Project Proposal – Flight Board for IlliniSat-2

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1 Introduction

1.1 Background

This project was originally proposed by Alex Ghosh for the CubeSat team. The Illinisat-2 is a scalable CubeSat satellite bus developed at the University of Illinois. The problem statement was to design a carrier board that both mounts the flight computer and interfaces with other components of the satellite, including the power system, payload, and radio connections. The carrier must be built to flight electronic specifications using high reliability parts, leaded construction to prevent tin whiskering, and conformally coated. The board must also conform exactly to the Illinisat-2 mechanical component outline in order to properly fit in the satellite. Developing CubeSat busses is an active area of commercial investment and by providing a system with a Linux based microcontroller for ease of software development, providing Attitude Determination and Control Systems (ADCS) capability as described, reliable storage, and providing multiple methods of payload communication, our design will be attractive to investors.

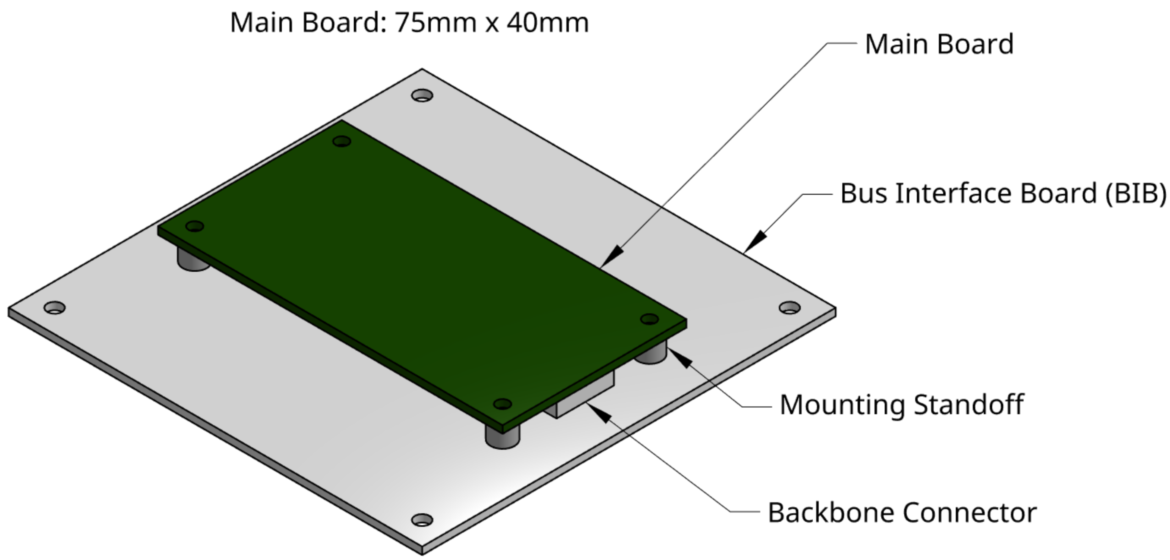
1.2 Objective

The original solution utilized a MitySOM module from CriticalLink as the primary flight computer. This module was then mated via a SODIMM connector to the rest of the satellite bus, including all payloads, additional NAND flash storage via two memory controllers connected over USB, and the power system. The payload connections (four RS422 and one UART) were designed specifically for the original mission that this bus was intended to be used for: Lower Atmosphere/Ionosphere Coupling Experiment (LAICE). Designing for the LAICE mission was an understandable first step, however the use case for the IlliniSat-2 flight board was quickly extended past the LAICE missions. As a result, the original design was not flexible enough to be conveniently used in later missions.

Our new solution is focused on correcting certain design decisions and oversights made in the original project, as well as extending it for better performance in a wider array of CubeSat missions, and reducing the overall cost and size of not only the flight board but the IlliniSat-2 bus as a whole. We will integrate communication to a wide range of payloads on the same board as the flight computer including specific hardware for (ADCS) that the original solution neglected to specifically address despite it being a critical component of most CubeSat operations. This is critical because at a minimum, ADCS operation requires what is known as “detumbling” which is the initial process on satellite launch that puts the satellite in an initial known orientation. This can be accomplished with the IMU and magnetometer that we provide. This solution will be a significant improvement over the original design for any user of the bus. This flight board will utilize a backbone connector to attach to a customer designed bus interface board (BIB) which provides the physical interfaces to a mission’s payloads and power system. Having the BIB allows for convenient swap in/out of hardware. The design of the BIB is beyond the scope of this project and is left to the end user create.

1.3 Physical Design

Our main flight board PCB (shown in green) is small enough to allow two side-by-side flight boards to co-exist on a BIB designed for the dimensions of a typical CubeSat.



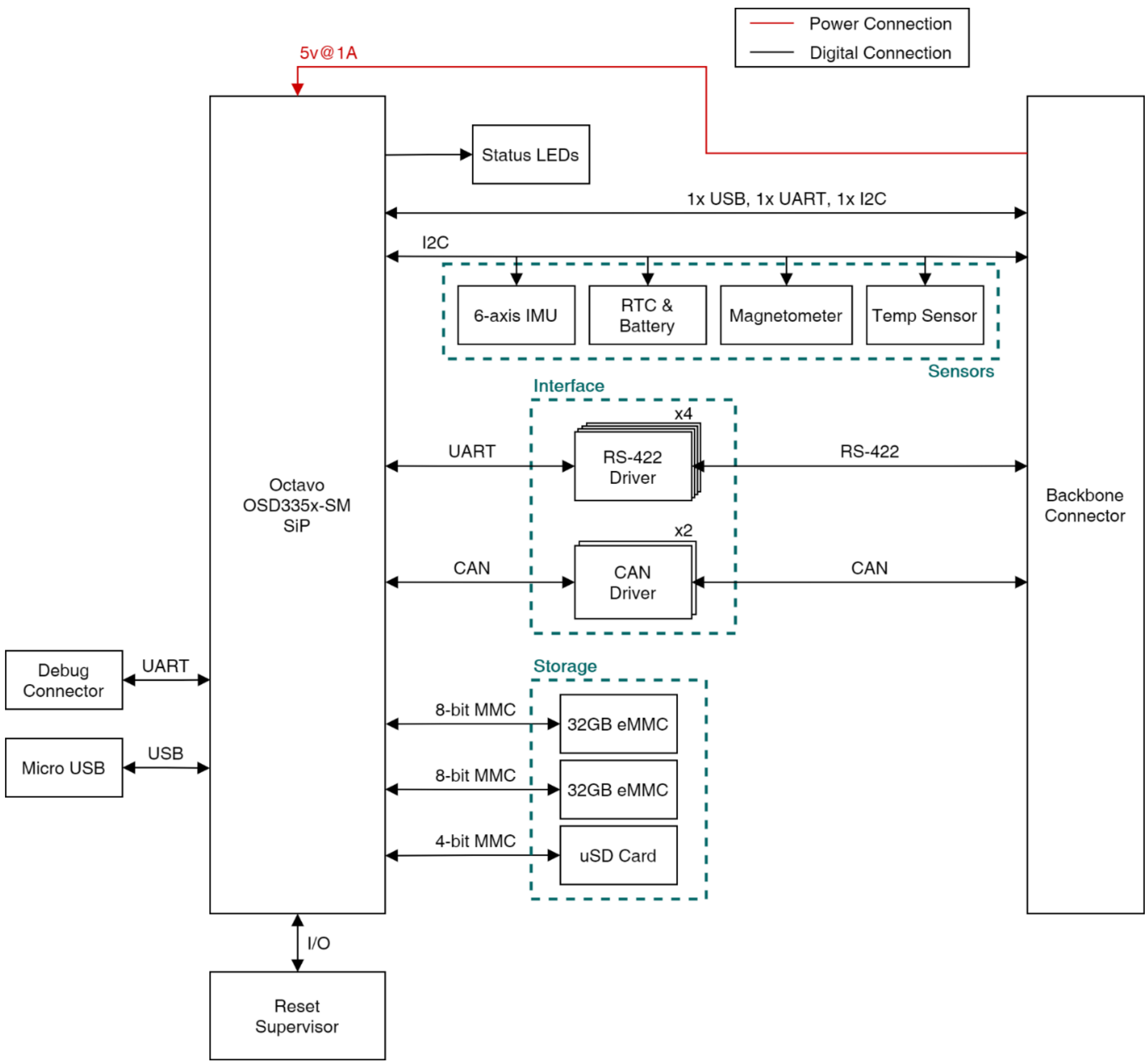
1.4 High Level Requirements

- Successfully boot Linux and communicate with all the interfaces described: RS422, CAN, UART, USB 2.0, I2C, and read and write persistent data to the eMMCs.
- The IMU and magnetometer must report data to the flight computer accurate enough for meaningful ADCS (further defined in block-level requirements).
- The new solution should cost less than $1,000 for a fully assembled unit and be less than 90x90x10mm in size.

2 Design

2.1 Block Diagram

The two primary components of this flight board are the Octavo SiP and the backbone connector. The flight board contains the minimum hardware necessary for the flight board operation (besides power) via the sensors and storage groups. Generally the SiP will communicate with the sensors and storage to monitor flight status and record any desired data points. Many interfaces are listed as crossing from the SiP to the backbone connector. This allows the customer to create their own BIB which connects to the backbone and provides hardware using these interfaces. The uSD card, micro USB, status LEDs, and debug connector are all use primarily for lab testing. The reset supervisor is crucial in preventing system lockups.



2.2 Functional Overview and Block-level Requirements

2.2.1 Micro USB

The Micro USB connector is provided to allow easy powering of the flight board when no BIB is connected, as well as debugging over USB.

Requirement: The Micro USB interface can power the flight board by providing 4.3 v – 5.8 v at 1 A.

Requirement: The flight computer can communicate with USB devices via the Micro USB connector.

2.2.2 Debug Connector

The debug connector provides a simple UART interface to the flight computer. Typically, this used as a serial console for Linux.

Requirement: The debug connector shall provide a serial interface at a minimum of 115.2 kbaud.

2.2.3 Reset Supervisor

The reset supervisor acts as a watchdog for the flight computer. If the flight computer ceases to message the reset supervisor or if the voltage supplied to the reset supervisor drops below a threshold, it resets the flight computer.

Requirement: In event of a software lockup, the reset supervisor will reset the flight computer within 60 seconds.

Requirement: In event of a single event upset (SEU), the reset supervisor will reset the flight computer within 100 uS.

2.2.4 Flash Storage

Non-volatile storage is critical for IlliniSat-2 CubeSat operations as nearly all missions require storing data for extended periods of times (at least days) which is either eventually transmitted to the ground or is used for in-flight operations of the satellite. Given that the data stored is critical to science missions and satellite operations, it is important to provide redundancy in case of an in-flight data storage failure.

Requirement: At least 32 GB of non-volatile flash storage is available to the flight computer.

Requirement: The non-volatile flash storage shall provide redundancy in case of a failure.

Requirement: The non-volatile flash storage shall provide a sustained read speed of at least 1 MB / s.

Requirement: The non-volatile flash storage shall provide a sustained write speed of at least 1 MB / s.

2.2.5 Micro SD Card Slot

The micro SD card slot can be used for easily extracting information during debugging as well as flashing the Linux image and root filesystem to the flight computer.

Requirement: The flight computer can be flashed from the micro SD card.

Requirement: The flight computer can read or write data arbitrarily to the micro SD card.

2.2.6 Flight Computer

The flight computer controls the operations of the satellite including communication via radio, interfacing with payloads, and collecting science data. It must be capable of utilizing all the desired interfaces for this board. For simplicity of programming, this chip will run Linux.

Requirement: The flight computer shall be capable of booting a Linux operating system.

Requirement: The flight computer shall be capable of communicating over all interfaces specified in 2.2.9.

Requirement: The flight computer shall provide hardware floating point calculation capability.

2.2.7 Real-Time Clock (RTC)

Keeping accurate time in orbit is very important for attitude determination and control. A time error of just one second can lead to a positional error of over 8 km.

Requirement: The RTC shall not drift by more than 1 second / day when running on backup battery power.

Requirement: The RTC shall provide an I2C interface.

2.2.8 RTC Battery Backup

A good CubeSat can keep accurate time even when fully powered off. The backup battery should rechargeable which means it never needs to be replaced. This is important because some missions must wait more than a year to get launched.

Requirement: The RTC's backup battery shall be rechargeable.

Requirement: The RTC's backup battery shall hold enough charge to power the RTC for one year at room temperature.

2.2.9 Interfaces

Having a wide range of interfaces allows the flight computer to communicate with a variety of on board hardware and off board payloads. At a minimum, this project should provide the same number of interfaces as the original project (four RS422 and one UART).

Requirement: There shall be at least four RS422 interfaces to the flight computer.

Requirement: There shall be at least two CAN busses interfaced to the flight computer.

Requirement: There shall be at least one UART interface to the flight computer.

Requirement: There shall be at least one USB 2.0 interface to the flight computer.

Requirement: There shall be at least two I2C busses interfaced to the flight computer.

2.2.10 6-Axis Inertial Measurement Unit (IMU)

Since every CubeSat should have basic attitude determination, an IMU should be included in the flight board instead of attached externally as in the original design.

Requirement: The IMU shall provide an I2C interface.

Requirement: The IMU shall provide a resolution of at least 50 milli-degrees / s of angular rate with a full scale of at least +/- 30 degrees / s.

Requirement: The IMU shall sample at a minimum of 100 Hz.

2.2.11 3-Axis Magnetometer

The magnetometer uses inductive coil pickups to measure magnetic fields with no temperature based drift. This is important for an active ADCS algorithm as it can sense Earth's natural magnetic field (~50 uT) and then perform attitude adjustments with this information.

Requirement: The magnetometer shall provide an I2C interface.

Requirement: The magnetometer shall provide a resolution of at least 50 nT with a full scale of at least 100 uT.

Requirement: The magnetometer shall sample at a minimum of 100 Hz.

2.2.12 Temperature Sensor

The AM335x (the processor we will use) includes an onboard die temperature sensor, but due to silicon errata it does not function correctly. A local/remote digital temperature sensor was added to replace the built in one.

Requirement: The temperature sensor shall provide an I2C interface.

Requirement: The temperature sensor shall have an accuracy of +/- 3 deg Celsius on the local sensor.

Requirement: The temperature sensor shall have an accuracy of +/- 3 deg Celsius on the remote sensor.

Requirement: The temperature sensor shall have a resolution of at least 0.5 deg Celsius on the local sensor.

Requirement: The temperature sensor shall have a resolution of at least 0.5 deg Celsius on the remote sensor.

2.2.13 Backbone Connector

The backbone connector is used to connect the flight board that this project is designing to a customer's BIB.

Requirement: Any interface (2.2.9) not already used for flight board hardware must be available through the backbone connector.

Requirement: The backbone connector shall provide an interface for the BIB to power the flight board.

2.2.14 Status LEDs

These are user programmable for conveying any desired information, primarily during testing.

Requirement: The flight computer shall be able to individually control the status LEDs.

2.3 Risk Analysis

The highest risk component of this project is the eMMC interface. On the AM335x, the eMMC interface runs at 52MHz by default. This provides very fast access to storage but adds many timing related challenges. The eMMC interface is composed of a clock signal, eight data lines, and a command signal. Timing integrity between these signals is extremely important to prevent read and write errors. On the current IlliniSat-2 bus, the eMMC interface was slowed significantly in software in order to prevent read errors. It is very important that we do not repeat their mistakes.

To estimate the speed signal propagation in FR4 PCB substrate, we can use the material's relative permittivity. The relative permittivity of FRC material is usually between 3.5 and 4.5.

$$v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3.00 \times 10^8}{3.72} = 80{,}645{,}161 \frac{\mathrm{m}}{\mathrm{sec}}$$

Since there is air above the trace, the actual permittivity seen by the signal is close to 2.0. This leads to a propagation speed of approximately 150 micrometers per picosecond. According to the JDEC 4.2 MMC standard, the maximum time skew allowed between and data signal and the clock, is 100 picoseconds [1]. This corresponds to a length difference of 15mm. The standard also specifies the maximum signal delay to be 650 picoseconds, which equates to a maximum trace length of 100 millimeters [1].

Reaching these required lengths is not particularly challenging, but this knowledge must be incorporated into the implementation of the design.

3 Safety and Ethics

The primary ethical concerns with our project involve ensuring the customer has an accurate understanding of the product we are delivering. In order to satisfy section 7.8.3 of the IEEE code of ethics [2] and section 1.3 of the ACM code of ethics [3], we present a clear description of our project, in particular emphasizing that our flight board on its own is not enough to create a useful CubeSat. A BIB is necessary for a flight configuration of a CubeSat as at a minimum it provides the power to the flight board for operation. A customer would additionally likely want to purchase a radio for communication with the ground.

There are several safety factors relevant to our flight board. The most immediate is the presence of the backup battery for the RTC. This battery is a Manganese Lithium coin cell. It contains very little actual Lithium and has a small capacity (around several mAh) is therefore an extremely safe choice [4].

The remaining safety factors are interactions between our flight board (and the CubeSat enclosing it) and the surrounding environment (launch vehicle, deployer pod, International Space Station (ISS)). NanoRacks, who sells CubeSat deploying services, provides a list of many requirements. Some of the most relevant safety requirements are space debris, battery failure, and structural failure. Our flight board satisfies the section 4.4.6 requirement of not producing any debris [5]. Our RTC battery, as discussed, is very safe. Additionally, section 4.4.7.10 classifies our battery as a "Button Cell" which means acceptance testing is not necessary [5]. To ensure that our flight board does not suffer from any outgassing issues, we will ensure that all materials used satisfy the section 4.4.10.3 requirements [5]. Finally, no components that we utilize shall have issues passing a random vibration test as specified in 4.3.2-1 [5].

4 References

[1] Toradex, "Layout Design Guide," 2015.

[2] IEEE, "IEEE Code of Ethics," IEEE, 2020. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed 2 April 2020].

[3] ACM, "ACM Code of Ethics," ACM, 2018. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed 2 April 2020].

[4] Panasonic, "Manganese Lithium Coin Batteries (ML series): Individual Specifications," 2014.

[5] NanoRacks, "NanoRacks CubeSat Deployer (NRCSD) Interface Definition Document (IDD)," 2018.