an introduction to the various subsystems within BoB to help the reader to explore the concept.

Figure 2 represents the 3U BoB system. It is envisaged that the final CubeSat will have a 3U format with 2U allocated for the experiment. The pressurized, thermally controlled 2U system provides the internal atmosphere for O_2 and CO_2 exchange between the sample in the chamber and the localized environment inside the pressure vessel. While 1U is allocated for the CubeSat bus. The 1U BoB bus is designed to hold the on-board data handling module and to interface with the BEXUS gondola. This configuration is similar to the previous NASA and SpacePharma bioCubeSats.

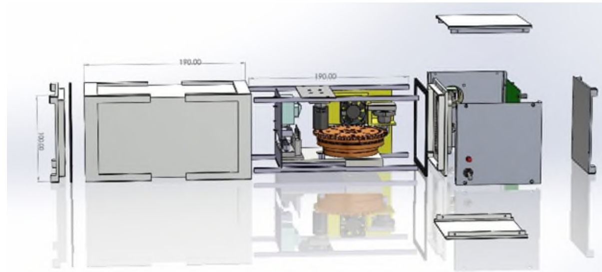

Figure 2: Exploded view of the BoB system. (Left) 2U pressure vessel, (middle) BoB experiment payload, and (right) BoB 1U bus

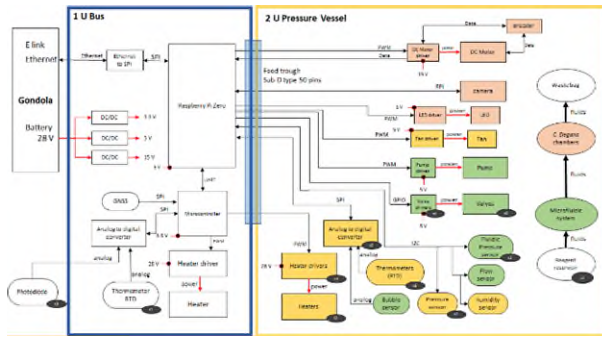

Figure 3: Block diagram and interface between various subsystems.

Figure 3 provides a further overview of the BoB systems and interfaces. There are three primary interfaces to connect the three components, i.e., BEXUS gondola, 1U bus, and 2U pressure vessel. From the left, the 1U bus and BEXUS gondola are interfaced to provide a power source and a communication line to access the antenna on the gondola. The 2U pressure vessel is sealed with o-rings and mechanically bolted to the 1U bus. Data transfer and power connect via 50 pins hermetically sealed feedthrough. The feedthrough couples various sensors and actuators inside the 2U with the primary computer and a microcontroller inside the 1U bus. Figure 4 represents the sensors and actuators inside the 2U pressure vessels. They can be grouped into microfluidics subsystem, imaging subsystem and thermal subsystem.

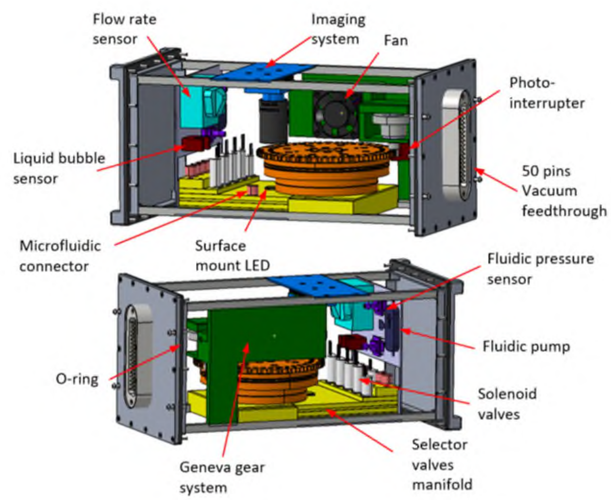

Figure 4: CAD images representing the BoB experiment payload with the pressure vessel covered removed.

Fluidics subsystem

The microfluidics subsystem comprises of COTS actuators and sensors which controls and enables the fluidic network. The fluidic network transports growth media, drugs and fixative from the reservoir bags to the sample chambers. Figure 5 represents the fluidic flow path.

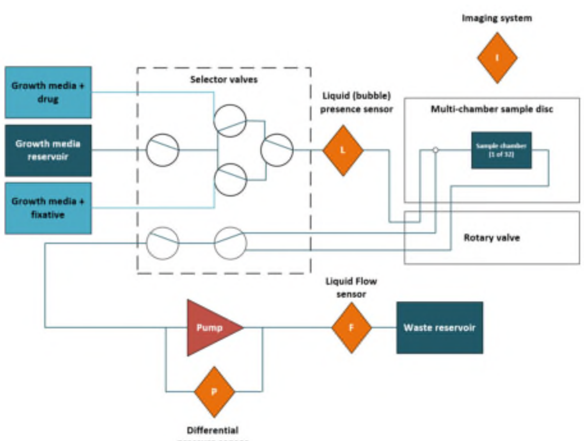

Figure 5: Microfluidic flow path and related sensors and actuators on BAMMsat-on-BEXUS in an unpowered configuration.

The components are placed carefully, for example, in Figure 5, the pump (mp6-hyb; Bartels Microtechnik) will be pulling the growth media and reagent from the reservoirs on the left. Since various fluidic medium will travel across the same pump, to avoid cross-contamination, the pump is placed at the end of the fluidic network where the state of the medium is no longer critical. A differential pressure sensor is connected between the pump to detect any potential pressure loses. Fluidic flow rate (lpg10-1000; Sensirion) is placed immediately after the pump to measure the mass flow rate of the fluid pulled by the pump.

The selector valves manifold controls the flow path and direction of the fluid, see Figure 4 and 5. A combination of 2/2 and 3/2 solenoid valves provides a combination of fluidic openings and closing that can direct the fluids to the required path when pumped. The selector valves manifold is made up of solenoid valves placed in between laminated layers of laser-cut polymethyl methacrylate (PMMA). The layers of acrylic are bonded together using laser-cut double-sided pressure-sensitive adhesive.

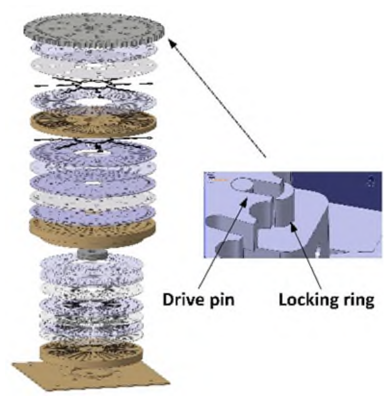

Figure 5: Exploded view of the 20 layers multi-chamber sample disc and Geneva gear mechanism.

The multi-chamber sample disc (MCSD) is a crucial component of BAMMsat and was developed and manufactured in-house at Cranfield University. The layers are mechanically bolted together instead of bonded by adhesive. The design eases pre-flight late-access integration of biological samples compared to when its bonded by adhesive. The sealing is provided when compressing a layer of silicone elastomer between the layers to prevent any fluidic leaking.

The rotary valve (RV), the bottommost layers in Figure 5, is the interface between the disc and the rest of the fluidic system. The configuration of a stationary interface and the rotating interface allows the fluidic path to connect to one chamber at a time, which is selected by rotating the disc while closing the fluid access to the other chambers. The combination of MCSD and RV provides the flexibility to perform a broad range of scientific experiments and biological systems. The rotating capability of the RV allows 96 valves (3 valves per chamber x 32 chambers) to be assembled in a compact configuration. For the BoB flight, only 16 chambers (Three chambers per strain and one baseline chamber) will be used instead of the full 32 chambers, see Figure 1. The 16 chambers were viewed as sufficient to meet the experiment objectives.

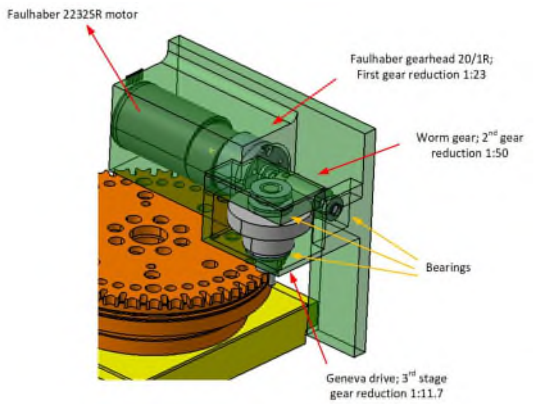

Figure 6: BoB motor subsystem to drive the Geneva gear mechanism.

The rotation of the MCSD is driven with an aluminum layer (upmost layer in Figure 5) and Geneva gear. The gear was CNC manufactured on the outer edges of the aluminum. The design of the Geneva gear provides an inherent mechanical indexing capability to fluidically address and observe discrete samples and ensure alignment of the rotary valve. Compared to another gear system, Geneva gear provides intermittent motion (to move the disc between discrete position) and locking the disc when in place.

Imaging subsystems

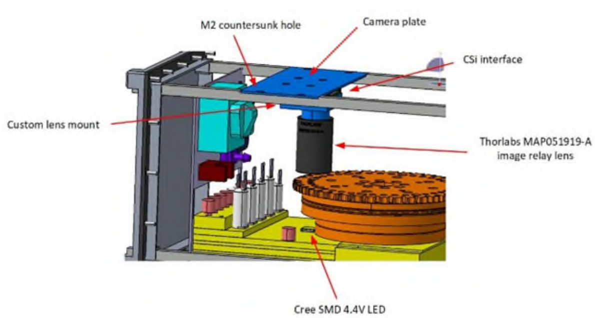

Figure 7: BoB imaging subsystem using Raspberry Pi v2 camera

BoB imaging subsystem is based on the combination of Raspberry Pi V2.2 camera, custom lens mount, 1:1 image relay lens, and a surface mount LED. The Raspberry Pi (RPi) camera was selected to shorten development effort and has demonstrated to image *C. elegans* and flown in space. Further studies highlighted that it is uncommon to find an 8MP camera in a small packaging format as the RPi camera. The CSi interface and cabling provides a high-speed communication line and comparatively high-quality image. The camera also complements the main computer, Pi zero. It has an encoder/hardware-accelerated compression chip which is beneficial for data budget. The illumination source is provided by a surface mount LED.

Thermal subsystem

Thermal regulation is required to ensure a viable temperature for *C. elegans* during two phases. The first is the pre-flight with a temperature requirement at 12 °C ± 2 °C, and the second is the flight with a temperature requirement at 20 °C ± 2 °C. During the pre-flight, the low temperature of 12 °C ± 2 °C will keep the *C. elegans* in a low metabolic rate, slowing the growth rate and maintaining the optimal developmental stage for the flight.

The driving factor for the thermal subsystem is the surrounding temperature at the ESRANGE launch site, located north of Sweden. The temperature is expected to be cold at around 0 °C and -15 °C in October. The thermal control is achieved by a combination of active heating and passive heat retention. Active thermal is achieved using a combination of Kapton® thin-film heaters, resistance heating wires, and RTD sensors, see Figure 8. The previous bioCubeSat, Genesat have used a "bang-bang" control system [11]. This type of controller also seems to fit the BoB's requirement.

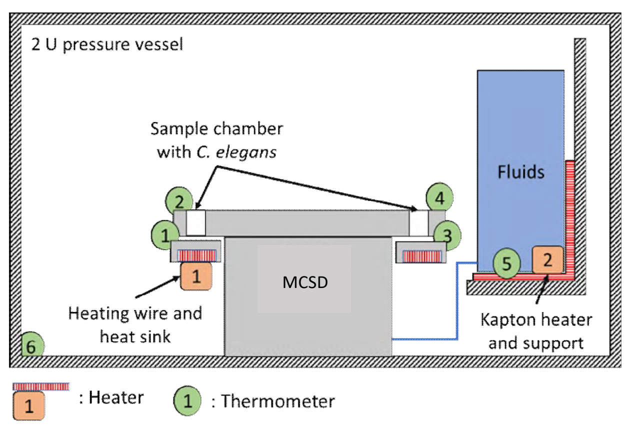

Figure 8: Schematic representing the thermal subsystem design inside the 2U pressure vessel

Passive thermal control is designed to insulate the experiment to reduce the power consumed by the heaters. Since active cooling is not available, it should also protect the experiment from sun radiation and avoid a dramatic increase of temperature above 22 °C, which is the upper temperature limit of the *C. elegans*. The challenge with the passive insulation design is to find the right balance between emissivity and absorptivity to cope with the flight environment and the heating of the system.

The current design of passive thermal control is being finalized. The existing design is using adhesive tapes with different colour and hence high/low absorptivity and emissivity. Using an adhesive tape has the benefit of easier installation and removal for testing,

A specific strain of heat-sensitive *C. elegans* was chosen to help validate the thermal subsystem in-flight. They will coil if it is too hot or slow down if it is too cold. The captures videos and images will be used to assess the performance of the thermal subsystem.

2U pressure vessel

The pressure vessel will be pressurized at the ambient pressure at ESRANGE ~ 1 ATM or 1 bar upon assembly. The vessel needs to maintain the required pressure for the operating lifetime of the flight on BEXUS and do not explode when place in a near-vacuum environment of stratosphere. The vessel will be manufactured from Aluminum 7075-T6 chosen due to its high strength to weight ratio. The vessel was also designed to meet requirements imposed by P-POD deployer in anticipation for spaceflight.

BoB 2U pressure vessel contains 1.5 L internal volume designated for the experiment. The volume is 0.3 L more than PharmaSat [8]. Figure 9 represents an FEA performed to simulate the pressure difference of 2 bar. The 2 bar was selected for a margin of 2 times safety factor. During the flight, the pressure difference is expected to be at 1 bar internally and ~11 mbar externally. The stress is primarily located on the centre of the 2 mm wall thick cube shape vessel.

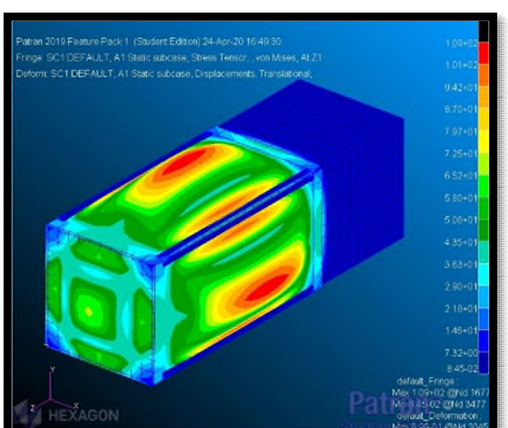

Figure 9: FEA analysis of simulated von-misses stress on the aluminum 7075-T6 2U pressure vessel.

Computer architecture and software design

The flight software is responsible for on-board data handling, sensor observations, communications, systems monitoring, and control of the experiment and environmental hardware.

The main computing module is an RPi Zero W, running a Linux-based Operating System. Most BoB operations will be controlled using the RPi Zero W, hence, the designated primary flight computer. The RPi Zero W has available several interfaces, i.e., GPIO (General Purpose Input Output), UART, SPI, and I2C. All communication protocols are used to support 24 sensors due to specific mission requirements. The primary flight computer will be linked to the BEXUS Gondola’s communication system via Ethernet. Most operations will be autonomous, with the majority of communication being experiment data and telemetry downlink.

The secondary flight computer is linked to the primary flight computer via UART. The secondary computer’s operations include thermal monitoring and control, some part of the microfluidic system, and monitoring of the primary flight computer. In the event of primary computer failure, the secondary computer can maintain a viable thermal environment for the biological payload and will attempt to reboot the primary computer.

Additionally, due to interface hardware limitations on the primary computer, some sensor information and control actions are routed through the secondary computer. Particularly noteworthy are thermal sensor data and thin-film heater control. The design and software philosophy for the secondary computer is such that the hardware and software must both be highly reliable.

The software architecture is designed according to modern agile methodologies to ensure it can be rapidly developed and tested within the concise timeframe. Python and C++ are the utilized languages, providing a flexible, fast and safe combination that best suit’s the requirements for a rapid student-led mission. Python and C++ are a utilised languages. The former interpreted language is quick to prototype, develop, and test; the latter is compiled and statically typed, providing more type-safe and faster-running code for safety-critical operations. This combination suits the requirements for a rapid student-led mission that still requires safety-critical code, while ensuring development meets the tight time constraints

Mission control and ground support software utilizes NASA’s OpenMCT open-source software as a telemetry viewer and event monitoring platform, in conjunction with custom software supporting telecommands and experiment data downlink.

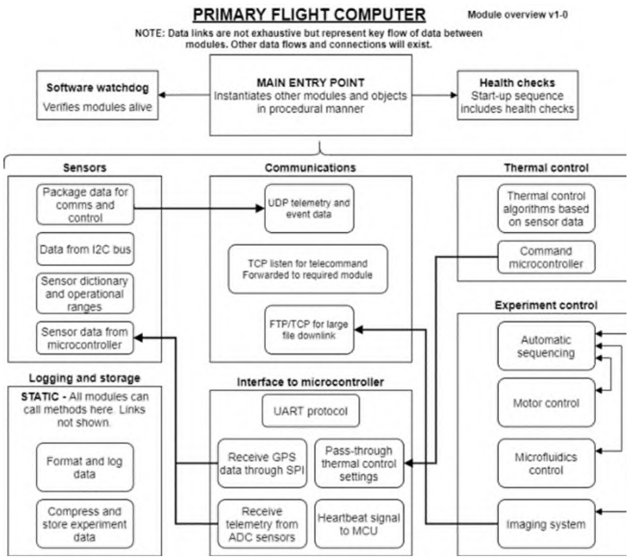

Figure 10: Top-level software architecture of primary flight computer

Electrical power system (EPS)

The EPS draws power from the battery on-board the BEXUS gondola at 28V. The highest power consumption is taken by the thermal control subsystem, followed by the fluidic subsystem. Table 3 provides the current estimation on the peak and average power and current consumption for the pre-flight and flight phases.

Compact DC/DC converters are used to do large voltage conversions (I.e. 28V to 5V) and switching voltage regulators are used for medium voltage translations. RC low pass filters are used on the main power line and will attenuate the high frequencies and impede AC signals from propagating. Once the power line is filtered, it is passed to the DC/DC converters which are in a parallel configuration allowing multiple redundant DC/DC converters for safety. Diodes are placed in front of the converters to protect the circuit in case of current reversing. A standard LCL circuit is implemented on the main power line to protect from current overloads.

A pushbutton kill switch is placed on the 1U bus, and when closed, it will complete the circuit with the BEXUS battery and power the DC/DC converters and the other electronics. The kill switch has an integrated LED which will be connected to the flight computer main power line and ground. It is particularly useful in this configuration as it gives experimenters visual evidence that power is live to the primary flight computer, especially during pre-flight checks.

Table 3: Table showing the peak and average power and current drawn out of the battery on the ground pre-flight phase and flight phase. Note that the values included margin at this stage of development and therefore overestimations of the power and current consumption.

Pre-flight phase	
Peak power consumption 28.1 W	Peak current consumption: 1.1 A
Average Power consumption: 13 W	Average current consumption 0.5 A
Flight phase	
Peak power consumption 30.7 W	Peak current consumption: 1.2 A
Average Power consumption: 23.3 W	Average current consumption 0.92 A

BAMMsat-on-BEXUS 1U bus

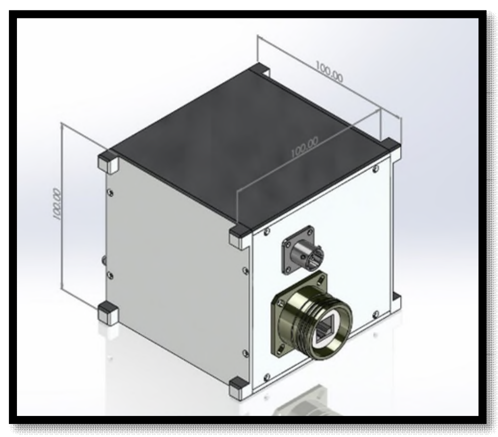

Figure 11: BoB 1U bus

The BAMMsat-on-BEXUS bus provides the necessary support for the 2U experiment payload assembly. The 1U bus has an internal volume of 0.9L to house the RPi Zero W, custom main PCB, and environmental sensors. BEXUS batteries provide power to the experiment on the gondola. Communication with the ground is established via an ethernet connection and an airborne antenna on the gondola. The BAMMsat-on-BEXUS bus will be mount structurally to one end of the 2U pressure vessel.

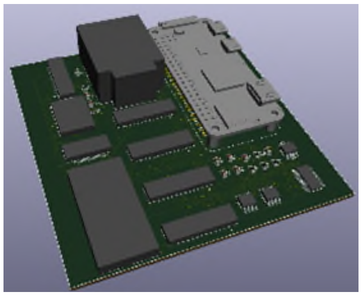

Figure 12: BoB main PCB

The main features of the primary 1U bus PCB are the Raspberry Pi Zero W, the microcontroller, ethernet-to-SPI bridge and GNSS receiver. The main flight computer will be raised from the PCB plane using spacers (see Figure 12) and this is to facilitate heat dissipation to the surrounding area. Wire-to-board connectors are used to connect the primary PCB to other PCBs in the 1U bus as well as to the vacuum feedthrough with the pressure vessel.

BEXUS gondola

BEXUS experiments are lifted by a large balloon with a volume of ~ 12 000 m^3. It can reach an altitude of 25-30 km, depending on the total experiment mass (40-100 kg). The flight duration is 2-5 hours, depending on the weather condition and flight path. BoB will be mounted on the BEXUS gondola, see Figure 12. The positioning of BoB was placed to expose the experiment to the dynamic solar irradiance for varying the thermal load, taking consideration the low sun elevation in October 2020 in Sweden. The temperature sensors will be used to assess the BoB thermal subsystem performance. Placing the experiment inside the frame also protects the experiment in the event of a hard landing.

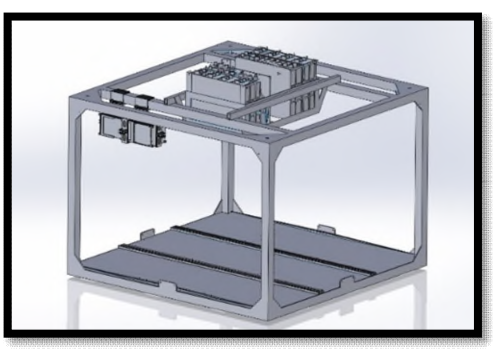

Figure 13: BoB's accommodation on BEXUS gondola

BOB'S PRE-FLIGHT OPERATIONS

Previous NASA bioCubeSat missions have opted for model organisms such as *E. coli. S. cerevisiae, B. subtilis, H. chaoviatoris,* and *C. richardii*. These single cell organisms are great for their ability to remain stasis for an extended period before being reinvigorated with a nutrient medium. In most cases, CubeSat often launches as a secondary payload and in a rideshare program. For the previous bioCubeSat, the complete system had to be delivered 4-8 weeks before launch for launch vehicle integration and testing[11][12].

Not all organisms have the ability to remain viable after for an extended period without continuous maintenance. Mammalian cells such as humans have to be maintained around 37°C with 4-10% CO_2 level to stay alive. Such requirements add complexities in terms of pre-flight operation and AIV.

BoB experiment provides the opportunity to develop and test flight operation for *C. elegans* on bioCubeSat. The pre-flight operation has been developed in anticipation for spaceflight operation. The current timeline to demonstrate a nominal 24-hour pre-flight handover to the BEXUS launch provider, see Table 4. The operation will allow up to 48-hour launch delay by maintaining viable nematode samples with minimal interaction. The reason for 24-hour up to 48-hour is to accommodate future flight opportunity, see Table 5. The flight of BAMMsat-on-BEXUS will be used to develop a pre-flight operation that is translatable to an orbital flight scenario.

Table 4: BoB pre-flight operation

Day/hours	BoB's operation
T -6 days	*C. elegans* sample preparation
T -3 days	Experiment hardware preparation
T -24 hours	Experiment handover to the launch provider
T + 48 hours	The experiment can cope with launch delay up to 2 days.

Table 5: Late access timing for various type of launch vehicles

Types of launch vehicle	Typical CubeSat launch	BEXUS	Hosted in larger spacecraft platform (ISS, Bion satellite)	New Space launcher
Late access timing	Two weeks – Dido-2 satellite from SpacePharma and ISIS*	BEXUS launch campaign is between 24-hours up to 96-hours depending on weather	8 to 10 hours – Bion satellite [13] 48-hours – ISS, based on previous launch procedure for the Molecular Muscle Experiment which flew on the ISS	8 hours to 4 days – Blue Origin late access on New Shepard [14]

* Conversation with ISIS at the IAC 2019

BAMMSAT-ON-BEXUS SUMMARY

This paper reports on the recent development of the BAMMsat concept. In particular, the design of the BAMMsat-on-BEXUS experiment on-board the BEXUS program. The experiment takes advantage of real-mission scenario to perform technology and operational demonstration of the BAMMsat hardware. At the time of writing, the hardware is currently being build and tested in preparation for the flight campaign in October 2020.

The current design of BoB has a 3U format with P-POD design requirement. The core BAMMsat hardware is placed in a 2U pressure vessel and 1U bus to interface to the BEXUS gondola. The summary of the experiment parameters is summarized in Table 5.

Table 5: BAMMsat-on-BEXUS system summary

Parameter	Remarks
Experiment mass (kg)	4.8 kg
Experiment dimension (mm)	300 x 100 x 100 mm*
Power (W)	Peak: 30.7 W Average: 20.5 W (pre-flight and flight)
Data downlink (Kbit/s)	Continuous during float phase: 31.8 Kbit/s 47.7 Kbits/s (50% margin)

* 3U CubeSat format; 2U for the BAMMsat experiment payload assembly and 1U for the BoB bus

Future work involves further development of the BAMMsat concept which involve 1) validating the fluidic subsystem functionally in microgravity, 2) development of BAMMsat fluorescence microscope and 3) in orbit demonstration (ISS or free-flying CubeSat).

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