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Anomaly Detection PCB for CubeSat Missions

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I. Introduction

IrishSat is a satellite-design team with the mission of designing, building, and testing CubeSats to launch using NASA's CubeSat Launch Initiative (CSLI). The CSLI is a program that provides opportunities for CubeSats built by U.S. universities, high schools and non-profit organizations to fly on upcoming launches. Each year, NASA releases an Announcement of Partnership Opportunity with detailed instructions on how an interested eligible organization may submit a proposal for a CubeSat project. IrishSat plans to complete its first CubeSat proposal by the end of the 2022-2023 academic year for submission to NASA in November 2023.

Since the creation of IrishSat in Fall 2020, the team has been developing the infrastructure to build and operate a CubeSat. For example, IrishSat has built a ground station on campus for satellite communication and an air bearing that can test the satellite's orientation system by rotating it on a frictionless surface. Our team plans on designing a 1U CubeSat, which is a 10x10x10cm satellite that typically weighs less than 2 kg. The CubeSat will be launched into low-earth orbit which encompasses the area of space under 1,200 miles from Earth.

II. Problem Statement and Proposed Solution

The CubeSat will operate over a 3 year cycle, but components and subsystems are expected to start experiencing significant failures in as early as 6 months. Additionally, the satellite will burn up when returning to earth, rendering most data unrecoverable.

For the satellite to be successful over its lifetime, we must ensure that it will operate and transmit data despite any malfunctioning equipment. The data transmitted must be adjusted to reflect the state of the satellite and properly modify or ignore any faulty data, for example, from sensors. A haywire sensor's inaccurate data could disrupt and invalidate the operation of multiple subsystems. If this error could be detected, the sensor could be rebooted (in an attempt to recover it) or otherwise ignored. The CubeSat's actuators would then continue to function based on the best data, which would also be stored for future reference.

A subsystem providing proper power allocation to all other subsystems is also needed. Integrating this feature with the monitoring subsystem could optimize the CubeSat's power consumption dynamically.

Transmission will need to be handled by a digital radio that will interface with the rest of the CubeSat's components using another subsystem. This communication subsystem will be responsible for selecting, compiling, and handling data transmission to the radio, which will then handle the modulation and physical transmission.

In order to properly transmit and receive our data, we need a robust communication system. We already have a software defined radio (SDR) in our possession that we will be using for our communications. This SDR, which will be programmed by the IrishSat Communications team, will interface to our PCB that contains an ESP32 and a Raspberry Pi microprocessor. This microprocessor will act as the flight computer for our satellite and will be programmed by the

IrishSat computing team. The ESP32 will serve as a sort of protection component for the flight computer and the overall board. We will have the ESP32 read in the data from all the sensors on the board (the same signals the flight computer is reading). The ESP32, which will be programmed by our Senior Design team, will be used to detect any anomalies in the sensor signals, shutting sensors and entire systems off if they are acting abnormally. Having this protection will ensure the success of our mission as it will prevent any adverse effects to the rest of the system due to bad sensors. The ESP32 will also be used to read out all the data from the sensors during our testing stages. It will additionally communicate with the flight computer through an I2C connection, relaying SDR transmissions, detecting anomalies in the sensors, and notifying of the shut down of any failed sensors.

In addition to connecting with the SDR, our board will also interface with the ProtoSat PCB with a pinstack. We will not be designing this additional PCB, which will contain the subsystems the flight computer intends to control, such as the reaction wheels. To interface with this board, we will route the Pi’s designated output pins to the pinstack to make the signals available to the ProtoSat PCB.

III. System Requirements

Our PCB will provide power to a multitude of sensors and components. Four solar cells, implemented with an external controller, will charge a battery with maximum efficiency. The battery will output 3.7V to a voltage regulator that will step down the voltage to 3.3V because the ESP32 and other components require this voltage level. For components that require 5V, a boost converter will be implemented to step up the voltage.

Our PCB will monitor the sensors in the system to detect anomalies. The current output from the solar cells, battery, and voltage regulator will be sent to the ESP32. All sensors will send their readings to the ESP32. The ESP32 will determine the state of these devices and of the overall system based upon these readings. An anomaly detection system will be implemented using software running on the ESP32. Different specifications will be required for each device based on their expected data ranges. If a device continuously transmits data outside of its expected range, the ESP32 will reboot the device. If the device continues to malfunction, it will be shut off in order to preserve power and minimize risk to the rest of the system.

Since the ESP32 will be receiving all sensor data, it will be used to format and send data packets to the SDR. Our team will determine the data that is necessary to transmit and the frequency at which to sample the data.

The size limitations are substantial for this project. There is a separate PCB being designed by the IrishSat ProtoSat team that will control three motors used for attitude control. Our PCB will power this board, so we must send it power signals through a pin stack. Both PCBs and the SDR must stack to fit within a 5.5cmx6.5cmx4.25cm space. To satisfy this requirement, we will design our PCB with four layers, so we can utilize the top and bottom layers to mount parts. PCBs are lightweight, so we are not concerned about exceeding any weight limits.

IV. System Block Diagram

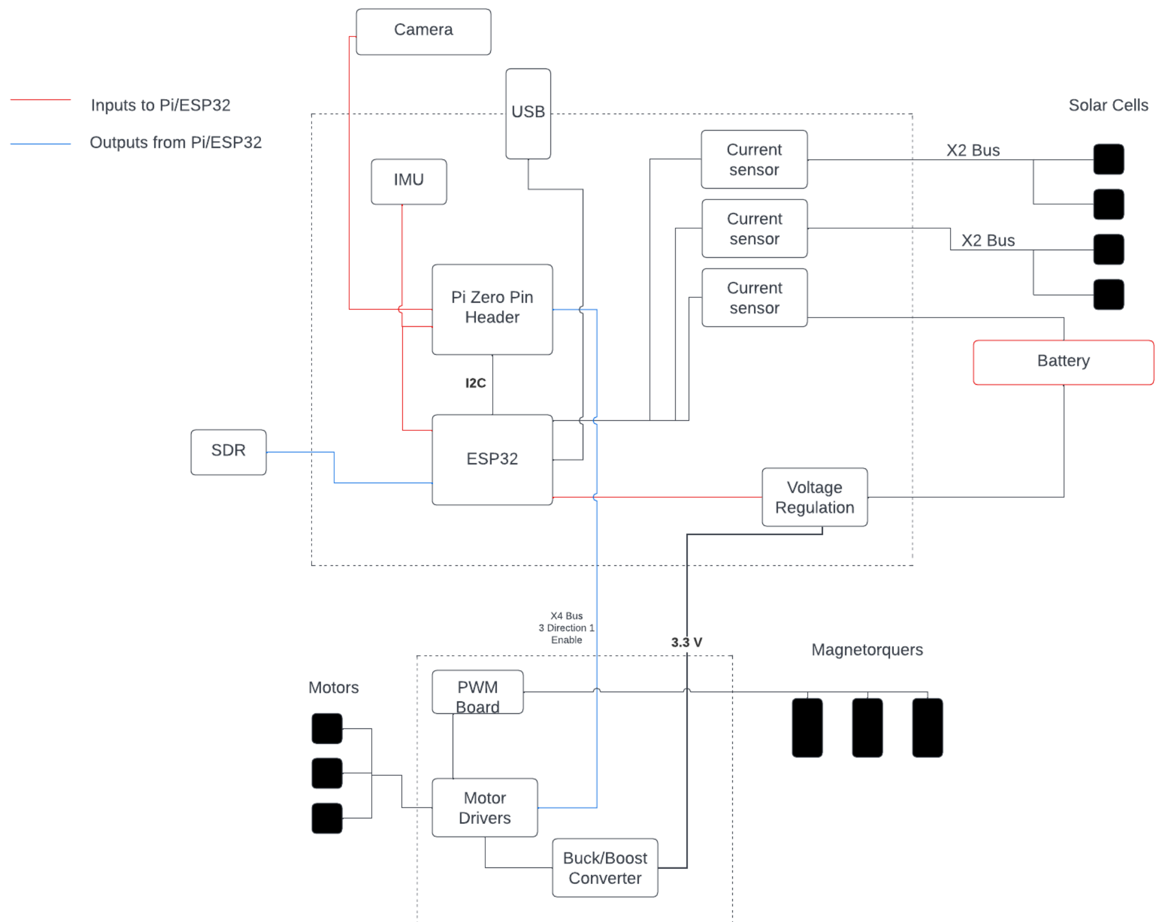

Figure 1: *System Block Diagram*

i. Overall System:

The system will operate as an anomaly detection unit for various sensors across the CubeSat. As seen in **Figure 1**, the main PCB connects to a separate PCB for motor control, as well as solar cells, batteries, an IMU (inertial measurement unit), and an SDR. For proper operation of the system, it is necessary to have multiple subsystems. The subsystems were broken down into power, anomaly detection, communications, and major interfaces for the general ease of completing this project. Future enhancements that are beyond the scope of this project are also discussed below.

ii. Power

Our power subsystem will need to be relatively complex as it will be regulating the power for our PCB as well as some of the major interfaces to our PCB. Our subsystems will be powered by rechargeable LiPo batteries that will be charged by deployable solar cells that are on the

CubeSat. Although these solar cells are not in the scope of this project, there is a possibility that we will need to include MPPT controllers on our PCB to drop the voltage coming from the solar cells to an acceptable value for the batteries. Ideally, external controllers will accomplish this, but the ProtoSat team has not yet decided if they will be purchased or not.

Additionally, we will need to include a boost converter to amplify the voltage to 5V in order to power both the ESP and the Pi. A voltage regulator will also be needed to regulate the voltage from the batteries for our PCB as well as the motor PCB that our ProtoSat team is developing.

iii. Anomaly Detection

The anomaly detection subsystem is responsible for monitoring current and voltage levels for sensors and ensuring that all devices are operating within recommended tolerances. Additionally, this subsystem will include an overall CubeSat state detection system which will be able to classify the current state of the overall system and the validity of the current sensor data. For example: if the CubeSat is tumbling, oscillating unstably, stably oscillating, etc.

One of the main requirements for the anomaly detection subsystem is an I2C interface between the ESP32, which will be monitoring all of the incoming sensor data and the current coming from the solar panels and battery, and the Pi, which controls all of the subsystems on the CubeSat, so the Pi can be informed when anomalies occur.

iv. Communications

The Senior Design delegated portion of the communications system will be required to take in sensor data and flight commands and package them in a packet format that will be readable by the SDR signal processing application. The terminus of our data stream will be a Sidekiq Z2 SDR, manufactured by Epiq Solutions, which includes both a Linux computer and an RFIC chip.

v. Major Interfaces

The selected flight computer is a Raspberry Pi Zero, which is what the ProtoSat team is currently using for software development.

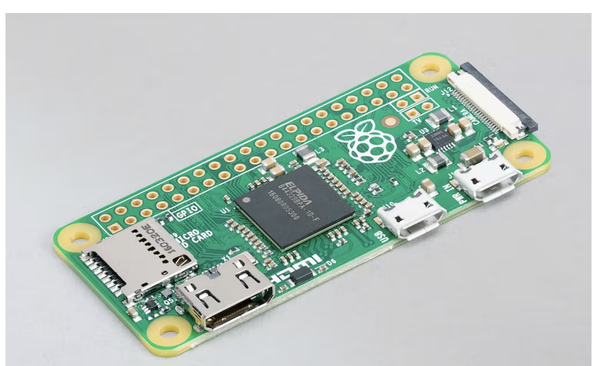

Figure 2: Pi Zero (source: Raspberry Pi Website)

Aside from communicating with the ESP32, the main requirements for the flight computer is that it is powered and interfaces with all the required sensors, the motor drivers, and the external memory storage. The software in this subsystem will be handled by the ProtoSat team.

The second major interface is between the board and the motor board, which will include motor drivers to interface with the motors and magnetorquers, and requires power from our board and control signals from the flight computer.

Our board will be interfacing with a few other independent modules. The IMU will be included on our PCB for the ProtoSat team to use to measure the state of the CubeSat. Our PCB will also be interfacing to the SDR that was discussed above in the communications section. For the purpose of this project, the CubeSat will demonstrate the proper functionality of this research module with a sun sensor attached to the flight computer. Any additional research payloads that may be added next semester would have to be connected to, powered by, and read by the PCB. Finally, we will be connecting both the solar cells and the batteries to our PCB, which were discussed in the power section above.

iv. Future Enhancement Requirements

As mentioned above, there will be a sun sensor as a testing module for our actual research payload. It is still being decided what the research payload for the CubeSat will be. Potential options currently include a radio spectrum analyzer called RadioHound that is being developed by SpectrumX and the Wireless Institute on campus and infrared-seeking nano-antennas that are being developed by Professor Gary Bernstein.

V. High Level Design Decisions

i. Power

The power subsystem will interface with four solar cells and a battery.

The control for the solar cells will be handled by an external component selected by ProtoSat. The ESP32 will be monitoring the current from the battery and the solar cells for anomalies.

The on-board power subsystem will include a voltage regulator to convert the ~3.7V coming from the battery to 3.3V to power the ESP32 and the current sensors. It will also include a boost converter to step the ~3.7V from the battery up to 5V to power the Pi Zero.

ii. Anomaly Detection

The anomaly detection subsystem contains two major sensors; an IMU for orientation and current sensors associated with monitoring the power.

The ESP32 will be an ESP32-U4WDH, chosen for the dual-cores as the ESP32 will have multiple jobs and for the 4MB of embedded flash.

Table 1: Maximum ratings for draw from battery from motor board

Parameter	Nominal	Maximum
Current draw from battery	3A	7A
Voltage draw from battery	3.7V	4.2V

The output of the solar panels are less than the output of the battery to the motor board, so the maximum ratings for current and voltage drawn from the battery will inform our current sensor selection. The current sensors will be CT416-HSN820DRs from Mouser, and the version used will be one with the current sensing range of -20A to +20A. The supply voltage is 5V, which is already being generated to supply the Pi, and the output is a linear variable voltage with an absolute maximum of 2.65V, which is acceptable as the ESP32 has analog input pins that are 3.3V tolerant. The current sensing range is far outside the acceptable current from all three sources, so detecting anomalies will be feasible.

The sun sensor will be a Zero Spy Camera for Raspberry Pi Zero from Adafruit, chosen for its small size (8.6mm x 8.6mm) and use of the Pi's CSI interface, which is designed specifically to interface with cameras. When presented as an option to the ProtoSat computing team, it was noted that it is also similar to a camera used in previous years.

The IMU, chosen by the ProtoSat team, will be an ICM-20948 from Mouser, which can provide sensor data from 9 sensors (3 gyroscopes, 3 accelerometers, 3 magnetometers) through I2C or SPI connections. The IMU will be primarily routed to the Pi for use in orientation, but the ESP32 will monitor the communication line as well.

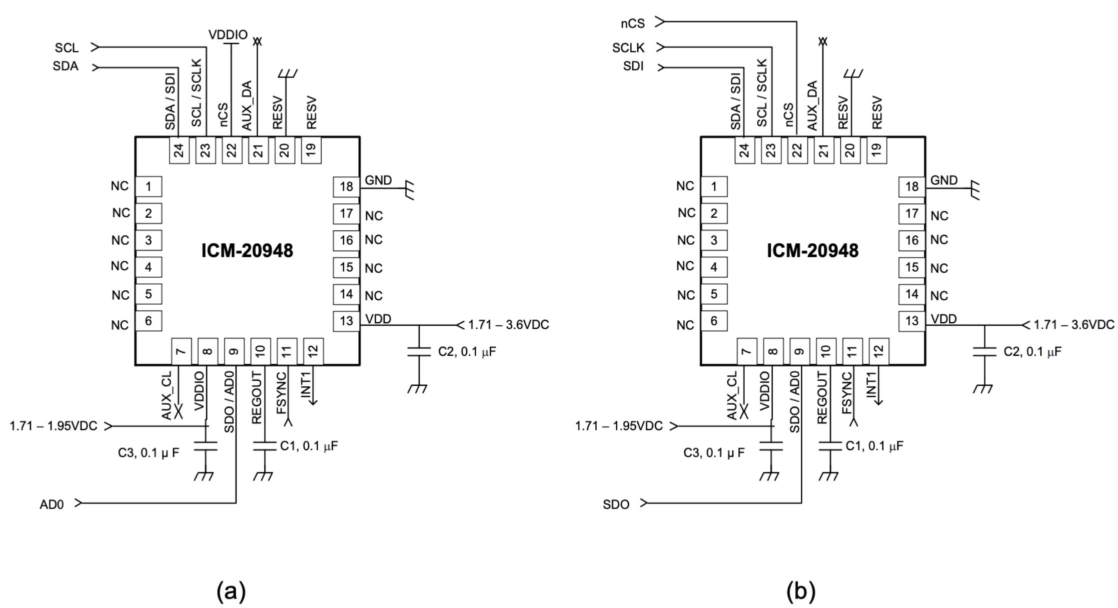

Figure 4. ICM-20948 Application Schematic (a) I²C operation (b) SPI operation

Figure 3: IMU I2C and SPI Schematics (Source: ICM-20948 Datasheet)

iii. Communications

The communications subsystem will consist of a Sidekiq Z2 SDR from Epiq Solutions with interfaces to the ESP32 and the flight computer. For the purposes of CubeSat communications, a space-tested, high-quality software-defined-radio is generally recommended. These are typically expensive and hard to come by. The particular SDR that we have decided to use in this project was donated to the IrishSat team by Epiq Solutions. Therefore, even if better solutions are available on the market, the cost consideration of acquiring a high-quality SDR forces us to choose the option that was given to us for free. Regardless, the Sidekiq has shown robust operation in space on previous CubeSat missions, so given cost and quality it is currently our best option.

iv. Major Interfaces

The purpose of the flight computer is to control every subsystem within the prototype satellite. The purposes that are relevant to the design of this board include processing IMU data for orientation, taking in sun sensor data for orientation and as a payload, and sending control signals to the motor drivers to control the motors. The Pi Zero will be mounted on top of the PCB with 40 female pin headers. The board will route all Pi I/O signals through this pinstack.

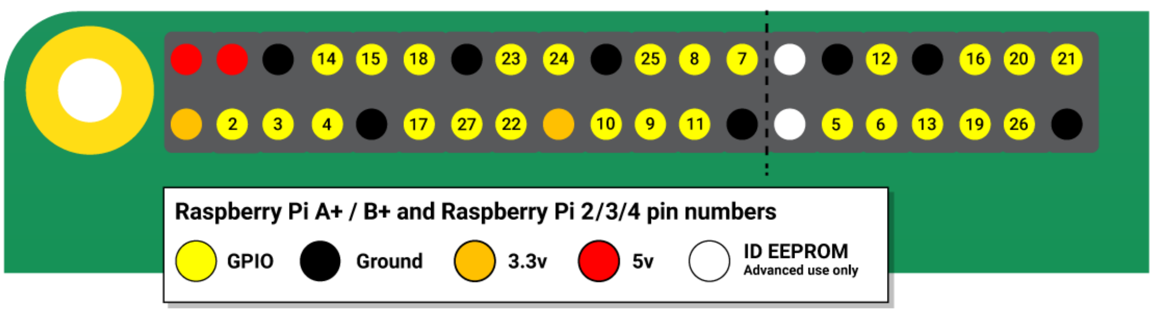

Figure 4: Pi Zero GPIO Connections (Source: Raspberry Pi documentation)

The 3.3V power will come from the voltage regulator, and the 5V power will come from the boost converter. The external memory will be a 128 GB SD card, with a MicroSD card breakout board from Adafruit.

A secondary pinstack will provide the connections to the motor board. The power signals will be a 3.3V power and a ground signal from the voltage regulator. The control signals will be four digital signals, three directional and one enable signal from the flight computer, through the board, and to the motor board to connect to the motor drivers. So in total, there will be 6 connections through the pinstack.

VI. Open Questions

There are several features of our design that have not been finalized. One open question is whether the ProtoSat team will be purchasing a control module to work with the solar cells, or if MPPTs will have to be included on the PCB to provide the interface between the solar cells and the battery. ProtoSat has indicated that purchasing a control module will be the likely situation, but have not made a final decision.

Should the MPPTs need to be included on the PCB, then it is also an open question whether our MPPT algorithm will be implemented using passive sensors or active sensors, which will alter the biasing circuits necessary for their operation and would require some analog voltage control.

Additionally, if it is feasible, voltage sensors might be included to work in tandem with the current sensors to monitor the solar panels and the battery.

VII. Major Component Costs

Table 2: Major Component Costs

Component	Manufacturer	Cost
Zero Spy Camera for Raspberry Pi Zero	Adafruit	$19.95
MicroSD card breakout board	Adafruit	$7.50
128GB MicroSD Card	Best Buy	$50.00*
CT416-HSN820DR current sensor	Mouser	$6.50
3.3V to 5V Boost converter	DigiKey	$4.51
ICM-20948 IMU	Mouser	$11.21
ESP32-U4WDH	Digikey	$2.07

*Found item on sale, recorded non-sale price

VIII. Conclusions

The work done by this senior design team will serve to assist IrishSat in their goals of becoming the first Notre Dame design team to operate a satellite in outer space. This project will eventually be implemented as an integral part of IrishSat's prototype CubeSat, and will be extremely useful to the team as they move forward in their CubeSat development cycle. Having a senior design team design the central PCB for ProtoSat takes much of the strain off of the ProtoSat team, allowing them to work on tasks in parallel which will result in faster completion of the CubeSat prototype.

References

Major Components

Zero Spy Camera for Raspberry Pi Zero
MicroSD card breakout board
128GB MicroSD Card
CT416-HSN820DR current sensor
3.3V to 5V Boost converter
ICM-20948 IMU
ESP32-U4WDH

Figures

Raspberry Pi Zero
ICM-20948 Datasheet
Raspberry Pi hardware documentation