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A Modular Hardware and Software Architecture for a Student-Designed BioCubeSat Prototype using Autonomous Operations

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ABSTRACT

BAMMsat-on-BEXUS is a student-led project aiming to design, manufacture, and fly a CubeSat-compatible payload on a stratospheric balloon. The payload – BAMMsat (Biology, Astrobiology, Medicine, and Materials Science on satellite) – is a modular CubeSat-format laboratory termed a bioCubeSat. The mission is realized under the bilateral REXUS/BEXUS programme run by the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA), with the Swedish payload share available to students through a European Space Agency (ESA) collaboration. The core objective of the prototype payload is to perform a technology demonstration of the core bioCubeSat technology, demonstrating its capability to support biological experiments in space. Additionally, the mission aims to validate pre-flight and flight operations, with a particular focus on biological operations. This will increase TRL for future bioCubeSat spaceflight with the goal to eventually enable better and cheaper biological, pharmaceutical, and materials science research in space environments.

The BEXUS mission follows a typical space mission framework with reduced timeframe, therefore trade-offs prioritize commercial-off-the-shelf components and simple software using open-source solutions. The payload comprises a 2U pressurized laboratory payload (BAMMsat) and 1U avionics bus. The former contains experiment hardware including a Multi-Chamber Sample Disc, rotary mechanism, imager, the microfluidics system, active thermal control, and supporting avionics. The bus contains two flight computers, multiple custom avionics PCBs, and serves as the interface between BAMMsat and the BEXUS balloon gondola.

The BAMMsat-on-BEXUS prototype will likely fly in October 2021. The prototype flight should prove that the system can perform varied microfluidics operations on multiple *C. elegans* samples, capture detailed imagery of the samples, provide general system housekeeping and communications, and provide life support for samples, including stable temperature and pressure despite operating within an extreme temperature and near-vacuum environment.

The system and biological operations are designed to be fully automatic during flight, with some subsystems continually autonomously operating and others following sequenced events. Future work will aim for greater use of autonomous operations to reduce operating costs and enable more advanced system control, particularly for precise active thermal control and experiment sequencing. The next iteration of BAMMsat is targeting low Earth orbit missions, after further hardware upgrades and the inclusion of fluorescence microscopy and additional chemical sensors.

INTRODUCTION

BAMMsat-on-BEXUS (BoB) is a student-led project aiming to design, manufacture, and fly a CubeSat-compatible payload on stratospheric balloon. The payload is the 2nd iteration of BAMMsat (Biology, Astrobiology, Medicine, and Materials Science on satellite), a modular CubeSat-format laboratory termed a bioCubeSat.

The primary objective of BoB is to demonstrate a capability to support biological experiments in space. Increasing TRL of the BAMMsat platform via this initial flight will support future work on orbital versions of the platform with the goal to eventually enable better and cheaper research in space environments.

The BoB mission and stratospheric balloon flight test is realized under the bilateral REXUS/BEXUS programme between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA), with the Swedish payload share available to students through a European Space Agency (ESA) collaboration.

BIOCUBESAT HERITAGE

For this paper, the term bioCubeSat refers to a nanosatellite in a CubeSat format with a biological experiment on-board. This concept has been established with six successfully launched in LEO by NASA and a private company, Space Pharma.

While volume and mass restriction in a CubeSat will be challenging, the success of these bioCubeSats is proven and de-risks the basic concept of a bioCubeSat.

The seven bioCubeSats are GeneSat [1], PharmaSat [2], O/OREOS [3], SporeSat [4], Dido-2 [5], EcAMSat [6], Dido-3 [7]. Five of these bioCubeSats shared a common heritage coming from NASA Ames. While Dido-2 and Dido-3 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 [8].

The BAMMsat concept leverages experience gained from these other concepts to contribute to the advancement of this field.

SYSTEM ARCHITECTURE

BoB is split into two core systems: a 2U pressure vessel comprising BAMMsat's core laboratory and sensing systems; and a 1U avionics bus providing housekeeping, payload control, and communications. The latter also serves as an interface between BAMMsat and the BEXUS gondola. An exploded view of the system is provided in Figure 1, with the 1U bus visible on the left, the 2U BAMMsat payload internals in the middle, and the 2U payload's pressure vessel on the right.

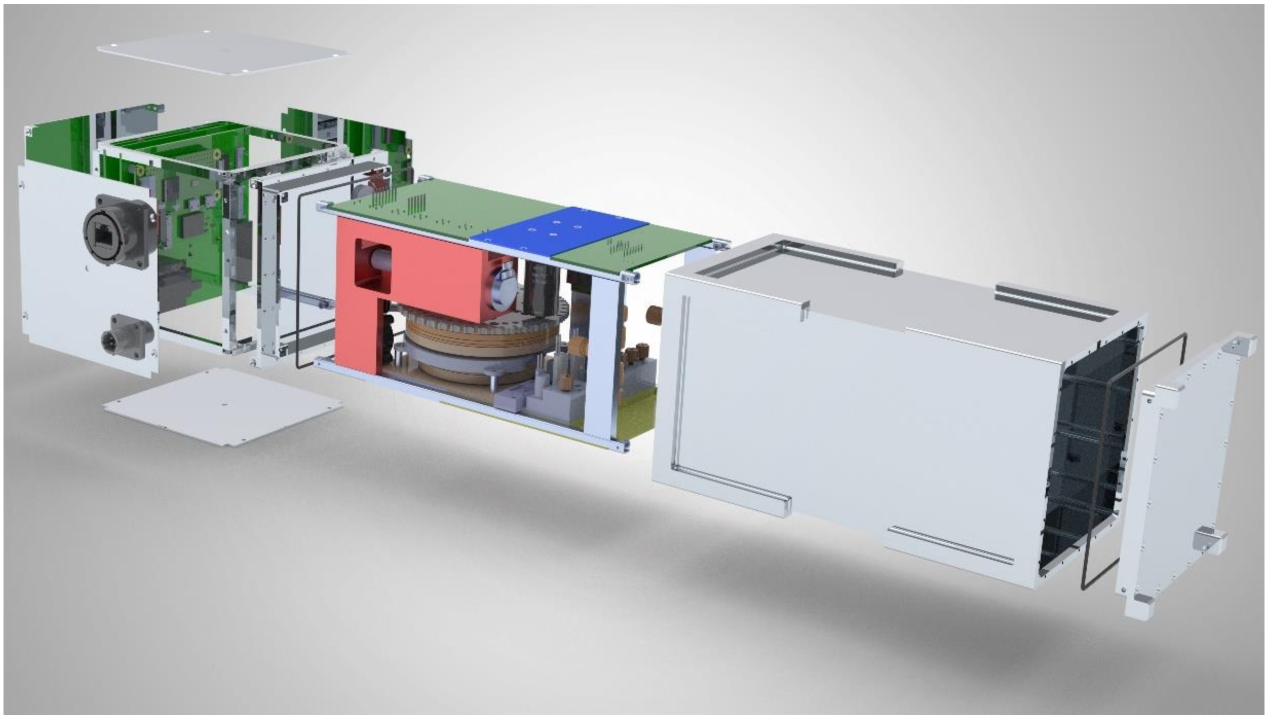

Figure 1: Exploded CAD model of BAMMsat-on-BEXUS

Design Ethos

The REXUS/BEXUS programme follows the framework of a typical space mission, but in a shortened time frame of one year (two, in this case, due to the impact of Covid-19). As such, the hardware and software of BoB was scoped to best meet tight deadlines on design, development, and verification phases.

The hardware design uses commercial-off-the-shelf (COTS) components where available; software design and development are agile and uses open-source solutions where possible, reducing development time. This design ethos would also help to reduce costs and development timelines for future space missions. However, all systems must still meet high quality and safety-critical standards, therefore scope is limited, and an extensive verification campaign is required.

2U Payload

The 2U payload contains BAMMsat's core systems, including:

- The Multi-Chamber Sample Disc (MCSD), where the biological samples are housed.
- A Geneva Drive rotary mechanism allowing direct access to each discrete sample chamber.
- An optical camera and LED to take observations of each sample chamber.
- A microfluidics system enabling various fluidic media to be pumped in and out of each discrete sample chamber.
- An active thermal control system, enabling life support for the biological samples.
- Various additional sensors, monitoring internal environmental conditions, and enabling the microfluidics and MCSD hardware to operate.
- Custom-purpose PCBs.

The MCSD subsystem contains 32 discrete sample chambers. The MCSD – displayed in Figure 2 – further comprises multiple pressed layers of differing materials, with laser-cut pathways enabling fluid transfer in and out of the sample chambers.

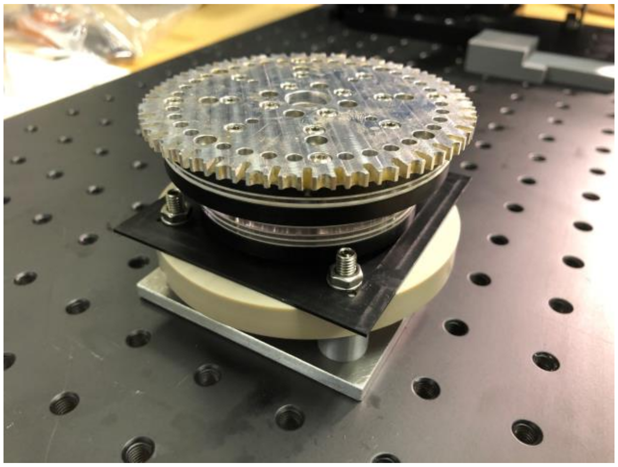

Figure 2: Multi-Chamber Sample Disc

The MCSD is mounted on a Geneva Drive rotary mechanism, therefore enabling independent access to each sample chamber for the external microfluidic pathways (with associated sensors in the lines) and imaging system. Combination of an incremental rotary encoder and slot-type photo-microsensor enable semi-autonomous operations without visual monitoring of the system.

1U bus

The 1U bus houses the Command and Data Handling system (C&DH) and the Electrical Power System (EPS). Additionally, the bus contains the electrical interfaces to the BEXUS gondola, an external rocker kill switch for disabling power to the experiment post-flight and three external photodiodes to measure sunlight exposure during flight. The 1U bus design does not follow CubeSat bus design conventions due to the hard requirements set to match the BEXUS power and communications interface designs. Both the experiment power connector (MIL-C-26482P series) and the data interface connector which uses Ethernet (Amphenol RJF21B) are relatively large and are not optimized for CubeSat applications. Due to the space and platform constraints, the use of miniaturized electrical components and an uncommon PCB configuration and wire harness design were selected.

The C&DH and EPS PCBs are slotted into and constrained by the internal rails of the 1U bus and oriented on the same plane as the lid of the BioCubeSat.

Bulkhead interface

Electrical and data interfaces between the pressurized 2U payload and 1U bus are provided via a hermetic feedthrough, housed using jackscrews and aluminum-filled flourosilicone O-rings suitable for the extreme environmental temperature differences. The feedthrough uses Micro-D connectors, frequently used for spaceflight applications.

HARDWARE ARCHITECTURE

Microfluidics system

The microfluidics subsystem comprises 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 3 represents the fluidic flow paths.

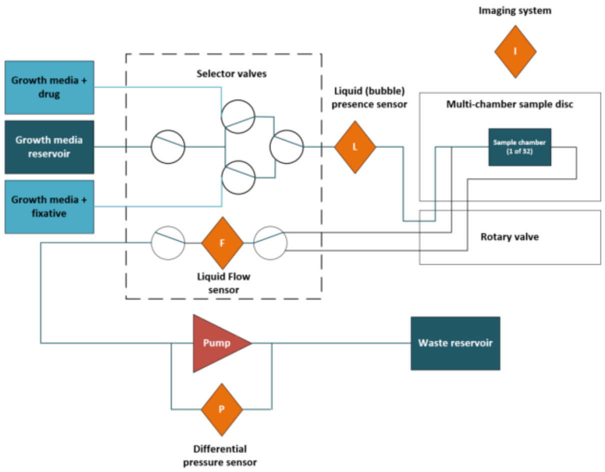

Figure 3: Fluidic flow paths

The pump pulls the growth media and reagent from the reservoirs on the left. The selector valve manifold controls the flow path and direction of the fluid. A combination of 2/2 and 3/2 solenoid valves provides a series of fluidic openings and closings that direct the fluids to the required path when pumped.

The rotary valve (RV) - the bottommost layer in Figure 2 - is the interface between the disc and the rest of the fluidic system. Various sensors displayed in Figure 3 monitor microfluidics system operation.

Electronics design

Figure 4 provides a simplified overview of the electrical design, centered around the Command and EPS system in the 1U bus. The EPS is powered directly from an external battery via the electrical power interface with unregulated 28 V line. The EPS filters the voltage on main power line and provides voltage conversions to 3.3 V, 5 V, and 12 V and distributes these power lines to the relevant subsystems in the experiment. Furthermore, the electrical and PCB designs are adapted to reduce conducted EMI emissions which arise from the use of the chosen DC/DC converters [9]. Safety circuits are also in place to reduce the damage to electrical components in the event of overvoltage, and the power consumption is measured using analog sensors.

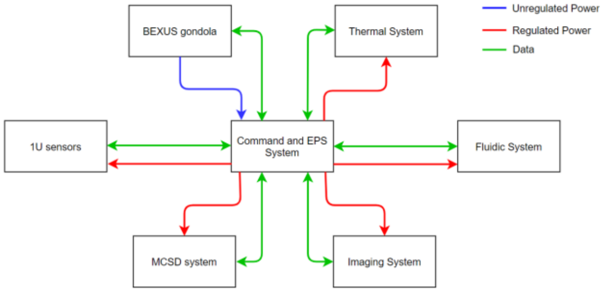

Figure 4: Electronics system overview

The thermal system electronics comprise MOSFET drivers which actuate the experiment heaters using PWM, controlled by the C&DH system and on-board software.

The fluidic system electronics include a fluidic pump driver, analog and digital I2C fluidic sensors, and six latching solenoid valves. The solenoid valves are actuated via a circuit which switches the polarity on the valve terminals after every actuation and by sending a short 5 V signal.

Data handling

Selection of the communications bus was primarily driven by the interfaces available on various COTS hardware components, enabling significant cost savings. It is not surprising therefore that the primary communication buses selected were I2C, UART, and SPI for specific devices. A combination of all three is utilized to meet a trade-off between communications architecture complexity and the price and availability of critical COTS hardware components.

Given the combination of communications buses used, strict software control is required to prevent any issues, and several components can be restarted if required.

CAN bus and SpaceWire were also reviewed, however were not determined to be good options due to the limited compatibility of available COTS hardware and the bulkiness of SpaceWire, making it currently unsuitable for most CubeSat-compatible platforms.

Avionics

The computing architecture of BoB comprises two main systems: a primary flight computer (a Raspberry Pi 0) – seen clearly on the right of Figure 5 - controlling most key functions and central to the primary I2C & SPI communications buses, additionally providing Ethernet connection to the BEXUS Gondola’s E-Link system; and a secondary flight computer (M4 Express microcontroller using ATSADM51 processor) providing additional functionality and system redundancy.

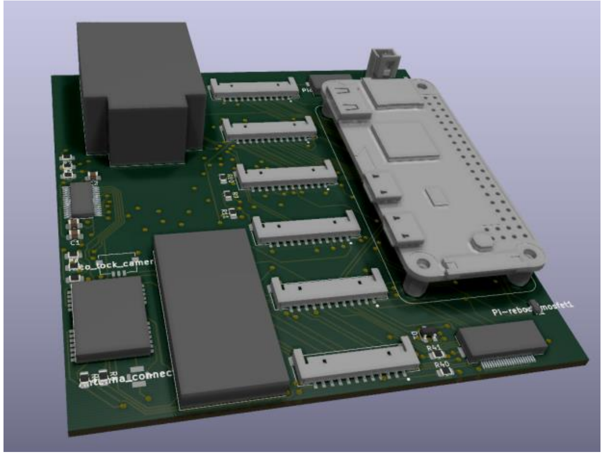

Figure 5: On-Board Data Handling PCB housing Primary Flight Computer

Thermal Control System

Thermal regulation must ensure an operable environment for the *C. elegans* samples during flight at 20°C ± 2°C, and 12°C ± 2°C during pre-flight to maintain low metabolic rates. An overview of the system's software and operation is provided in Figure 6.

Internal temperature measurements occur at least every second, requiring ± 1°C accuracy. Resistance thermometers (RTD PT 100) are placed inside the 2U pressure vessel. The pressurized environment means heating can be achieved primarily by convection. The secondary flight computer controls the heaters with Pulse Width Modulation (PWM).

To better assess performance of the thermal control system, one of the five strains of *C. elegans* within the MCSD will be a heat-sensitive strain, which will coil if too hot and become less motile if too cold. The imaging system will be used to monitor this behavior.

A small fan is used to force air circulation within the pressure vessel, making internal temperature more uniform and ensuring adequate oxygen circulation between the air and the fluidic media for the *C. elegans*.

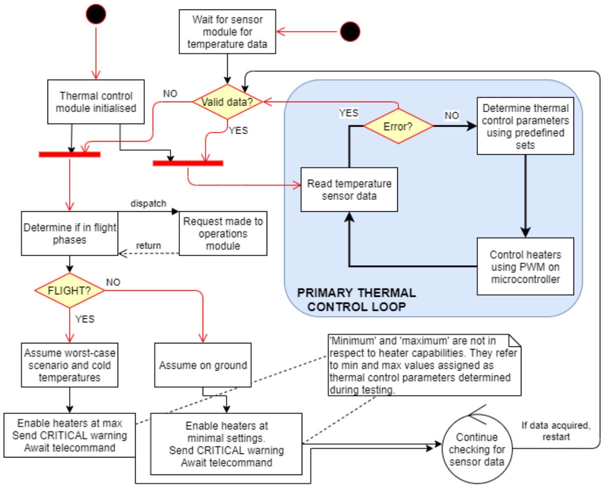

Figure 6: Thermal Control System Operation

SOFTWARE ARCHITECTURE

Primary flight computer

The Raspberry Pi 0 runs Raspbian Lite, as real-time functionality is not a requirement. Given the rapid prototyping nature of the mission, Python is used for the bulk of the software. This also allowed multiple team members to contribute to the software work packages, as otherwise only one team member had significant experience in more traditional languages used for embedded systems and safety-critical applications (i.e., C). Of course, Python was not designed for this type of application, therefore an extensive verification testing campaign was required.

The Raspberry Pi 0 includes a hardware watchdog, which will power cycle if the computer becomes stuck.

While this system is suitable for the BEXUS prototype mission and enabled us to verify diverse systems and hardware in a very short time span, it is not suitable for actual spaceflight and will be redesigned for the next BAMMsat iteration.

Secondary flight computer

The auxiliary computer provides specific mission functions, using C++. It also serves as a secondary watchdog to the primary flight computer, which may be restarted by means of shorting two jumpers on the primary computer via MOSFET in a worst-case scenario if it were to become otherwise unrecoverable.

It communicates with the primary computer via a UART interface. Generally, commands are provided via the primary computer – whether automated or by manual telecommand – and subsequently run. A notable exception to this rule is the watchdog and recovery procedures, which function mostly independently, except for listening for a heartbeat signal.

The functions provided include, as also shown in Figure 7:

- Polling ADCs for RTD sensor data via SPI.
- Polling GPS sensor data via SPI.
- Returning data to primary computer.
- Modifying thermal control mode via setting PWM duty cycles for heaters on reception of interrupt signal from primary computer.
- Switching solenoid valves on reception of interrupt signal from primary computer.
- Maintaining safe thermal environment automatically in the event of primary computer failure.
- Watchdog functions attempting to soft-restart and hard-restart (with power cycle) the primary computer.

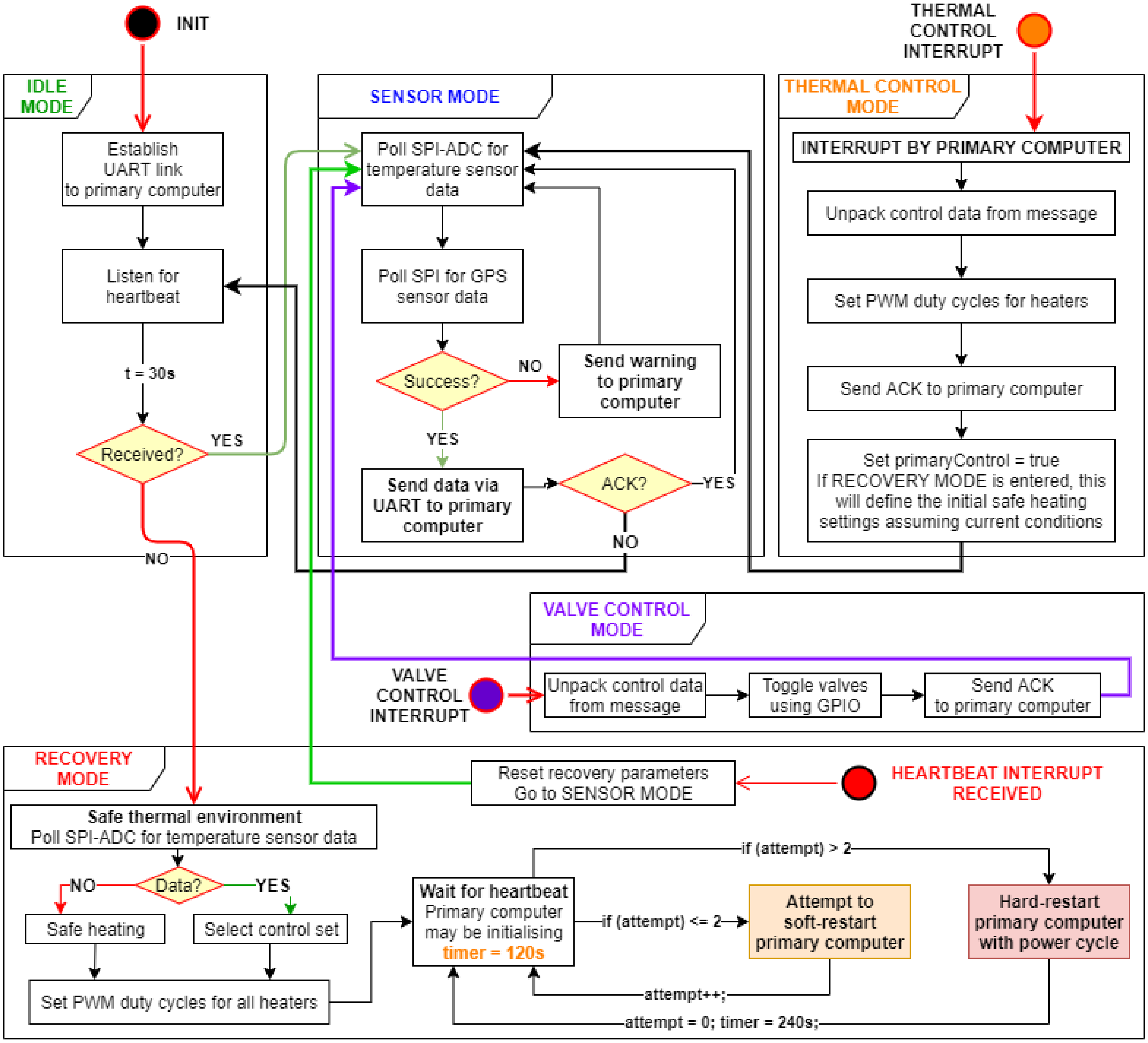

Figure 7: Secondary Flight Computer overview

CONCEPT OF OPERATIONS

Current Operations Procedure

At present, the bulk of system and biological operations are either automatic and continuous, or automatic but strictly sequenced prior to flight. Examples of the former include active thermal control and communications, which occur fully automatically yet can be interrupted via manual telecommand. The latter sequences comprise all current experiment operations: rotation of the MCSD, microfluidic operations, imaging, etc.

BoB is highly modular, and several systems can function concurrently. Exceptions to this are the sequenced operations that must occur in the correct order.

The current goal is for the entire flight to function automatically, though manual input is available at every stage of flight. Minor deviations from the pre-set sequence are possible with some automatic error-correcting behavior – e.g., correcting erroneous disc rotation – but otherwise significant changes and interventions require re-sequencing the operations or taking full manual control via telecommand.

Autonomous Operations

While the above semi-automatic system is suitable for the prototype flight and short-term experiments, total autonomous operations would enable significant cost-saving in operations for long-term, dynamic experiments; particularly where multiple different discrete samples are being flown and judgements must be made as to the best environmental control parameters and order of experimentation, while also operating all general spaceflight systems.

One of the most likely systems to be upgraded in the next iteration is the active thermal control system. Currently, the entire pressure vessel is maintained at a temperature viable for *C. Elegans*. However, upgrades to the MCSD and thermal control system would enable truly different discrete samples to be flown by maintaining each sample chamber at different, appropriate temperatures. Thermal control hardware in combination with appropriate operations algorithms, extensive testing, and simulation could enable autonomous precision thermal control of each independent sample chamber.

APPLICATION TO ORBITAL MISSIONS AND FUTURE WORK

While BoB has several systems not yet suitable for spaceflight, we expect that a successful demonstration on stratospheric balloon could increase TRL to 6 and validate the biological pre-flight operations.

The entire system has been designed to be CubeSat-compatible using appropriate COTS hardware. Attention has been given to automated operations with the goal for a fully-automatic demonstration flight; several systems – particularly active thermal control – are under consideration for upgrades for more complete autonomous operations in the next iteration of BAMMsat.

For future flights, the electrical and computing architecture require maturation. Software designs will use more traditional languages and architectures, though Python may still be used for some algorithms supporting full autonomy, if required.

Otherwise, the hardware is generally appropriate and ready for orbital flight. The significant modifications still required are to minimize outgassing, modify for launch vehicle and environmental compatibility, and provide further upgrades to the computing architecture to tolerate space environments. Further upgrades to the MCSD and microfluidics system will enable more complex experiments and a more compact design, and inclusion of fluorescence microscopy and other sensing hardware will improve research outputs.

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