OreSat Attitude Control System

Final report for the Oregon Space Grant Consortium 2017-2018 Undergraduate Team Experience Award Program

July 30th, 2018

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Supported in part through NASA/Oregon Space Grant Consortium, grant NNX15AJ14H

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1. Project Description

We designed, prototyped, and tested an Attitude Control System (ACS) for Oregon's first satellite, OreSat.

OreSat is a CubeSat with a 2U form factor that will be deployed into low earth orbit in late 2019 as part of the NASA CubeSat Launch Initiative. OreSat's primary mission is to connect Oregon K-12 students through space-based STEM outreach. OreSat will be transmitting live video from space. Oregon students will receive the signal with hand-built, handheld radio receivers pointed at the satellite. OreSat's secondary mission is to survey the global coverage of high altitude cirrus clouds using an inexpensive, innovative camera and filter system from Dr. Greg Bothun at the University of Oregon.

OreSat requires 3 axis attitude control for two reasons: to accurately point its high gain S-band (2.4 GHz) antenna for the live video transmission, and to point its multispectral cirrus cloud camera system. OreSat requires a minimum pointing accuracy of only ± 5° with a target of ± 1°, which is a very wide target: most commercial off-the-shelf (COTS) ACS have accuracies in the arcseconds, although they usually cost more than $50,000.

For this project, we design a low accuracy, open source, and inexpensive attitude control system comprised of reaction wheels (RWs) and magnetorquers (MT). Most of the focus on this project was on the electronics system needed to run the DC brushless motors of the RWs and bidirectional current in the MT coils.

Note that the attitude determination system (ADS) (the combination of a star tracker and GPS receiver) and the state space attitude control algorithm are separate OreSat projects being implemented by other teams, and are not considered here.

In our proposal, we had a list of six deliverables. We're happy to say we delivered on 4 and partially delivered on 2:

1. Determined RW Motor Configuration and Placement -- DONE
2. Selected and tested a RW Motor -- DONE
3. Create a RW Motor Controller Board -- DONE
4. Create a MT -- Partially complete
5. Create a MT Controller Board -- DONE
6. Test, Test, Test -- Partially complete

2 Requirements Gathering

A critical part of any project is gathering the correct requirements and having a design direction. Here is a summary of the top level requirements.

2.1 External Constraints

- Environmental constraints and problems
    - Cold welding
        - No moving parts that use metal at their interface.
    - Temperature
        - Ranges from -40° to 100° C
        - Only cooling available to satellite subsystems is conduction to satellite structure. Only cooling available to entire satellite is radiative.
    - Mass
        - Minimize mass, but maximize angular inertia of the RW
    - Acceleration
        - Needs to be able to control acceleration with high precision.
- Mechanical System
    - Size
        - Entire ACS size bounded by 4 OreSat Card slots: 40 x 90 x 90 cm
        - Each control board must be as small as possible
    - Heat
        - Minimize heat output from control ICs and RWs and MTs.
        - Control card needs to be thermally sunk to the the OreSat frame.
- Electrical Power
    - Supply voltage: 2.5 - 4.2 V and be capable of adapting to the range of 5.0 - 8.4 V
    - Supply current: ~ 1 A continuous, with up to 3 A peak (supplied by batteries)
    - Solar panels produce only 2.5 W continuously in sunlight
        - Hardware components must be capable of minimal power hibernation states in between brief periods of use.
- Attitude Control
    - Reaction wheels
        - To exert strong control authority over the satellite's orientation for brief periods of time to track a fixed point on the ground. Conserves the satellite's angular momentum.
    - Magnetorquers
        - To exert very soft, 2 axis only torque against Earth's magnetic field. Changes, very slowly, the satellite's angular momentum.

- Communication
    - OreSat uses a 1 Mbps Controller Area Network (CAN) serial bus for communication among all of it's different systems. The ACS must communicate via this bus.

2.2 Design Paradigm

- Firmware
    - ACS is a critical part of the satellite, a failure resistant design was desired.
    - Real time operating systems are ideal for time critical applications, in which some guarantee of an input being acted upon within a certain time frame is needed.
    - To reduce power consumption, as well as storage size, the code should be as compact and efficient as possible.

2.3 Maintainability

- Organizational
    - OreSat is a project primarily contributed to and worked on by students. This necessitates the ability for new individuals to be able to join the project and quickly contribute meaningful work. This requires comprehensive and efficient documentations as a whole, as well as quick "bring up" guides and "onboarding" specific documentation.
- Continuation
    - Portability
        - Code portability is highly desirable across all the different OreSat systems to aid fast development, efficient debugging, and allow developers to help where they are needed. To facilitate this, we try to use a single processor family and OS for as many subsystems as possible.
    - Adaptability
        - Research done while developing ACS can be used for other applications of BLDC motor control.
    - Maintainability
        - The ACS must be well documented in order for future engineers to catch up and contribute as fast as possible.

3 Results

This section is organized by the six deliverables outlined in our proposal.

3.1 Determined RW Motor Configuration and Placement

Only three reaction wheels (RWs) are required to do three axis attitude control on a satellite. However, there are some RW arrangements which provide unique advantages. See Figure 3.1.1.

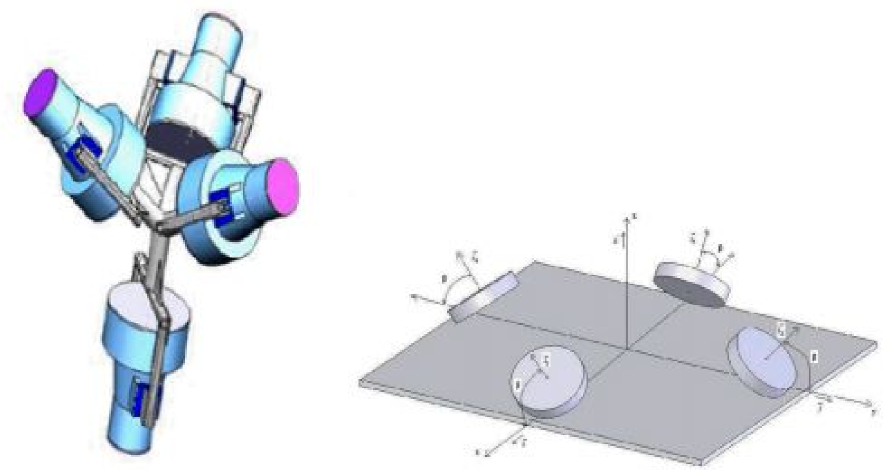

Figure 3.1.1 -- Tetrahedral and Pyramidal RW arrangements (Kök 2012, Figure 5.1)

We chose a pyramidal arrangement of reaction wheels (RWs), originally described in Logan 2008. The four RW pyramidal arrangement allows for a single RW system to fail without impacting total system functionality, as well as increased performance from smaller wheels working together. Further, the pyramidal arrangement packs better into a flat cubic shape like found in a CubeSat.

See Figure 3.1.2 and 3.2.3 for our RW aragement.

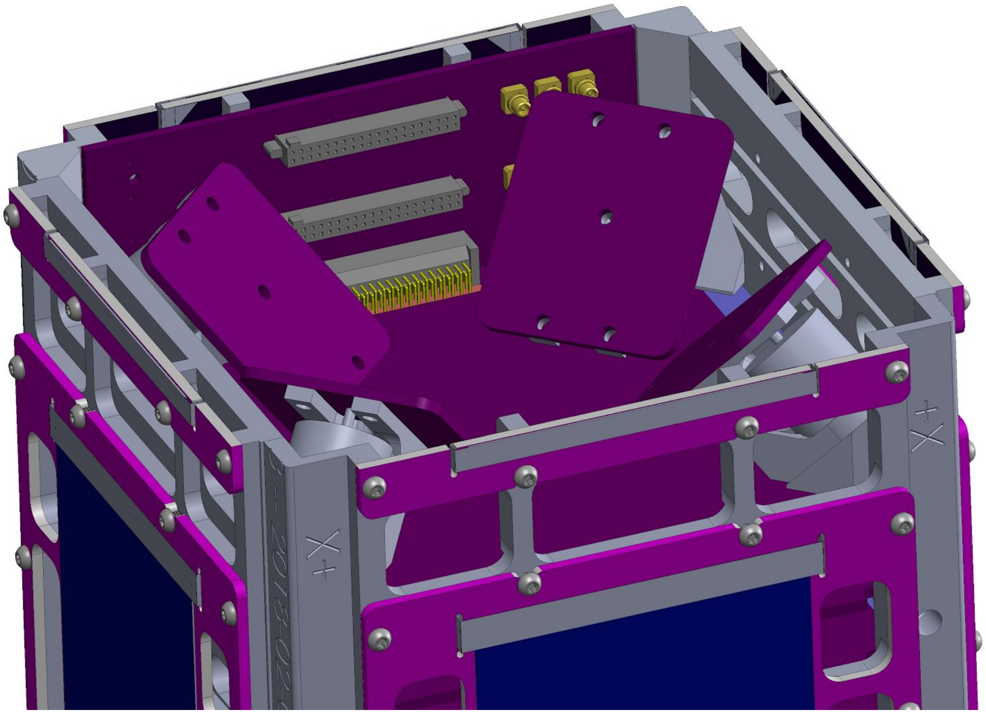

Figure 3.1.2 - Pyramidal arrangements of Reaction Wheels

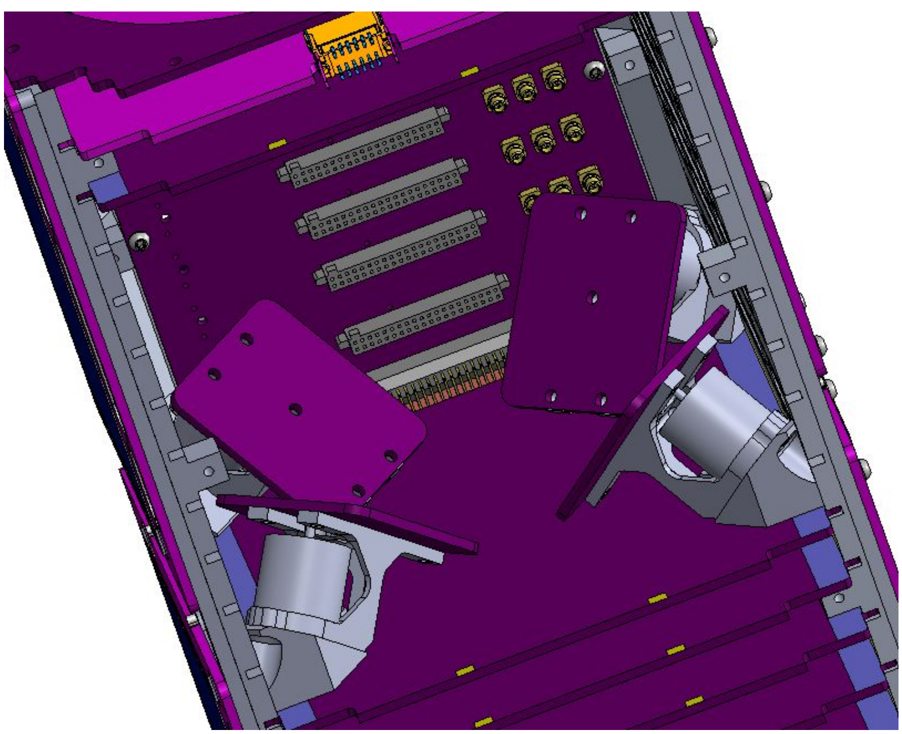

Figure 3.1.3 - Another view into the pyramidal system showing the space constraints

3.2 Selected and tested a RW Motor

A 2U CubeSat has such a small angular inertia that even extremely small reaction wheels (RWs) can be chosen, assuming they can reach sufficient speeds. A half dozen small DC brushless motors were chosen and tested. Figure 3.2.1 shows the D1104-4000KVA, a widely available, inexpensive, commercial off-the-shelf DC brushless motor chosen for the RWs. This particular motor has mounting holes on both sides, is compact, and it's "outrunner" topology of magnets on the outer rotor wall increases its moment of inertia, a positive outcome for a RW.

Figure 3.2.1 - D1104-4000KVA motor (courtesy Albert Kim, YouTube)

For operation in the space environment, the motor's small but standard sized metal-on-metal ball bearings must be replaced with hybrid bearings, which use cermaic balls to minimize vacuum welding and galling.

3.3 Create a RW Motor Controller Board

Most of the work for this project was put into the electronics control board that runs the RWs and MTs. Figure 3.3.1 shows the block diagram for the board, and Figure 3.3.2 shows the final results.

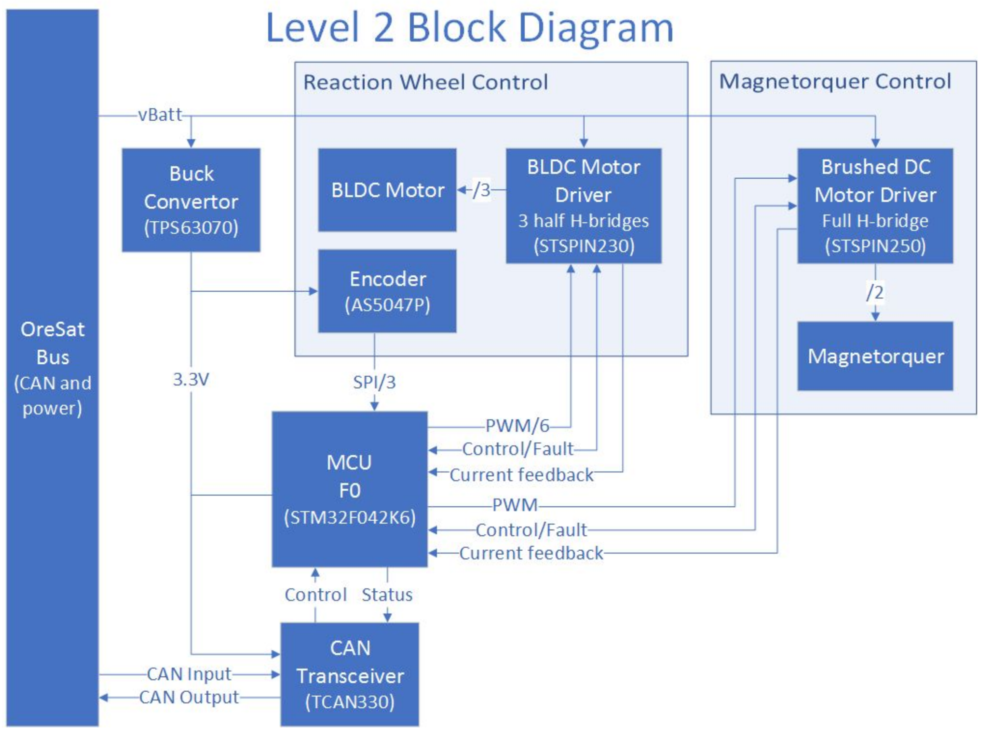

Figure 3.3.1 - Block diagram of ACS control board

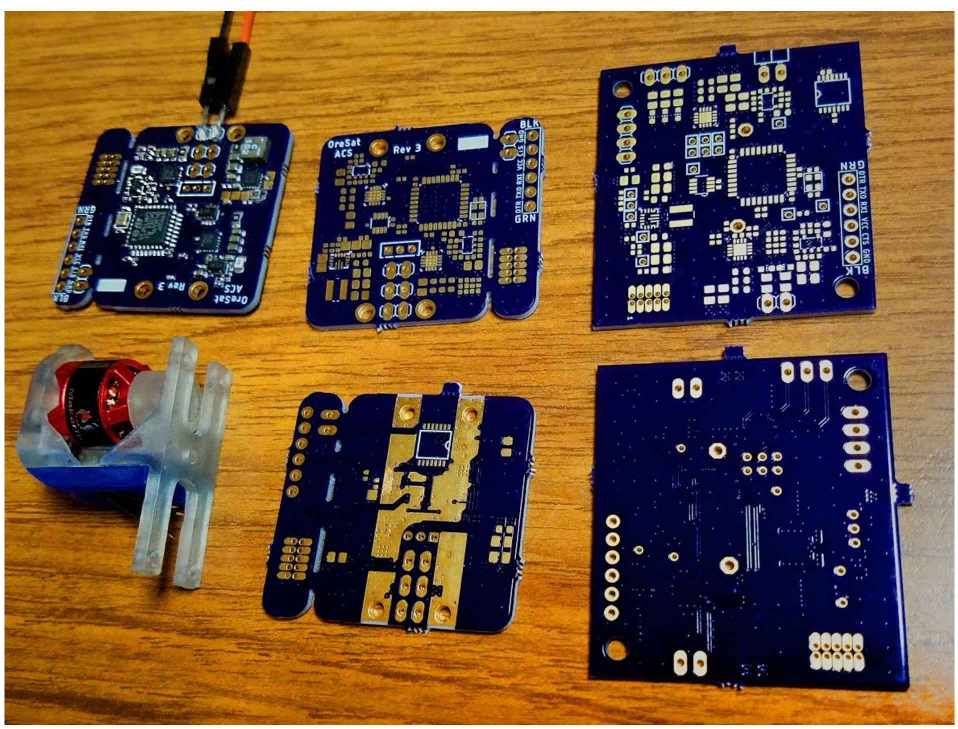

Figure 3.3.2 - Electronic control boards. Right two boards are "flat prototype" boards, middle two boards are unstuffed final design, upper left is a completed and working final design, and lower left is a RW with 3D printed mounting bracket.

3.3.1 Hardware

The following hardware was chosen:

- Microcontroller: STM32F042K6
    - This is the default development chip being used in the overall OreSat Project.
    - We did our initial development for this environment so we would be forced to make the bulk of the code lightweight and portable.
    - No floating point unit means that our development can be used for a much broader range on MCUs
- Magnetorquer controller: STSPIN230
    - Low voltage triple half-bridge bldc motor driver designed to operate with the stm32 MCU.
    - Even for use with other systems, this driver has a very small footprint as well as a very wide voltage range, making it useable with both 1 cell and 2 cell battery systems.
- Brushless DC (BLDC) Motor Driver: STSPIN250
    - Uses much the same structure as the STSPIN230.
    - Very small footprint.
    - Both systems have thermal and electrical failure modes that can be read back to the MCU.
- BLDC Motor Encoder: AS5047P
    - 14 bit on-axis magnetic rotary position sensor capable of accurately determining motor position at speeds up to 28k rpm
    - Communicates with the MCU using a SPI bus interface, API, Quadrature, and Synthesized UVW, allowing for a considerable range of applications.
    - Extremely small form factor for encoder.
    - No moving parts.
- Printed Circuit Board
    - 4 layers.
    - We designed multiple revisions of a custom PCB for our ACS. This board fit within space constraints identified and was compatible with the first design of motor mounts.
    - The board layout has a large bare metal interface to the mounting bracket to conduct the heat generated by the control board to the OreSat frame.
    - See Figure 3.3.3.

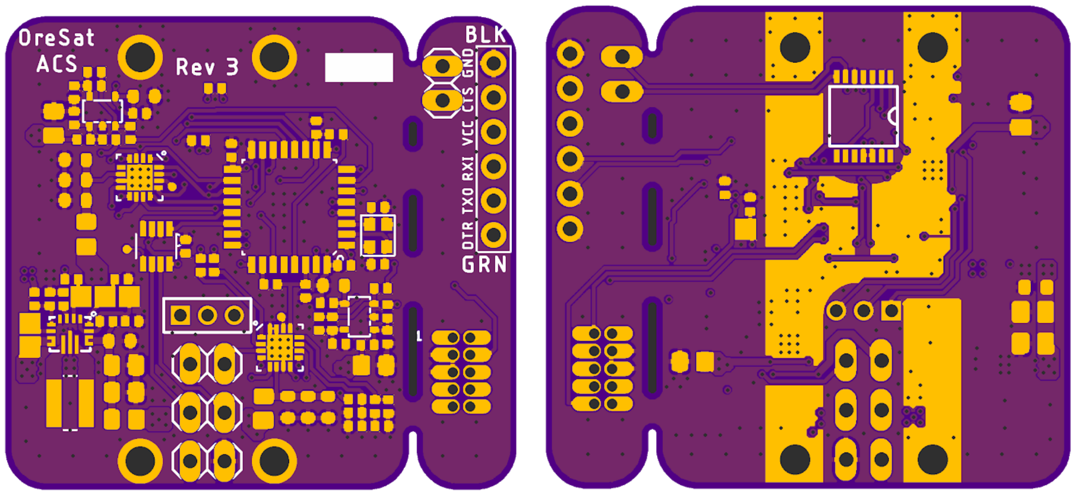

Figure 3.3.3 - Final board layout, top and bottom boards. Note detachable programming and debugging module on the side of the PCB. Also note the sections of ground plane exposed on the bottom of the board (right) for thermal contacts to the Aluminum mounting bracket.

3.3.2 Firmware

The firmware was written in C using the following tools:

- ChibiOS
  - Small, portable, open source real time operating system written in C that exposes low level drivers for PWM, ADC, CAN, and SPI. ChibiOS is compiled using gcc and written to a MCU via stmlink or JTAG connection and a utility such as OpenOCD.
- GNU toolchain
  - OpenOCD - open on chip debugger: Used to debug and write binary images on the MCU using JTAG
  - GCC- gcc-arm-none-eabi: Open source compiler for cross compiling ARM binaries on a Linux operating system.

We designed and implemented a Mealy state machine for the purpose of controlling the attitude control system. This provides a robust system where functionality can define exactly what actions are allowed in a givens state, and exactly what state transitions are allowed. When the system is powered on it begins in the initialization state where basic functionality such as interfacing with the CAN bus is activated. From this state the ACS can transition into the ready where it is possible to transition to either the reaction wheels state or, the magnetorquer state. It is important to isolate these states since pin usage is dependent on the state and the magnetorquer must share a pin with the reaction wheels. See Figure 3.3.4.

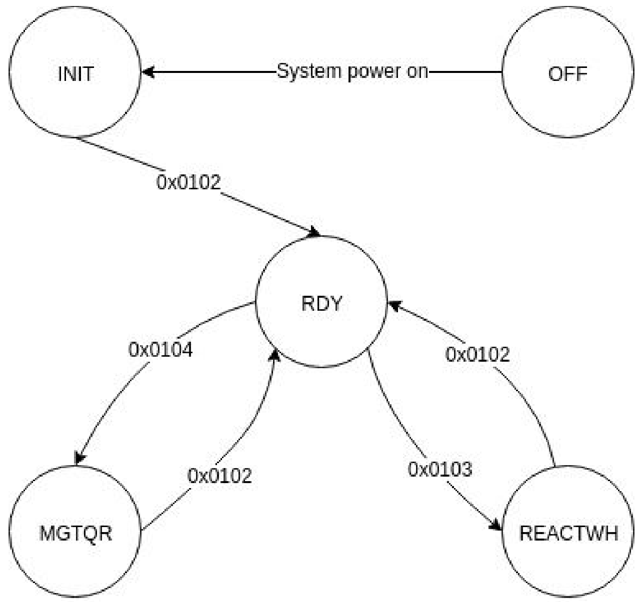

Figure 3.3.4 - This type of software architecture allows for modular design, making future maintenance and modification much easier

3.3.3 Communication over the CAN Bus

OreSat is designed to use a controller area network bus to communicate with all of it's disparate systems. A CAN bus is favored over other other implementations because of the certainty that OreSat will operate in the electromagnetically noisy environment of space. The CAN bus is implemented using the CANopen protocol. The ACS contains two shared buffers on the bus, one for transmitting system status and one for receiving commands from the flight computer.

Multiple ACS boards can be connected to the CAN bus, being controlled via CAN commands coming from a system controller. For debugging and system design, we used laptops with USB to CAN controllers. Each system can be individually address and sent commands that only affect that specific system. Each system is able to function with the removal of another, which will allow the flight controller to detect that a particular motor or magnetorquer has gone out, and use the remaining three to compensate.

3.3.4 BLDC Motor Control

Due to the limitations on processing power and lack of a floating point unit, we chose to implement Sinusoidal BLDC control. Three 120 degree shifted sine waves are produced using the PWM module of the F0. These sine waves are created using PWM, by ranging the duty cycle from 0% to 100%, in a sinusoidal pattern. The system used a Look Up Table (LUT) for generating the sinusoidal PWM:

- Low processing power, and no floating point unit
  - Duty cycle - Look up table vs calculation of values
    - Pros
      - We don't have a floating point unit so this is a good option
      - No need to perform calculations that are expensive for the processor.
      - Sine wave calculations are more flexible but slow. A lookup table is accessed via fast pointer arithmetic.
    - Cons
      - The m0 only has 32k flash memory
      - Less control of input waveform to the motor.

3.3.5 Sensors and Feedback

The system had two main forms of feedback:

- ADC
  - The microcontroller used the ADC to monitor RW and MT current consumption, using current outputs from the STSPIN2XX ICs.
- Encoder
  - The AS5047P hall effect IC provides absolute motor angular position to the MCU over the SPI bus. This information is used to determine the location of the next duty cycle in the lookup table.

3.3.6 Reaction Wheel and Control Card Mounting System

The PCB is attached to the BLDC motors using an innovative bracket system which holds the motor, magnet, and ACS PCB. The PCB is mounted in such a way that the ground plane is directly held against the Aluminum bracket in order to have maximum thermal contact.

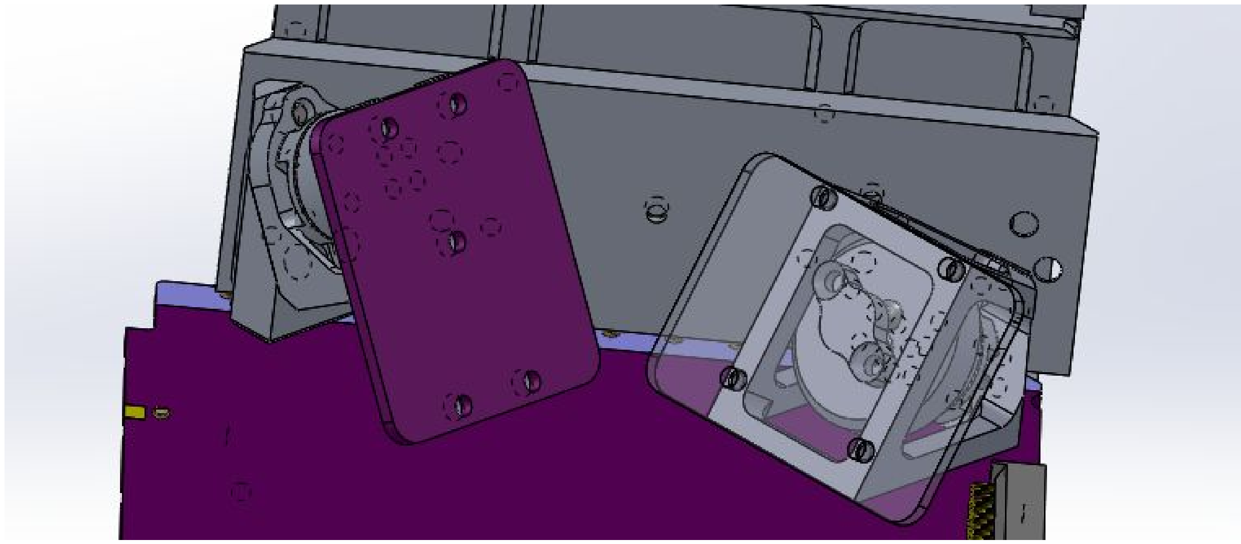

Figure 3.3.5 - New backet system on the right, show through transparent PCB

3.4 Create a Magnetorquer (MT)

The magnetorquer directly changes the satellite's angular momentum by weakly torquing against the Earth's magnetic field for long periods of time. The MTs were not fully designed at time of our project; too much was still unknown with the power and space budgets, as well as the lack of system requirements. However, MTs are simply solenoids (coils of wire), so we use small hand wound coils to prototype the MT drivers. Future teams will specify, wind, and connect the MTs to the current ACS board.

3.5 Create a MT Controller Board

The Magnetorquers are driven by the STSPIN 250 IC brushed motor drivers on the ACS board. This gave us a simple and readily available method for generating the controlled current necessary to drive a magnetorquer in a small form factor with integrated thermal and electrical fault feedback. The ACS board should be able to control a wide range of MT designs, as long as the voltage and current capabilities are followed.

3.6 Test, Test, Test

We demonstrated a fully operational reaction wheel (RW) system, and a full yworking magnetorquer (MT) control circuit. Tests were done to confirm rotational speed and current control. However, no time was left in the project to do environmental testing in a thermal vacuum chamber. Now that a thermal vacuum chamber has been acquired, we plan to do this testing later this summer.

4 Conclusion and Future Work

The team successfully design and built a reaction wheel and magnetorquer control board for the OreSat CubeSat. Reaction wheels were fully operational, and a mock-up magnetorquer was run.

The team would like to thank the Oregon Space Grant Consortium's Undergraduate Team Award Program (UTEAP) program for making this work possible.

Finally, we've identified future work to be performed before flight:

- The STM32F042K6 limited software development because of processing power. It also required multiplexing systems together to accommodate the number and types of output that were available. This forced us to separate the operation of the magnetorquer driver and the BLDC driver, making it ill advised to have both systems active at the same time. Therefore, we plan to upgrade to a larger, more powerful microprocessor; namely the STM32L452CE. This MCU is faster, has more pins exposed, and consumes less power than the STM32F042k6 because of its ability to utilize multiple low power modes.
- We intend to implement Field Oriented Control (FOC) as the next improvement to motor control, as our upgraded processor will be able to support the required processing power and now includes a floating point unit. This will allow us greater control over the motor at high speeds, and better performance overall.
- A new bracket design was created to fit a larger RW "flywheel" in a smaller space. The final board will be re-laid out to match this form factor.
- Extensive thermal and vacuum environmental testing, especially around the BLDC motor bearings and heat transfer from the motor controller ICs.

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6 Final Budget

WAITING ON FINAL NUMBERS FROM PSU DEPARTMENTAL RESEARCH ADMINISTRATORS...

A Appendix

A.1 Terms and Definitions

ADC - Analog to digital converter

CAN - Controller area network

ChibiOS - An open source RTOS

IC - Integrated circuit

JTAG - Joint Test Action Group is an industry standard for interfacing with, testing, and verifying the design of hardware.

LUT - Lookup Table

Magnetorquers - Electromagnetic coils used by a satellite system to stabilize, detumble, and barbeque roll. These coils interact with the Earth's magnetic field to control the attitude of the satellite.

MCU - A Microcontroller unit is a small computer processor on an integrated circuit.

Mealy State Machine - A Mealy machine is a finite state machine where the output is determined by its current state and inputs.

PWM - Pulse-Width Modulation

Reaction Wheels - a system of flywheels used to adjust the attitude of a satellite.

RTOS - Real-Time Operating System

SPI - Serial peripheral interface

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