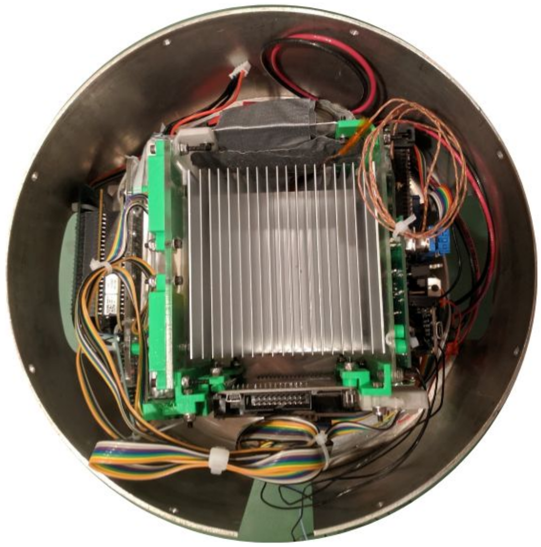
RockSat-C 2019 Final Report

Stevens Institute of Technology



Turbulent-Laminar Airflow Analysis of High-Speed Vehicles
Chris Blackwood, Chris Cowan, Sam Yakovlev

Reflow Soldering in Microgravity
Aidan Aquino, Kevin Gmelin, Joshua Gross, Jack Hymowitz, Stephen Kontrimas, Reinier Lazaro, Scott Maslin, Russell Whitsitt

Accelerometer Filtering
Zach Shoop, Jack Hymowitz

Power Management Board
Jesse Stevenson, Jack Hymowitz

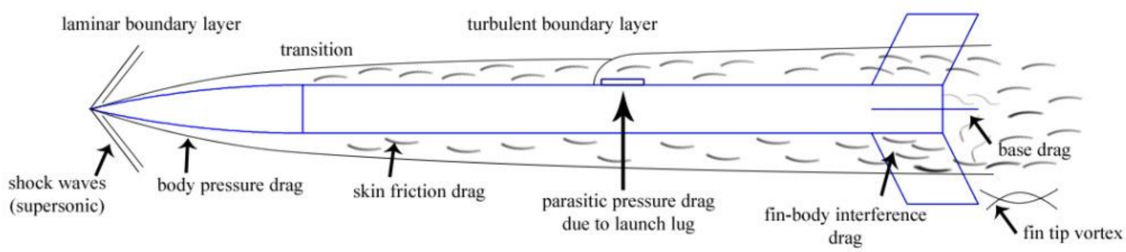
Advisors
Prof. Joseph Miles, Prof. Nick Parziale

School: Stevens Institute of Technology
July 26th, 2019

Turbulent-Laminar Airflow Analysis of High-Speed Vehicles

1.0 Mission Statement

This project aimed to measure the pressure oscillations created during the formation of the boundary layer transition from laminar to turbulent flow along the skin of high-speed vehicles; in this instance a Terrier-Improved sounding rocket. A high-frequency pressure sensor was mounted in a custom port-pocket window in such a manner that allows the sensor to sit flush with the outer skin of the rocket. This project is of interest to the research of aerodynamic phenomena in high-speed vehicles. The below image illustrates the distinction between the boundary layers formed in flight. Based on the transition zone existing at the base of the nose cone, the sensor was mounted in the uppermost port to capture the pressure readings of this transition zone as the turbulent region forms.



2.0 Mission Requirements and Description

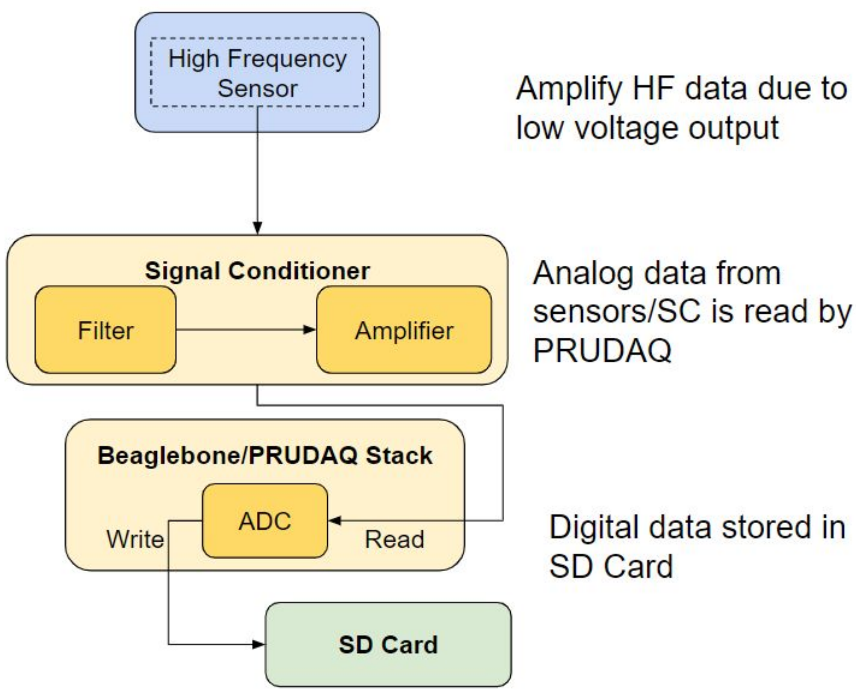
As rockets approach speeds on the order of Mach 4, a boundary-layer transition is expected to occur on the interface of the rocket skin and the surrounding atmosphere. Consider a rocket cutting through the atmosphere at high speeds: Directly on the outside of the rocket skin, there lies a film of air that "hugs" the skin of the rocket and moves at a velocity very close to the velocity of the rocket. Much further away from the rocket skin, atmospheric air is relatively still. Somewhere between these two streams of air, there is a "boundary layer" where these air streams must interact - this is referred to as the 'interface'. When the velocity of the rocket becomes sufficiently high, these two air streams will begin to act very chaotically at the interface, as the high speed air tends to "rip" away at the low speed air, which at a macroscopic scale contributes to the friction known as air resistance. At a much smaller scale, however, there are expected to be high-frequency acoustic noises produced at this junction. The pressure teams set out this year to analyze the nature of this acoustic energy. First, before the DAQ was designed to collect data, the team collected as much information as possible about the nature of these oscillations. With the guidance of Professor Nick Parziale, it was determined that the characteristics of the noise radiation are as follows: Amplitude: 0 - 100 Pa, Peak-Peak Frequency: 0 Hz - 1 MHz. In order to digitally sample analog signals up to 1 MHz, it was required by Nyquist's Sampling Theorem to sample at 2 MS/s or greater. The system must have sufficient analog signal gain to capture the 100 Pa peak-peak signal with good dynamic range. Other mission requirements were that the unit must sample for at least 5 minutes duration in order to ensure that the launch window is not missed. These real requirements were then translated into the Technical Design Requirements (TDR):

1. Analog subsystem must have analog gain of 1000 (30 dB).
2. Digital sampling subsystem must have a sample rate of at least 2 MS/s.
3. Digital Sampling subsystem must have storage for 5 minutes of sampling, which is equivalent to 2.4 GB of non-volatile memory.
4. System must contain all power regulation electronics to power the analog signal conditioner board, as well as digital sampling subsystem.

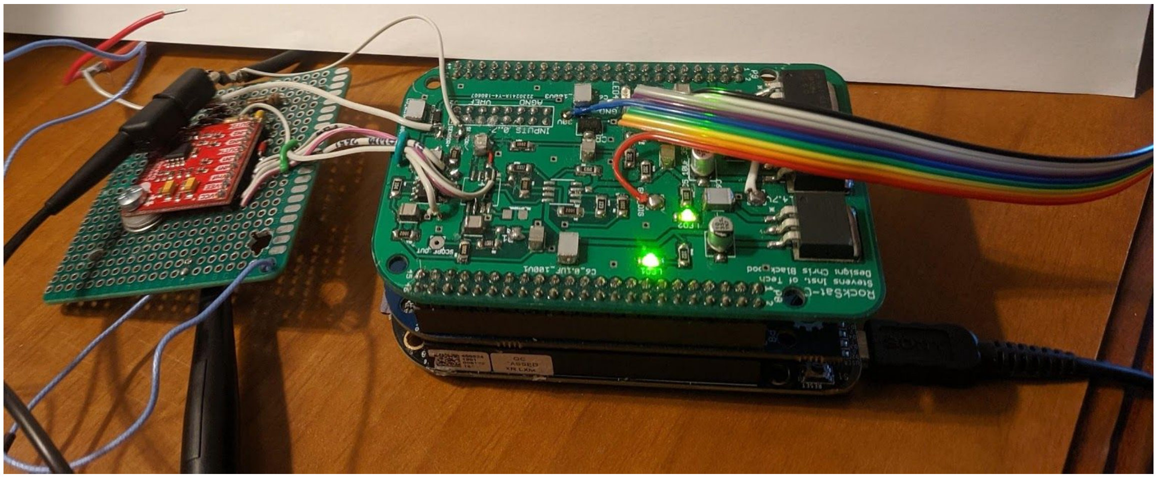
Once these key parameters were understood, the team procedure to designing the payload.

3.0 Payload Design

The hardware design for this experiment involved a stack of processing boards and a filtering board connected to both the power supply and the sensor. At the base of the stack was a BeagleBone Black. Attached on top was a PRUDAQ, an ADC board designed for the BeagleBone. A final custom-made board for filtering and voltage regulation (to fit the sensor's higher and the BeagleBone's lower voltage requirements) rested on top, which connected to the power input and a high-speed pressure sensor from PCB Piezotronics.



Functional block diagram describing payload design



Left: Signal Amplifier and Overvoltage Protection Circuit
Right: BeagleBone Black, PRUDAQ, filtering board

Modified port window with sensor installed

As the pressure sensor required access to the outside of the rocket's skin, the team used a multipurpose port provided by NASA, and machined a cover for the port to hold the sensor in place. After a tight pressfit, using 3D printed guides to ensure flushness, the sensor was secured in the port window using RTV silicone.

Software for the experiment was written in a single file, treated by the operating system on the BeagleBone Black as a startup process. This file included a modified quick-setup script for "BeagleLogic," a software library used by the PRUDAQ to interface with the BeagleBone and established parameters such as recording frequency (2MHz) and datapoint size (16-bit). After this setup, the process issued a "wait" command of approximately 150 seconds, and then a data-dumping command native to the operating system, which recorded data as quickly as the PRUDAQ would send it to the BeagleBone (2 MHz, in 16bit increments). The pause was included to reduce the amount of useless data recorded in case the total time to begin recording (BeagleBone power-on, BeagleBone startup, BeagleLogic startup) was too early and recording began during launch. [See: Potential Follow-on Work]

The team expected to recover raw binary data in a file of approximately 2.4 gigabytes. This number was derived based on the size and frequency of data points collected, and the required time of recording. The PRUDAQ reads in 16-bit (2-byte) samples at 2MHz per channel, from two channels in parallel. Over 300 seconds, this results in the stated 2.4GB. This raw data could then be trimmed and modified in post as needed.

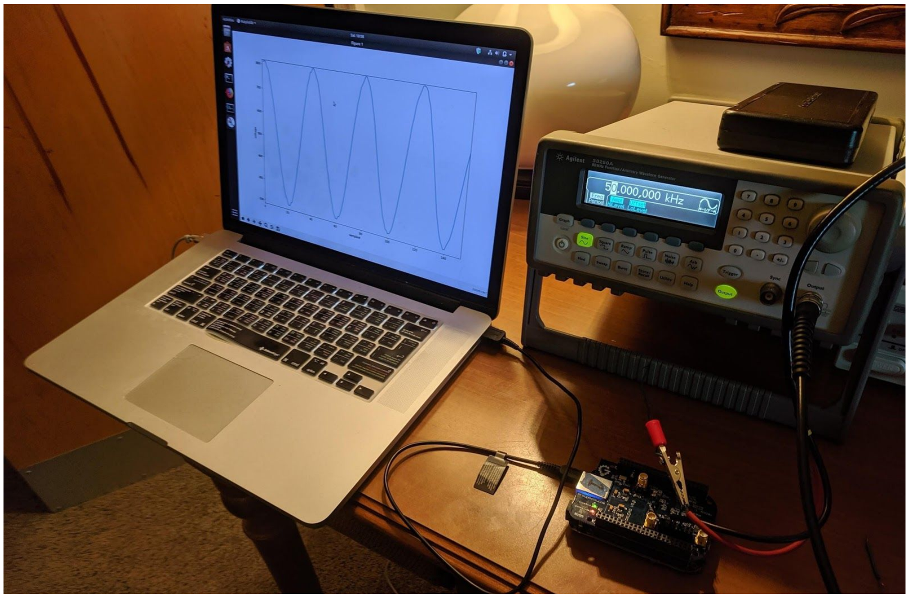
4.0 Student Involvement

Name/Major	Role	Responsibilities
Chris Cowan (Mechanical Eng.)	Mechanical Lead	Design and construction of modified port window, port pocket wiring/setup, and mounting of project to payload
Chris Blackwood (Electrical Eng.)	Electrical Lead	Circuit design and construction of board to provide necessary power to the microcontroller and associated PRUDAQ, design and implement analog signal conditioning including amplification and filtering, signal overvoltage-protection circuit
Sam Yakovlev (Computer Eng.)	Software/Data Lead	Write code to program the microcontroller to perform hardware initialization, data collection, and file-writing; provide testing resources to the team to visualize and analyze the collected data.

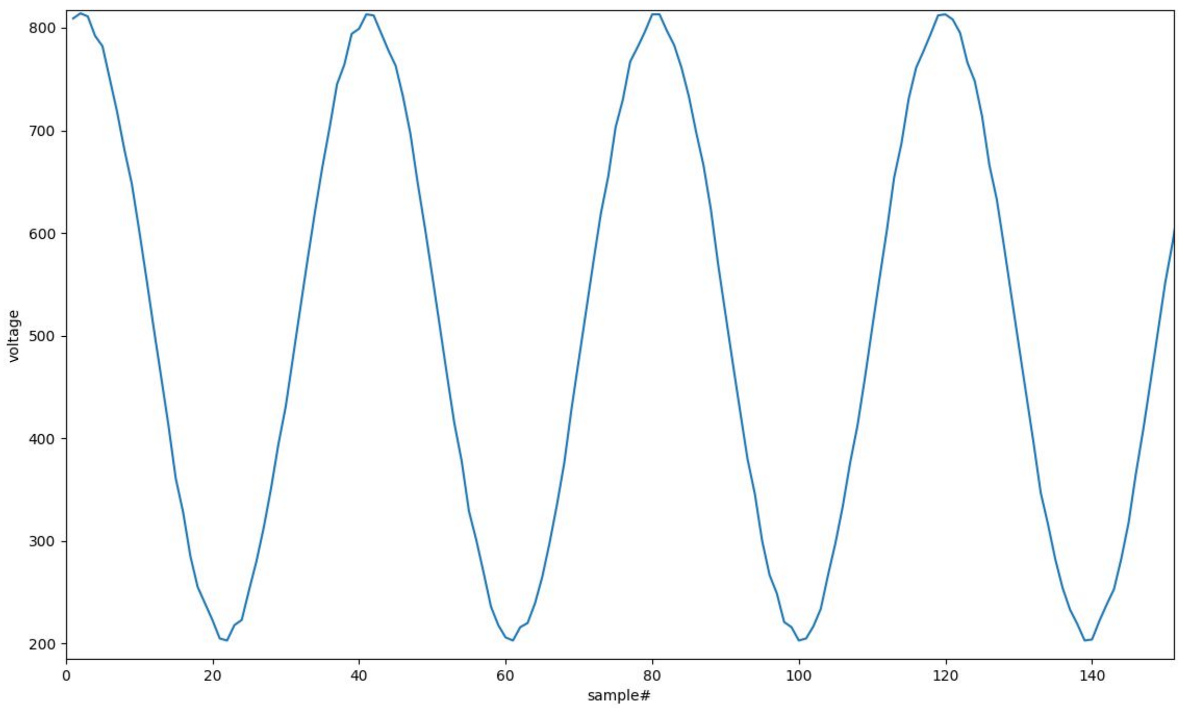
Due to the small size of the group, each member of the team was utilized as a lead for their skillset, creating an intertwined group with defined major roles, but subtasks involving all members.

5.0 Testing Results

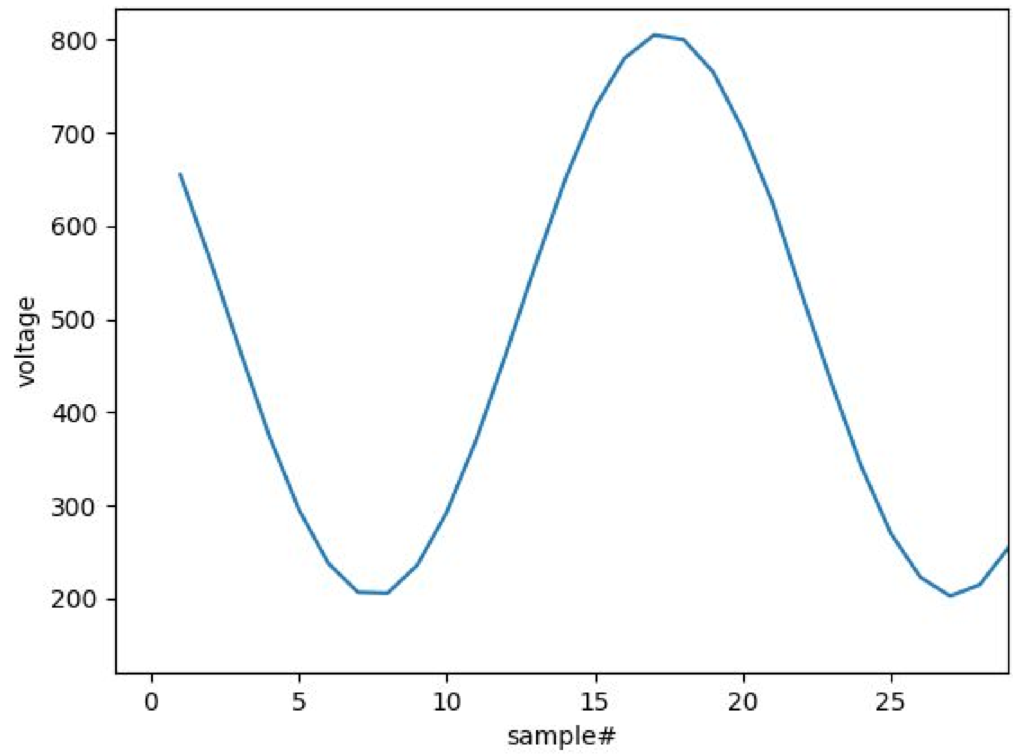
The Nyquist theorem states that to minimize artifacts in recording, observers must record with at least double the maximum experienced frequency. The sensor used had a high-frequency response of 1MHz, and the PRUDAQ was thus configured to record at 2MHz. To verify that this was a sufficient sampling frequency, the team connected the PRUDAQ to a signal generator, and recorded one second of data at 50KHz, 100KHz, and 200KHz. The test setup and results are shown below:



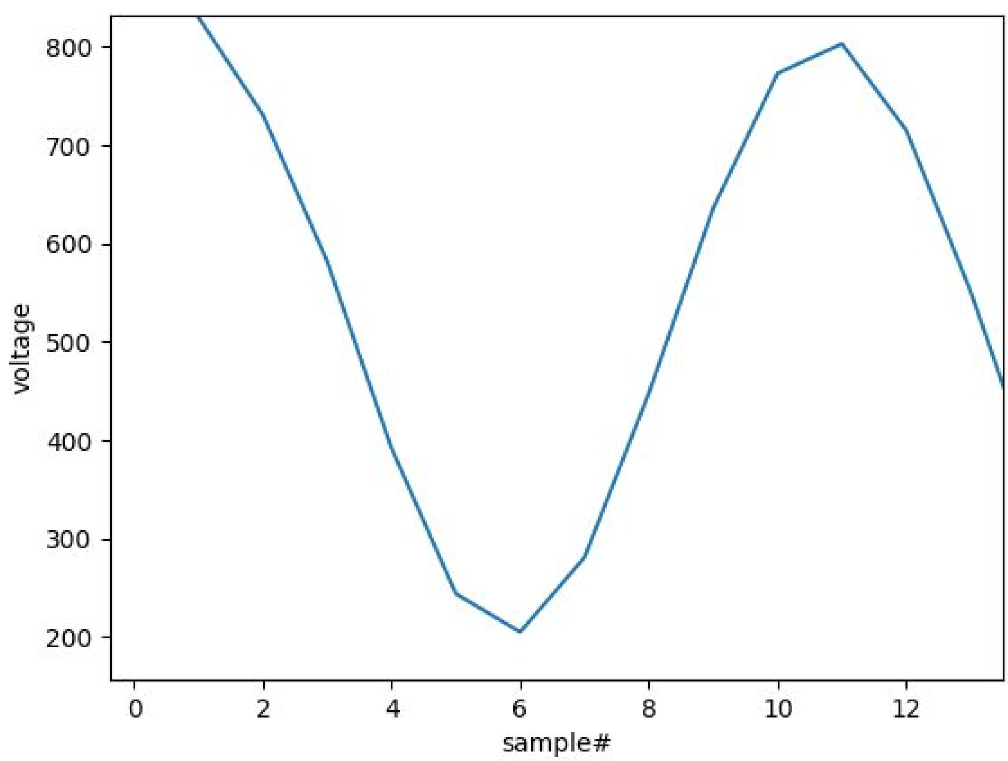
Power and control provided to BeagleBone/PRUDAQ stack by laptop, as well as post-processing.



Results of test with 50Khz input



Results of test with 100KHz input

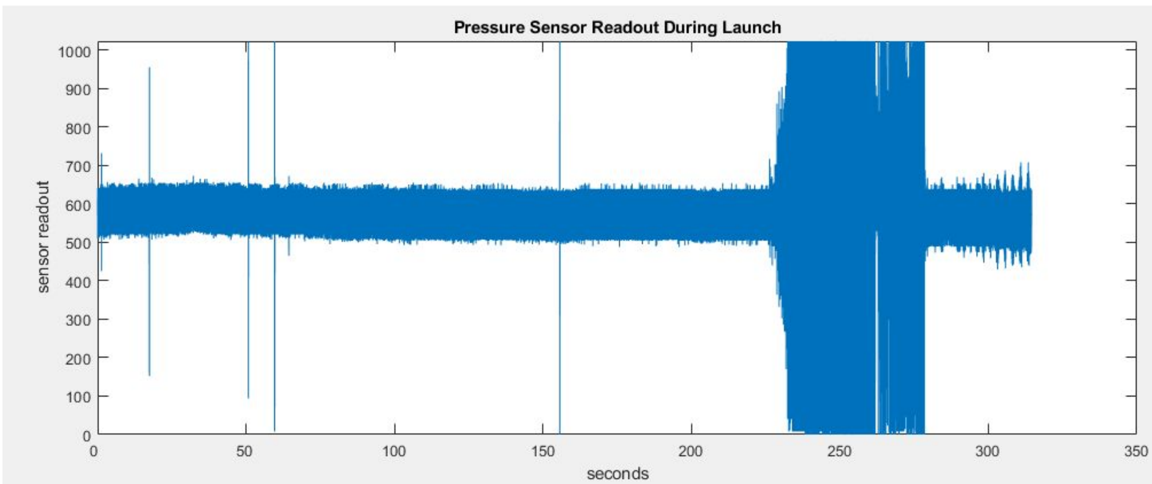


Results of test with 200KHz input. Note the deteriorating quality of recording

The precision of data acquired from these tests was deemed sufficient for runtime at launch, and so the recording frequency was kept at 2MHz.

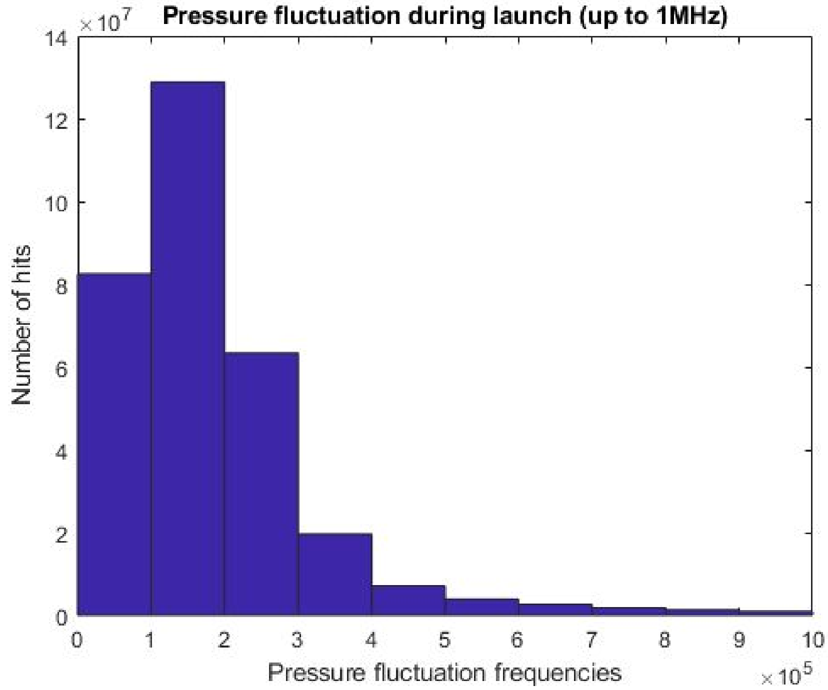
6.0 Mission Results

After recovery, the final raw datafile amounted to 2.52GB in size. This met the expected filesize, so the data was split in half (seeking only information from the channel the sensor was connected to), converted from raw binary to hexadecimal, and plotted. The results are below:



Given the average reading of the 10-bit ADC (~550 out of an available 1024 values) and the sensor's measurements of 140mV/psi, the following equation determines the average pressure:

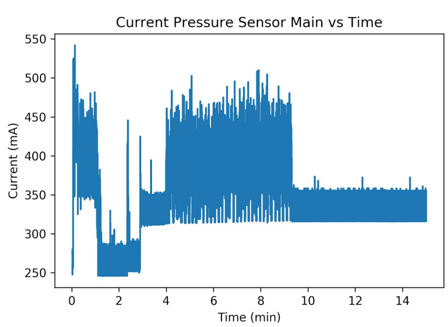
As the readout did not appear to change too dramatically, investigation into the frequency domain revealed further information. By taking a Fast Fourier Transform of the data, placing all frequencies found in a histogram, and removing anything over 1MHz (as this is the high frequency response of the sensor), the range of frequencies present in pressure fluctuation appears:

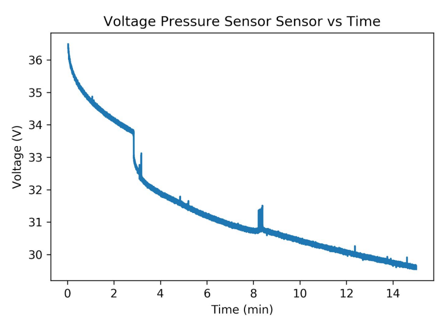


Number of hits refers to the amount of a given frequency found within the FFT

The average frequency of fluctuation thus appears to be 200KHz.

To verify that this data was in fact collected during launch, the team investigated current draw and voltage drops from the BeagleBone Black, as reported by the power regulation board. From these readouts:





A clear rise in current and steady decrease in voltage beginning from approximately three minutes from startup (which occurs at T-3 minutes), to eight minutes from startup indicates that the BeagleBone Black did in fact record for five minutes, beginning approximately around the time of launch.

With confidence that the recorded information was gathered during launch, the raw and processed data was handed off to the P.I., Prof. Nick Parziale, alongside launch data such as velocity and altitude vs. time, for future scientific investigation.

7.0 Conclusions

The average pressure reading in the transition between laminar and turbulent flow boundary layers is within the range of 6-7psi. Pressure in this region also appears to be isobaric, which is conducive with results obtained by Old Dominion University performing a similar experiment in 2017, albeit with much fewer data samples.

If this data is taken as correct, and the behavior of the transition region is isobaric, then improvements to rocket performance could be as simple as polishing the skin, allowing for smoother airflow and reducing turbulence and drag overall.

Future experiments are also an option now, with a definitively working recording platform that has been tested in the field and confirmed able to collect high-frequency data at commodity prices.

8.0 Potential Follow-on Work

While there are not many aspects of the hardware design that can be expanded upon without raising the system cost, there are ways to further the knowledge gained from it. The experiment can be repeated with several sensors spaced further apart, in order to acquire a more comprehensive breakdown of the entire transition region as opposed to a single point measurement. One of the additional sensors could be an atmospheric/barometric pressure sensor or similar nature sensor to measure the pressure of the surrounding atmosphere in coordination with the high pressure sensor data. This enables data analysis directly between the location of the rocket in its trajectory, including respective properties of the surrounding atmosphere, and the high pressure data recorded. Currently, the radar data is coordinated to the pressure readings recorded, which establishes the necessary link, but it is not a direct "side-by-side" real time data comparison. Furthermore, new filters can be designed to fit the existing sensor, to avoid recording too-high frequencies. The recording software can also be modified to begin recording sooner to achieve a proper baseline pressure reading from the launchpad, as this information was not recorded in this year's launch.

Whether this mission is worth continuing into the future depends on the conclusions of the P.I. (Prof. Nick Parziale). If more data is required, the mission can be run again, with the modifications listed above.

9.0 Benefits to the Scientific Community

The data collected from this project could be some of the first results capturing this phenomenon and examining the pressure readings in the transition region, outside of wind tunnel testing. Applying the results may lead to more accurate simulations and estimations of such parameters as skin friction thermodynamics and induced spin. The application may be suitable for validation of advanced transition-estimation methods, which can lead to further experiments to reinforce the validation and serve as strong support for the estimated effects produced by a simulation. Outside of the specific results of this mission, the data collection system created is a powerful, open source data acquisition system, which is absent from the market currently. The system can be modified to capture experimental data in a variety of situations where sensor input needs to be processed prior to proceeding to the microcontroller where it is written and stored. This system then enables repeatable experiments in cases such as this project along with a full system to aid in the research of new topics.

10.0 Lessons Learned

As this is the latest in a series of attempts, the list of new lessons learned would be brief, so rather than discuss this year, we will summarize everything so far:

1. ***Always* have redundancies.** Accidents resulting in damaged or destroyed hardware can set any project back by days or weeks, and loss of code can have catastrophic effects. Any software used should be stored in a repository such as GitHub, as well as some local storage. Any hardware, especially if the project emphasizes low cost, should have backups.

2. **Start early and have regular meetings.** In an environment where many team members have involvements such as school or other organizations, it is important to not let an engineering project fall by the wayside. It is easier to keep momentum than to build it up after ignoring it for any length of time. The team this year suffered through this, but after getting back up to speed, regular and consistent progress was made.
    a. **These meetings do not need to be productive, but they must be informative.** As long as there is a reminder of what work exists, and some plan developed, that is enough to keep one cognizant of the project.

3. **Do not hold off easy tasks for later.** If there is a simple solution to a trivial problem, it is very easy to fall into the mindset of "I can just do it later." This is an extremely dangerous trap, because while complex assignments with multiple facets to them tend to stay in your mind, simpler tasks such as "comment out this line" or "swap this one wire" will be overshadowed by things you perceive as more important, and thus be forgotten, often with catastrophic results.

4. **Your payload is going to space. Treat it like it.** This may sound like common sense, but it is easy to forget how delicate electrical components are, or how certain mechanical elements must be designed or assembled in order to survive. Especially for new team members, care must be taken throughout the entire process. Not only does being careful with the payload keep it alive, it also establishes good practice for future projects.

Reflow Soldering in Microgravity

1.0 Mission Statement

Until now, the only soldering that had been performed in space was hand soldering, which is limited by the skill of the operator and is physically demanding. In electronics manufacturing today, reflow ovens are typically used to solder several surface mount components to a printed circuit board's electrical contacts at once.

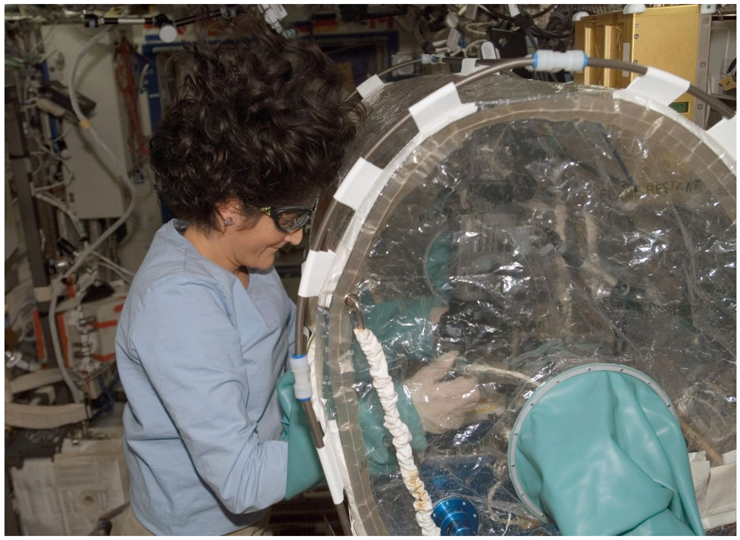


Figure 2.1: Hand Soldering on the ISS[See A1]

The goal of this project was to create a reflow oven capable of soldering surface mount electronic components to a printed circuit board in a near microgravity environment. This project can then inform the development of a reflow soldering oven to be used on long duration manned space missions.

2.0 Mission Requirements and Description (1-2 page(s))

At a minimum, the payload was designed to measure the temperature within the oven and follow the required temperature profile, Figure 2.2. Ideally, the oven would melt the solder and the solder would solidify prior to the rocket beginning to tumble. After recovery the components would be found mounted appropriately and function without further adjustment.

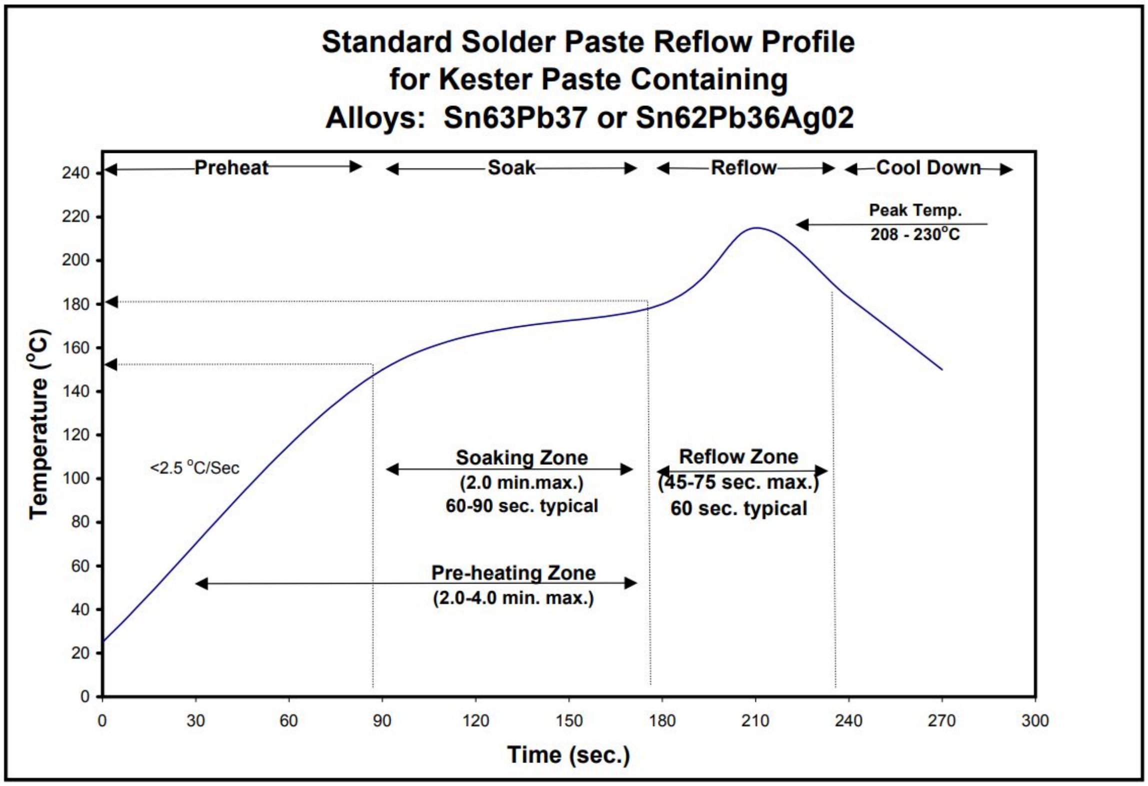


Figure 2.2: Reflow Profile of Selected Solder

During the process, Wallops Flight Facility raised concerns about the temperature that the canister would become. To address this, “hot” stickers were placed on the outside of the canister to alert anyone handling it would be aware if it was too hot to hold safely.

Figure 2.3: “Hot” Sticker

3.0 Payload Design

The oven was the largest component in the canister. As a result, the rest of the canister needed to be designed around the oven. Knowing that the canister would accommodate 3 experiments, all available wall space was used. The three electronics boards, a large battery, the cooling fan, and the four accelerometers were mounted on the sides of the heater. These four sides can be seen in Figures 2.4-2.5. Also visible in Figure 2.5 are the three battery mounts for the Pressure Sensor higher voltage power system.

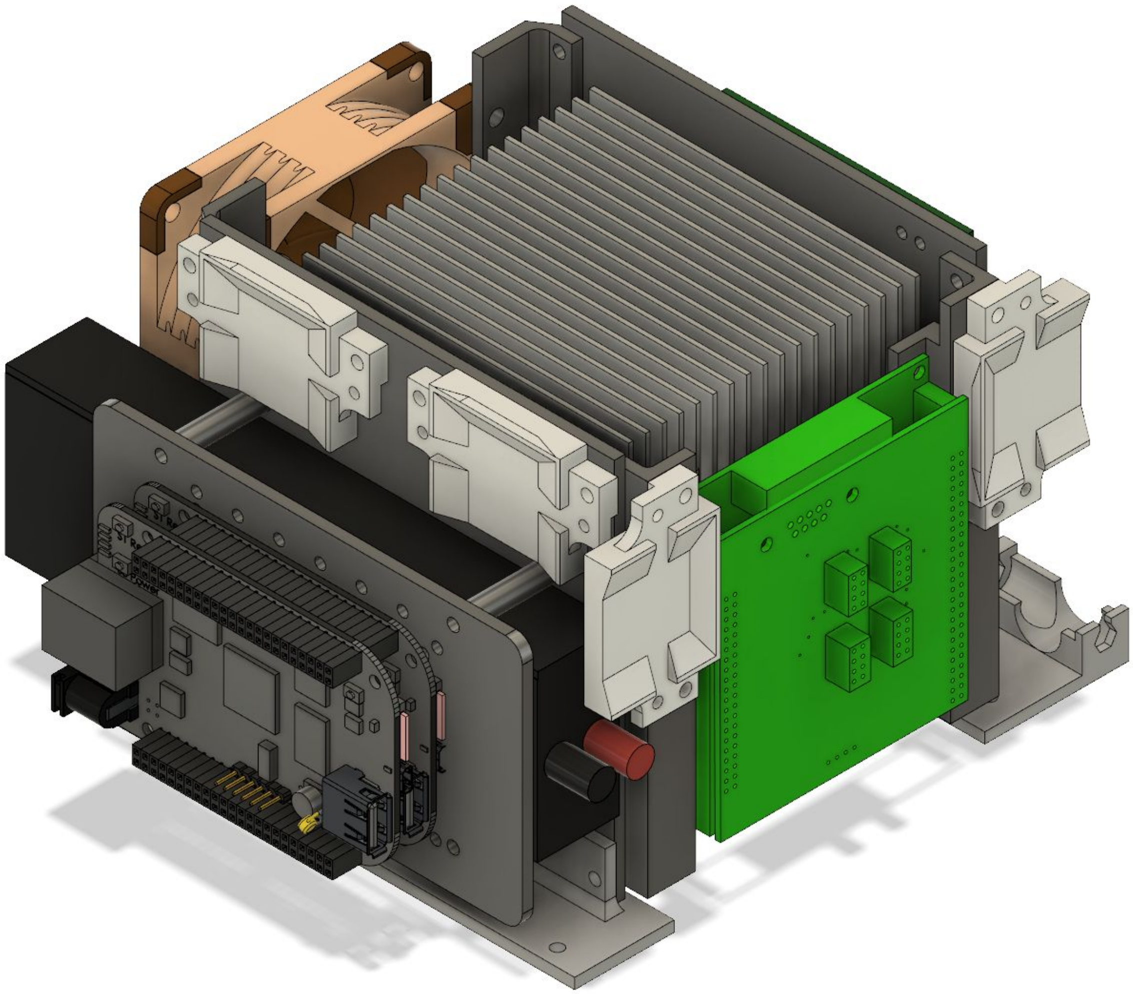


Figure 2.4: Isometric view of battery, Pressure Sensor and Accel. boards, Accelerometers

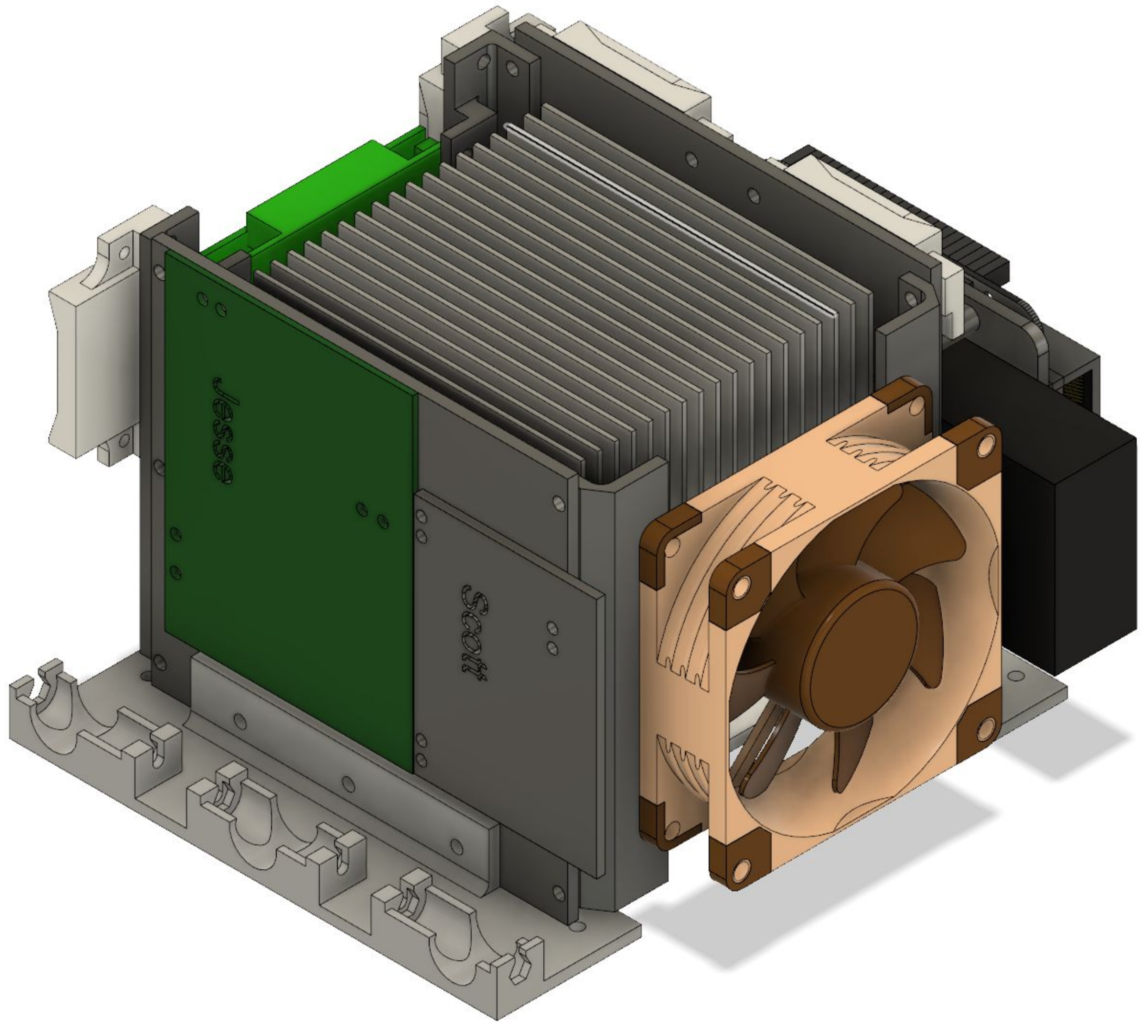


Figure 2.5: Isometric view of power board, heater board and fan

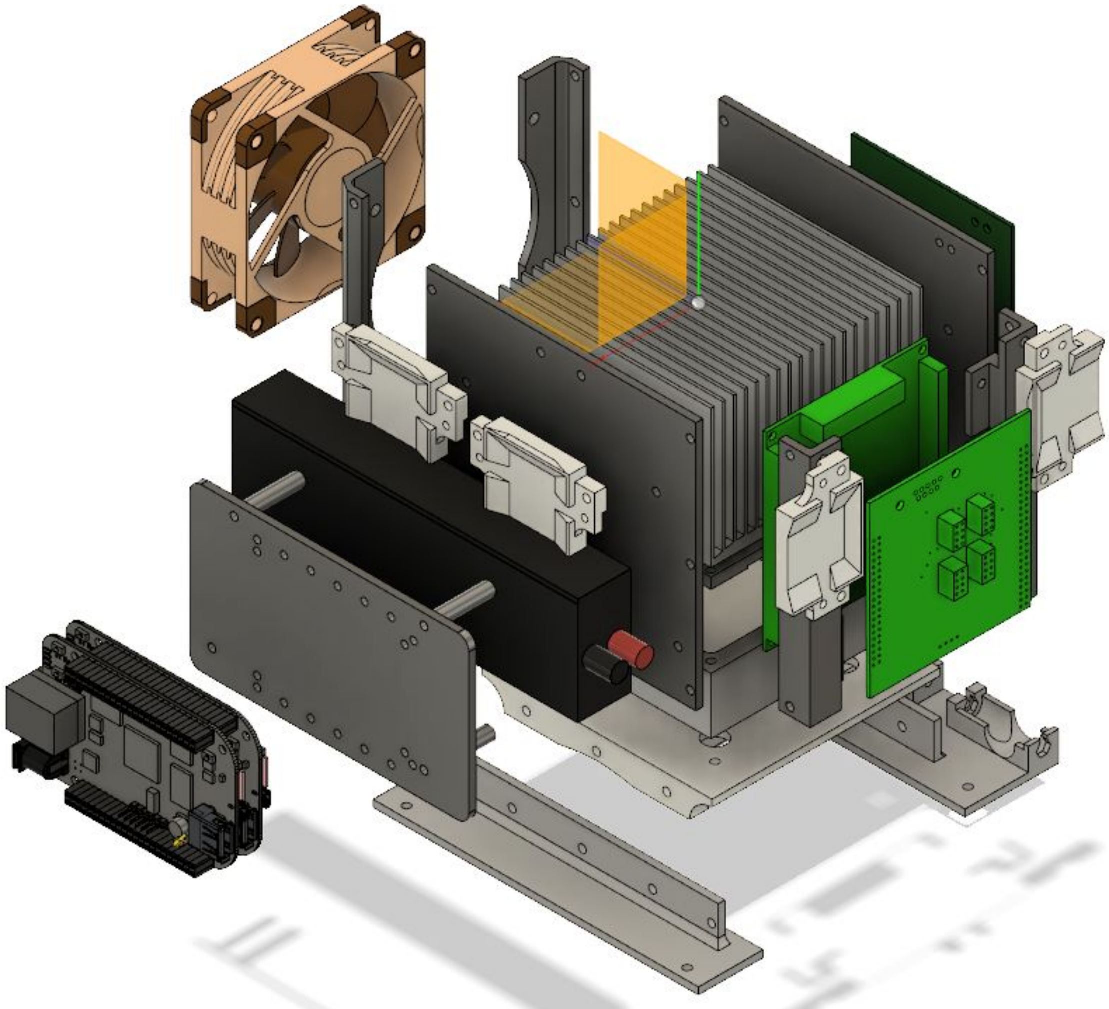


Figure 2.8: Exploded View of the Canister

The oven itself consisted of three main components: the oven chamber, oven internals, and the heat sink. The oven chamber itself consisted of a machined piece of aluminum with two sets of four holes for mounting to the canister and for mounting the heatsink. The screws which mounted the heat sink also secured the internals of the chamber.

The heat sink was purchased off-the-shelf as a computer processor heat sink, and had the bottom machined off. It was attached directly to the oven container, and was used to dissipate heat more effectively within the canister. A cooling fan accelerates the cooling process at the end of the heating profile. The overall assembly of the oven can be seen in Figure 2.7.

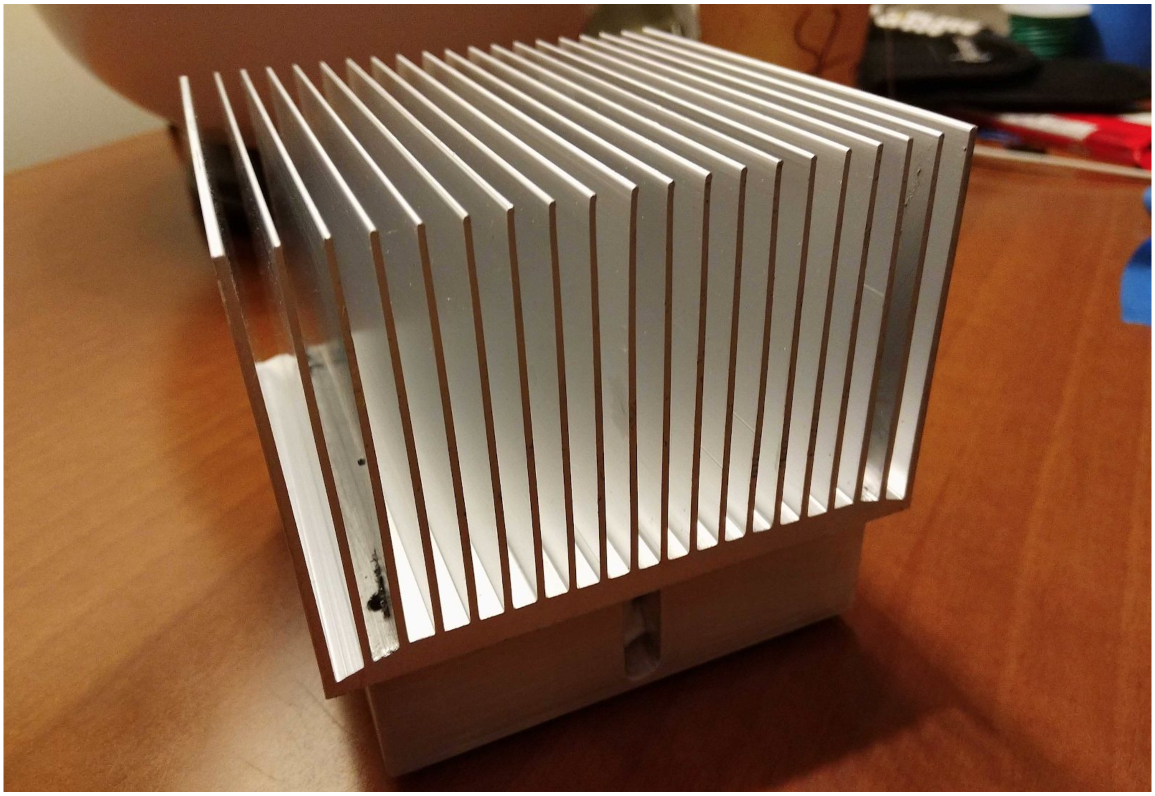


Figure 2.7 Oven Assembly

The internal components of the oven included thermal insulation with aluminum foil to reduce radiative heat transfer, spacers to allow for the insulation to fit, and a "clamp," which was used to secure the two heaters and can be seen in Figure 2.8. This clamp consists of two aluminum sheets designed to hold the test circuit board and its components in place. One sheet of aluminum was specifically cut to the shape of the clamp to keep the heaters secured. The test board with the specimens was attached on top of the clamp. The components had neoprene wedged between them and the heat sink to keep the components from becoming dismounted from the solder contacts during launch until the heater activated.

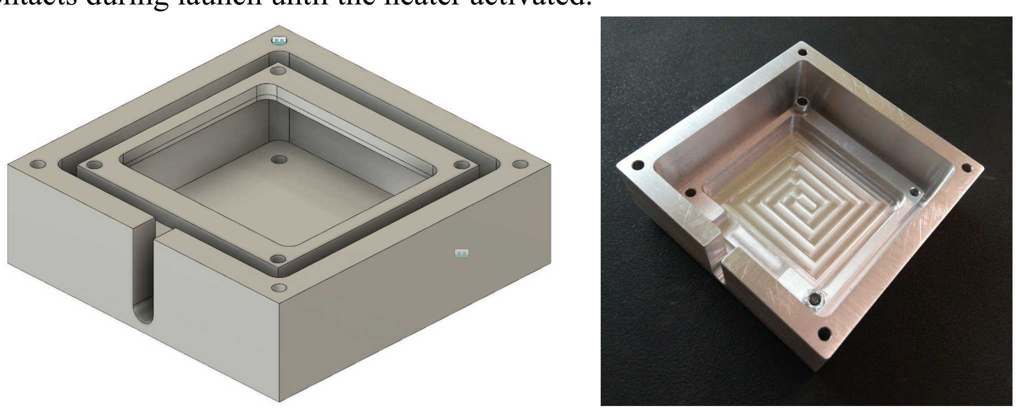


Figure 2.8: Heater Clamp shown within the Oven in CAD and actual

Figure 2.9 shows a high level system diagram for the mechanical components and the international with electrical subsystem.

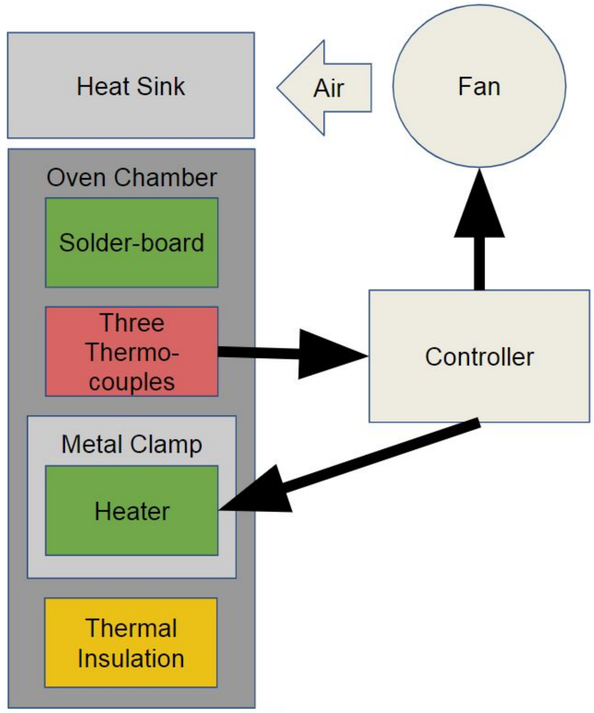


Figure 2.9: Mechanical System Block Diagram

The heater control system consisted of a printed circuit board, with two redundant integrated thermocouple control circuits. These connected to two thermocouples inside the heater. An Adafruit Feather M0 was used for control and debugging. The Feather communicated with the power control board and sent control signals for the fan and heater over the db9 cable. During Wallops integration the fan it was discovered that the fan was incorrectly wired and had burned out, so there was no fan in flight.

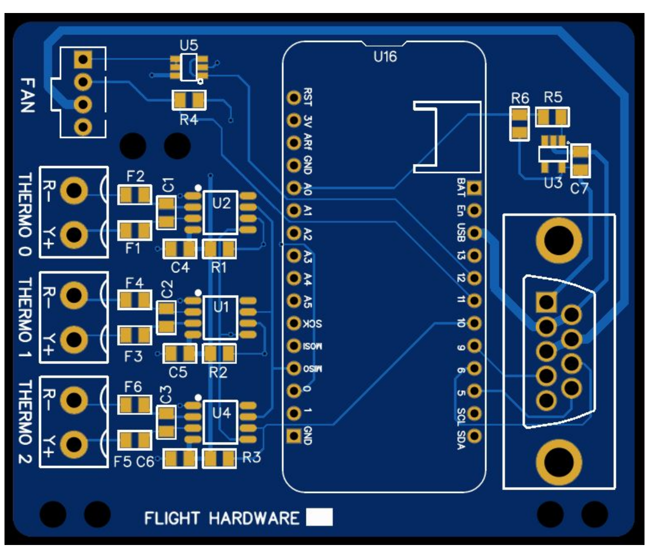


Figure 2.10: Electronics Board

The budget for the soldering project is in Table 2.1. As this project worked the closest with structures, the budget for that segment of the project, Table 2.2, and the Mass Budget, Table 2.3, are included in this section.

Table 2.1: Budget for Soldering

High Temp. Aluminum Tape (1.5 in x 15 ft)	1	$11.49	$11.49	Link	Amazon
Noctua NF-A8 FLX, 4-Pin Premium Quiet Fan (80mm, Brown)	1	$15.95	$15.95	Link	Amazon
6061 Flat Aluminium Bar (4" x 5" x 6")	1	$65.96	$65.96	Link	Midwest Steel & Aluminium
Insulation (with aluminum face)	1	$9.88	$9.88	Link	McMaster-Carr
High-Temperature Silicone Foam Strip with Adhesive Back	1	$14.58	$14.58	Link	McMaster-Carr
Leaded Rosin Activated (RA) Wire Solder Sn60Pb40 (60/40) 14 AWG, 16 SWG Spool, 1 lb (454 g)	1	$36.84	$36.84	Link	Digikey
IC MCU 32BIT 64KB FLASH 32LQFP	18	$1.0 5	$18.90	Link	Digikey
Thermocouple Type-K Glass Braid Insulated Stainless Steel Tip	1	$9.95	$9.95	Link	Adafruit
Thermocouple Amplifier MAX31855 breakout board (MAX6675 upgrade)	1	$15.95	$15.95	Link	Adafruit
TMP36 - Analog Temperature sensor - TMP36	2	$1.50	$3.0 0	Link	Adafruit
Adafruit Feather M0 Adalogger	2	$19.95	$39.90	Link	Adafruit
Ceramic Heating Elements (Model: Plate, L50*W50*T2.0 mm, Resistance: 1.5 Ω	1	$24.70	$24.70	Link	eBay
HOT HAND WARNING 50 C [122 F] PACK OF 20	1	$50.0 0	$50.0 0	Link	Scientific Instrument Services
ARCTIC COOLING ACALP00011A Silent Intel CPU Cooler	1	$21.78	$21.78	Link	Newegg
Thin AL Sheet	1	$7.47	$7.47	Link	Home Depot
Ceramic Heating Elements (Model: Plate, L50*W50*T2.0 mm, Resistance: 1.5 Ω	2	$24.70	$49.40	Link	eBay
			$395.75		

Table 2.2: Budget for Structures

4-40 1/2"	1	$8.89	$8.89	Link	McMaster-Carr
4-40 5/8"	1	$8.66	$8.66	Link	McMaster-Carr

4-40 1"	1	$7.80	$7.80	Link	McMaster-Carr
4-40 1 3/4"	1	$7.75	$7.75	Link	McMaster-Carr
4-40 1 1/2"	1	$12.24	$12.24	Link	McMaster-Carr
Spacers (JIC) 1/4"	10	$0.23	$2.30	Link	McMaster-Carr
Spacer (JIC) 5/32"	10	$0.27	$2.70	Link	McMaster-Carr
Lock Nut	1	$3.90	$3.90	Link	McMaster-Carr
Washers	1	$3.23	$3.23	Link	McMaster-Carr
Acrylic Sheet	1	$24.61	$24.61	Link	McMaster-Carr
Unthreaded Spacer	2	$2.70	$5.40	Link	McMaster-Carr
			$205.44		

Table 2.3: Mass Budget

Subsystem	Weight (lb)
Canister	3.35
Mid-plate	0.75
Oven and fan	2.25
Electronics Boards	1.5
Accelerometers Packages	0.2
Batteries	0.6
Mechanical Scaffold	1.55
Ballast	0.0 0
TOTAL	10.20
Over:	+0.2

4.0 Student Involvement

Table 2.4: Team Breakdown

Name/Major	Role	Responsibilities
Aidan Aquino/ Chemical Engineering	Analytical Calculations	Validated heater selection with hand calculations.

Kevin Gmelin/ Mechanical Engineering	Hardware and Test Engineer	CNC machined heat sink and tested the solder flow under high spin conditions.
Joshua Gross/ Electrical Engineering	Project Manager	Managed the project and kept the project on track.
Jack Hymowitz/ Computer Engineering	Software Developer	Wrote calculators for analysis, integration, testing, and verification
Stephen Kontrimas/ Mechanical Engineering	Mechanical Lead	Performed analytical calculations, designed oven and payload.
Reinier Lazaro/ Mechanical Engineering	Canister Design Lead	Designed canister payload and determined what parts to order.
Scott Maslin/ Electrical Engineering	Project, Electrical and Software Lead	Designed electronics board and board under test and wrote control system software.
Russell Whitsitt/ Mechanical Engineering	Hardware Analyst	Performed FEA to validate oven design and confirmed parts selection.

5.0 Testing Results

Prior to having the oven, a preliminary test was performed to observe the heat given off by the heaters. The heater was powered by 24 watts at 8V and 3A, or one fourth the power of flight. As the oven was unavailable for these tests, aluminum foil was used to create a basic approximation of the oven, and the whole canister was placed in a cardboard box.

Figure 2.11: "Canister" Heat Dissipation Experiment Setup

The heater was run for fifteen minutes. During no part of this experiment did the cardboard box feel uncomfortable to touch. The heating and cooling curves inside the box, but outside the aluminum foil can be seen in Figure 2.11 and 2.12.

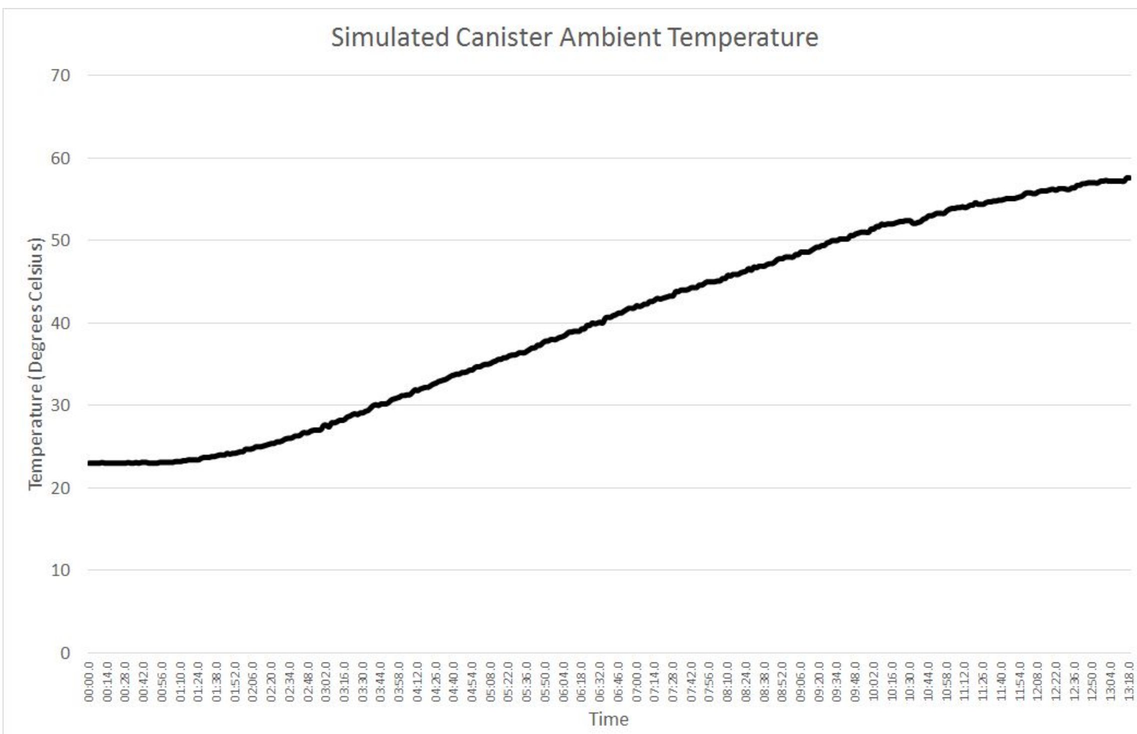


Figure 2.12: "Canister" Heat Dissipation Experiment Heating Curve

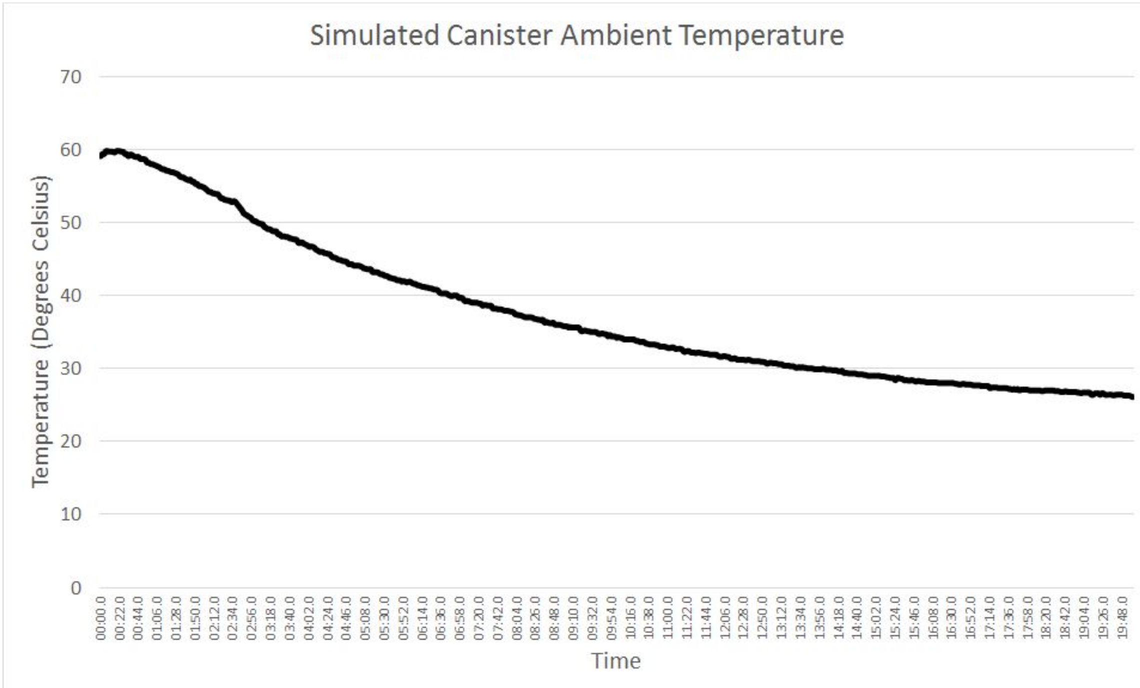


Figure 2.13:"Canister" Heat Dissipation Experiment Cooling Curve

Once the oven was in hand several other tests were conducted to determine if there were any safety concerns. The most extreme was running the oven on full power for three minutes. In this test the oven never became painful to hold, but did creep up to uncomfortable. Temperatures were also measured with a thermal camera to ensure they were within an acceptable range. This helped assuage any more safety issues as the rocket would likely sit for at least an hour prior to any internals being handled by a person.

6.0 Mission Results

During launch the oven did not heat up. It is believed it is a software error, but due to errors with data management the exact behavior of the Feather is unclear and we were unable to determine exactly what happened during the flight. Instead of the expected output file, it appears to have written several very short corrupted files.

After launch some tests were run to see how the oven would have performed if the heater had turned on during flight. In Figure 2.14 the temperature data can be seen below.

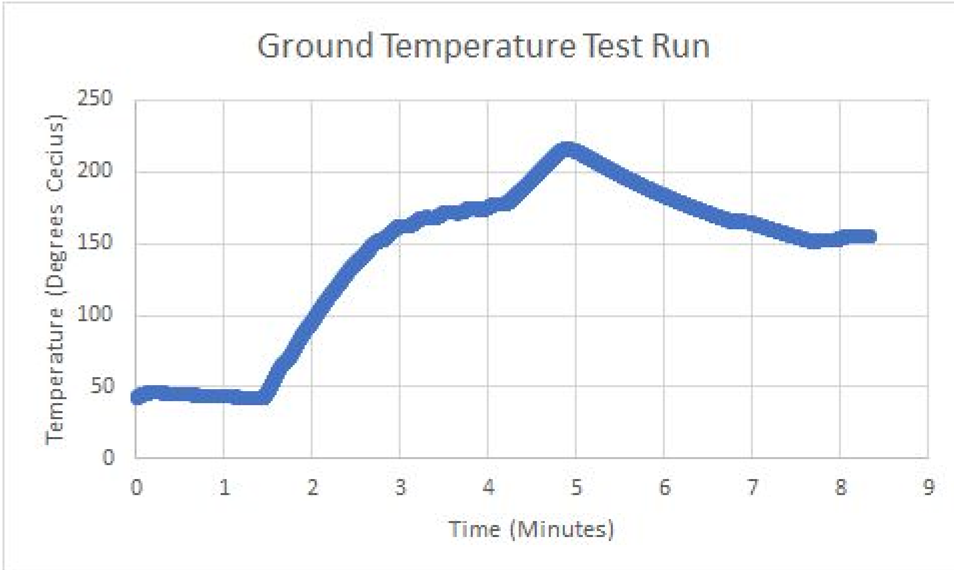


Figure 2.14: Post Flight Temperature data

To understand the accuracy of the response the data must be compared to that of the desired profile. Figure 2.2. A plot comparing the temperature can be found in figure 2.15.

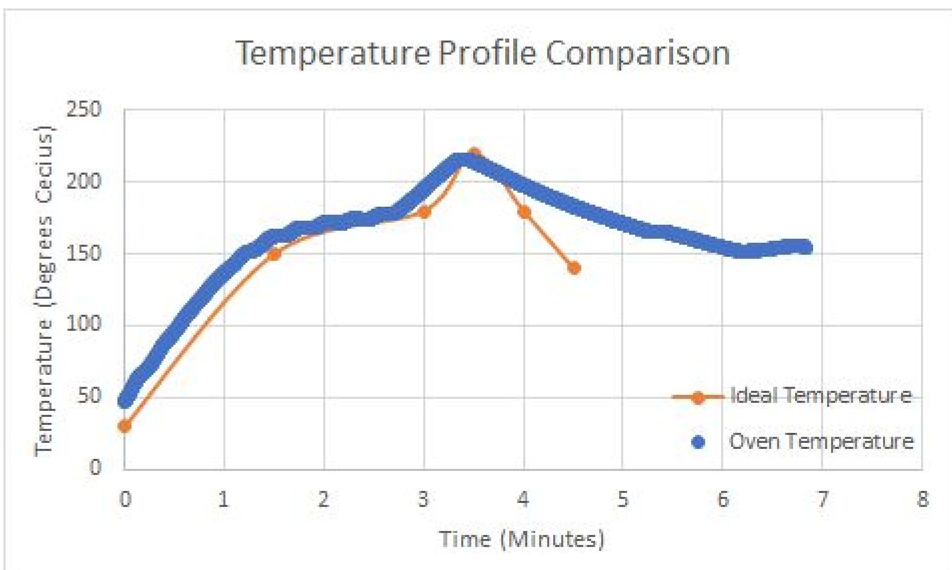


Figure 2.15: Temperature Comparison

While not a one-to-one match the temperature profile obtained was very close to the desired behavior, with the notable exception of the cooling section which was too slow. This cooling would augmented by running the fan. This confirms the system design both electrically and mechanically, at least on Earth.

However, on the software side they system still needs some tweaking. The controller behaved unexpectedly as the test continued, Figure 2.16. The heaters should turn off permanently after the peak temperature is reached and certainly after five minutes.

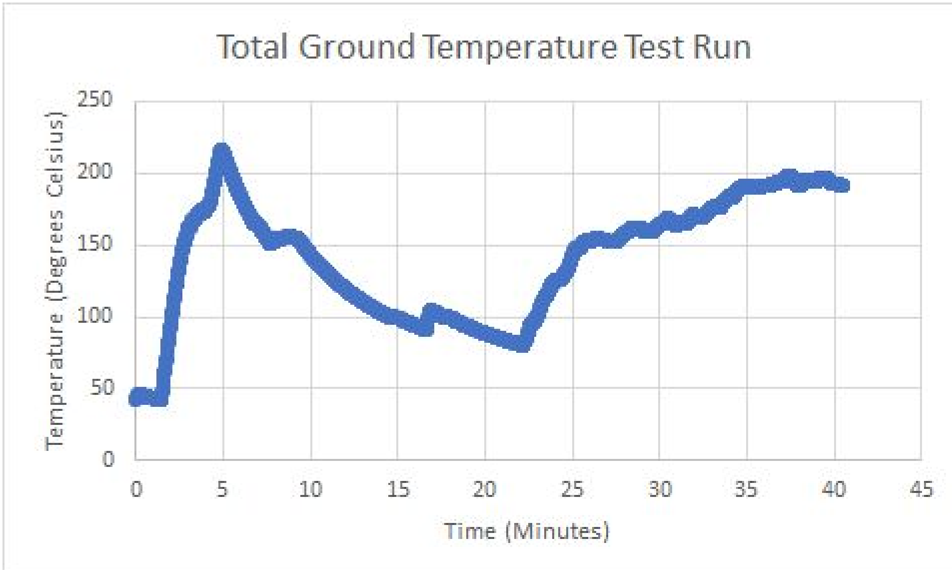


Figure 2.16: Total Test Data

An event like this during launch could cause serious problems. However, due to safety systems built in to the power board that were not in place during this test, this behavior would not have happened during flight. Further analysis of the software was planned but the current software release was not shared with the members doing post-launch testing so no further analysis could be performed short of a rewrite.

The solder for these components did melt, but the connections to the components were less than desired, Figure 2.17. During removal one component was ripped from its mount because of the strong adhesive to the neoprene.

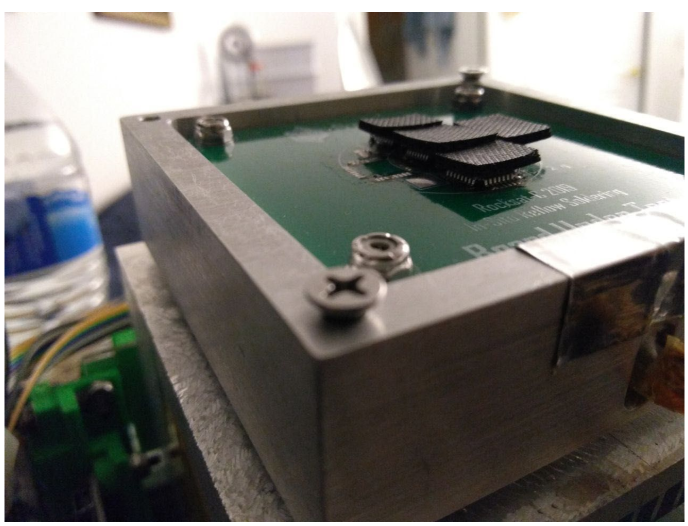


Figure 2.17: Physical result of the testing

7.0 Conclusions

While this project was not successful on launch day, it has since been demonstrated that each individual component works on earth, and there is a strong potential for this to be a successful project design if it were attempted again.

8.0 Potential Follow-up Work

RockSat was the most accessible space flight program for students interested in this project. But reflow soldering on a rocket launch is not an ideal situation due to the short timespan and challenges that imposes. The easiest way to continue progress would be to perform reflow testing on the ISS, similar to the hand soldering test.

In the more immediate future it would be interesting to test different solder types. However iterations of this style would be slow as the size of the half-canister do not allow for more than one oven so each successive launch would test one type of solder due to different reflow curves. Again this highlights the issues with testing on a rocket rather than a space station which would allow for much quicker testing: a technician could do many tests with different solder in a few hours time on the ISS.

The next course of action would be to get this system work consistently on earth. This project did not succeed in what it set out to do, but it is now is in a state where progress could be made should time be committed to it. The main reasons for the unsuccessful run was a lack of a full system test using all componentes. Now that all the parts are there, the project should have relatively smooth sailing.

9.0 Benefits to the Scientific Community

This project is the first foray into the possibility of mass production of electronics in space flight. Right now manufacturing a board in space is not necessary nor practical, but as people start to explore further from Earth with renewed excitement, people will need to tackle unknown challenges and problems separated from all other resources. Reflow soldering can be used to manufacture new boards as part of a solution to address these challenges.

10.0 Lessons Learned

Start seeking custom hardware earlier than anticipated.

The largest problem encountered in the project was the lack of testing time with the oven. The oven was not in hand until May. This was due to the machine shop being down to one machinist. As a result one person had to do all machining for senior design and the oven took a back seat. This set the project back substantially.

Full system tests were necessary for a successful project.

The issues preventing the project from working would have been caught prior to launch. This was due to many issues that all lead to less time committed to the project than was required.

Find the critical path.

The PID worked which is miraculous based on the amount of testing done. Some of the worry could have been mitigated if the electronics had been ordered in parallel with the oven construction. The final board was not ordered until late May, after the oven was in hand and these two tasks had nothing required from each other.

11.0 Appendices

A1 Hand Soldering hyperlink:
https://www.nasa.gov/centers/marshall/news/background/facts/issi.html

Accelerometer Filtering

1.0 Mission Statement

This project aims to build a simplified, cheaper version an Inertial Measurement Unit (IMU), using readily available and custom made accelerometer units, using a Kalman filter, and sampling from high frequency accelerometer data.

The goal of this project was to create a system that can record accelerometer data occurring in the payload during launch to build a model of the rockets telemetry. The system will be made inexpensive out of custom commodity hardware and with a small footprint.

The goal of this experiment was to determine a minimal viable product for a simple IMU for the purposes of making an easily implementable system for identifying telemetry in future experiments.

2.0 Mission Requirements and Description

The objective of this project was to implement a simplified version of last years design, using the same set of custom made hardware that we had used in last years experiment. Using this, we would develop a system for calculating the telemetry of the rocket in flight using accelerometer data, using the high frequency accelerometer data.

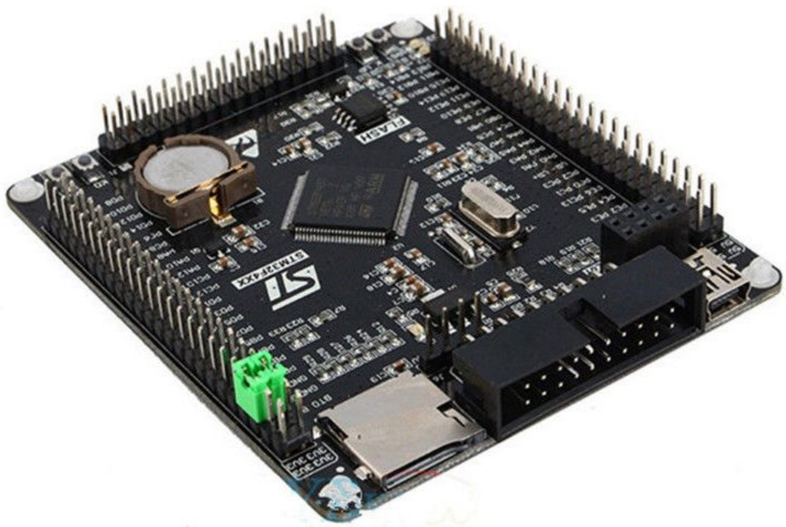
This accelerometer data was collected from two pairs of two axis accelerometer breakout boards with the ability to sample at 44kHz, built by the team in last years experiment. One accelerometer pair was used as a control measurement system, and another used a Neoprene base in order to determine the effects of vibration isolation in determining an ideal base for a telemetry unit. Using the two, we should be able to observe the relative difference in base material used on the effect of flight telemetry reconstruction.

The minimum success criteria for this project was to be able to create a telemetry model from the collected data. In more detailed terms, the hope is to be able to successfully sample from four units (two pairs of two accelerometer units) simultaneously, and be able to save that data to an SD card. For a stretch goal, the hope was to be able to detect apogee in situ.

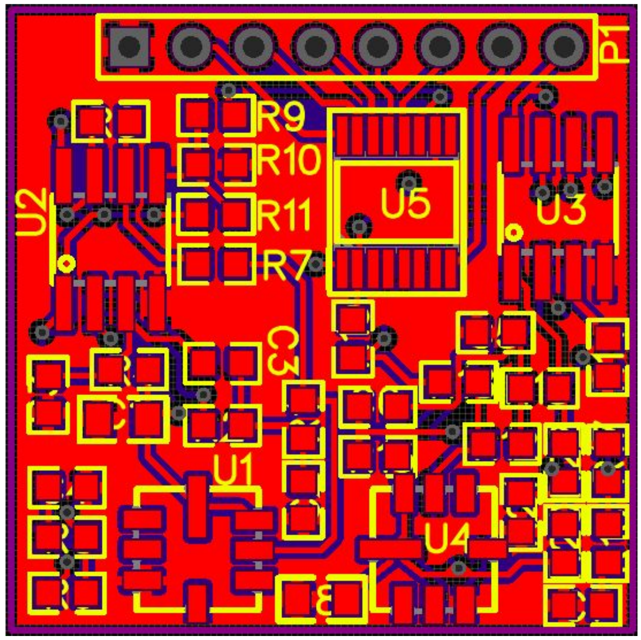
In order to do this all simultaneously, the project will leverage FreeRTOS, a simple barebones operating system which allows for multithreading with minimal additional overhead.

A Kalman filter works on a simple two step loop, a measurement, and from the measurement, a prediction of what the next movement will be, with a given confidence or variance. From that, the next measurement is taken, and modified using the prediction to be a gaussian average of the two, with the variance changing accordingly depending on whether the prediction was close to the next measurement. This can be used to calculate relative motion using the difference between the prediction and measurement with relative accuracy.

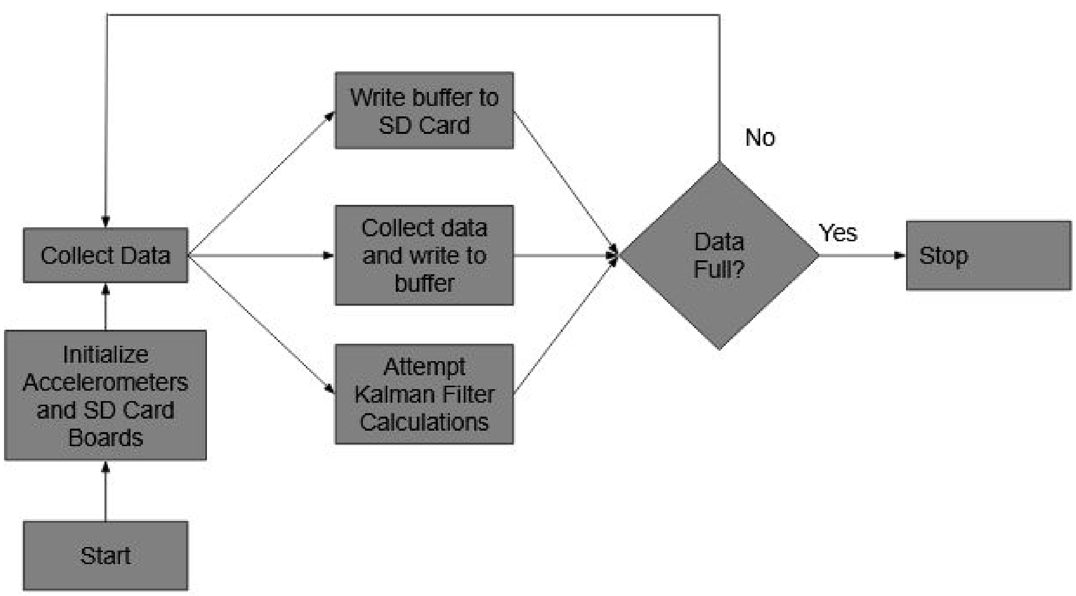
3.0 Payload Design



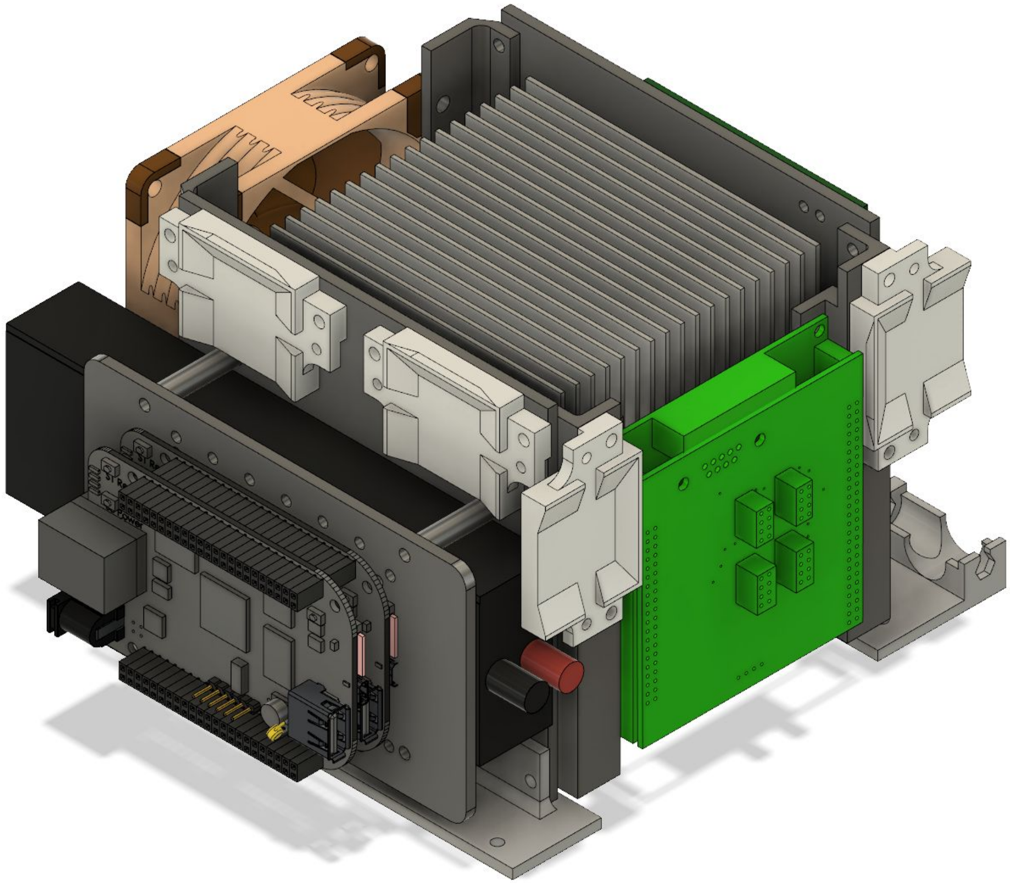
Above is the chosen microcontroller for the data acquisition system, the STM32F407VET6 "Black" Board. This board was used as opposed to the previous years board, the NXP LPC43S67, due to its more easily workable framework. The STM32 line of microcontrollers is well known, and has several well documented software frameworks to work. This is in contrast to the LPC43S67, which was a microcontroller aimed towards industry, and as such has no readily available open source and documented software frameworks, making integration difficult. In addition, the STM32 board is smaller than the LPC43S67 board, making fitting the board in an already crowded payload easier.



These are the custom made Accelerometer Breakout Boards, or accelerometer units. Each board is a single square inch, so the area one takes up is small. The actual analog accelerometers are labelled here at U1 and U4, where they are placed orthogonally from another, so as to get two axis acceleration. Beyond that there is a notch filter to reduce resonance, and a MAX11618EEE ADC for both channels in order to sample the accelerometers digitally. The accelerometer breakout boards interface with the microcontroller over an SPI bus.



Above is the software diagram for the data collection system. It initializes itself, preparing to write and collect data. It then splits into three threads, one which reads the data off of the accelerometer boards and writes it to a buffer, another writes from the buffer to an SD card, and the third attempts to perform the Kalman filter in real time. The first thread is on a high priority with a trigger on every completed conversion on the ADC. The second is performed to clear the buffer so that more data can be read. A third, low priority thread is the actual Kalman filter, which if it wasn't able to be done in situ, would be offloaded to be done post-launch.



The placement of these boards within the payload are displayed above. The four white mounts are the mountings for the Accelerometer Breakout Boards, placed orthogonally as such in order to get three dimensions out of the two dimensional ADC boards. The large green board is the STM32 board, with an added motherboard to route all cabling cleanly to the microcontroller headers.

The data expected out of this system should be a five column comma separated value file, which will contain nine columns: one for the reading number, and two values for each breakout board, corresponding to the ADC values. If Kalman Filtering was doable in flight, there would be three more additional columns, corresponding to the relative XYZ coordinates of the system to where it began recording.

4.0 Student Involvement

Name/Major	Role	Responsibilities
Zachary Shoop/ Computer Engineering	Project Lead	Designed and led software development for the data collection microcontroller
Jack Hymowitz/ Computer Engineering	Software/Test Engineer	Assisted with testing and development of data collection software

5.0 Testing Results

The system was tested first by ensuring proper functionality with a single accelerometer, first testing very basic SPI messaging, getting single channel readings from the accelerometer boards, then to both channels, and then expanding outwards into reading from all four accelerometer boards. With that, functionality on all three threads mentioned above were tested, as well as timing testing for figuring out the viability of in situ Kalman filtering.

It was found, due to limitations in the source code of FreeRTOS, that the fastest sampling frequency possible was 1 kHz. This was found to be unfortunate but amenable, as the increased resolution of samples would only add to the resolution of the final trajectory, and a 1 kHz sampling frequency was determined to be just enough for a precise trajectory mapping.

In addition, it was found that doing in situ Kalman filtering was not possible, as the additional Kalman thread would drop approximately 12% of samples with just a single accelerometer board, so it was removed from the program loop and instead performed in post launch analysis.

6.0 Mission Results

Unfortunately due to an error in the final implementation stage, directly before the payload was handed over, the microcontroller shorted out and broke before implementation, so no flight data was recorded to be used to try and reconstruct data. What occurred was an incorrect placement of the motherboard onto the STM32 board, which placed it off by one, and led to an internal short of the microcontroller as 5V was applied to a ground line, and thus on the power subsystem side cut off power, as it drew large amounts of current.

This does not mean that no information could be gathered from the concept of Kalman filtering with the custom boards. While we also failed to gather data with them last year, there was data gathered from an orbital sander which we could use to gather a preliminary proof of concept.

The data gathered from last year was made in order to test the relative vibration dampening of three kinds of materials and systems during a rocket launch: a Neoprene base (as mentioned above), a Cable Mount purchased from dB Engineering, and the MAPs system, a magnetic vibration dampening system leveraging polymagnets, and a fourth system was implemented for control. With these, we can map a two dimensional mapping of motion. Realistically this is a very poor way to get trajectory data, but some more informed design decisions can be made in the future with this preliminary data in hand. We should observe an increase in accuracy

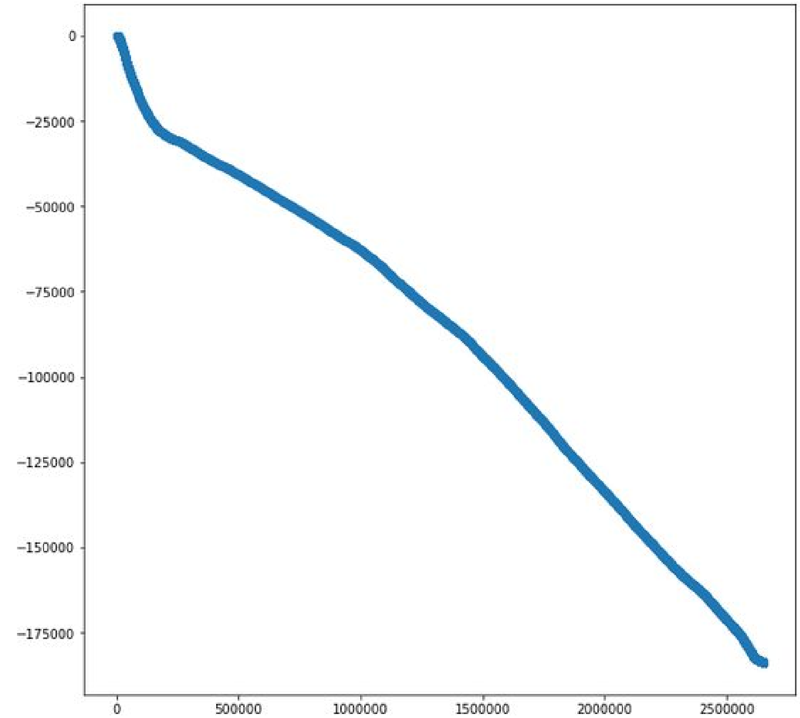
The analysis starts with a parsing of last years csv file data, which has a similar layout to the one described above, only that the pairs correspond to different materials only, and not to different orthogonal axes outside of the XY plane.

Once the data is parsed out and ready to be processed, the Kalman filtering is ready to begin. First thing that needs to occur is the obtaining of a relative motion array, which stores the difference between a previous reading and the current one. This was as simple as calculating the difference between them. After that, the two stages of Kalman filtering needed to be done, which is updating and predicting, for each X and Y axis.

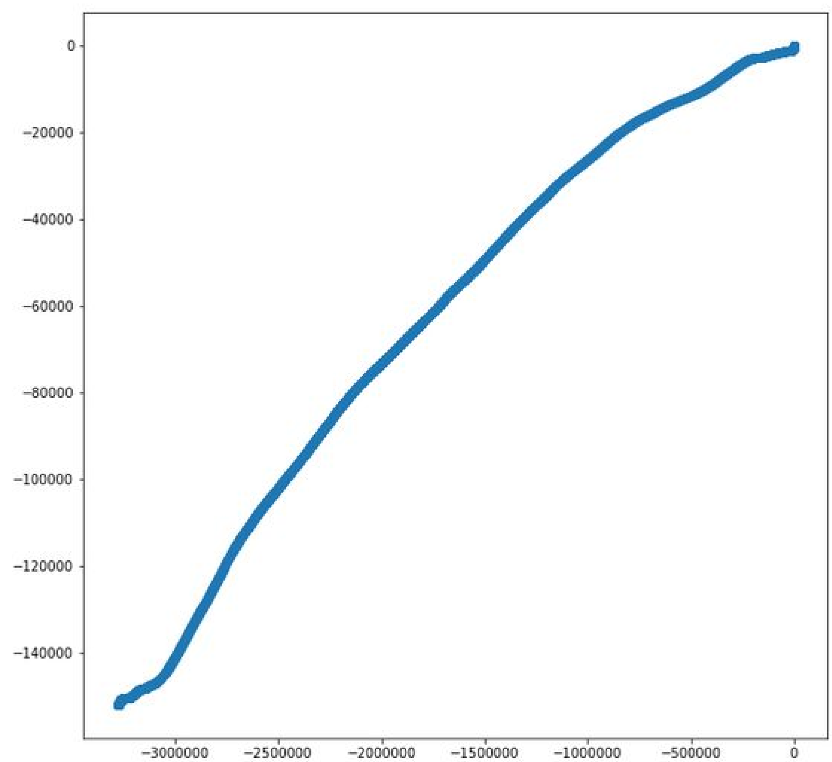
After the Kalman filtered acceleration plot is done, a plotting algorithm was done in order to show the relative motion of the accelerometers. A downsample was taken in order to make a more viewable final plot, as the original plot contained 1.3 million points, averaging all points lost in the downsample. From there a double integration is taken, first obtaining the velocity and then obtaining the relative displacement.

As this is placed on an orbital sander, what ought to be observed is a relatively straight line as the acceleration is in a constant direction with some added noise on each of the accelerometer boards. The accuracy of each material was determined using a line of best fit algorithm. The displayed score is calculated from a Root Mean Square Algorithm, with smaller scores indicating better scoring. Different orientations of the line should be discarded, as it is a function of the orientation of the accelerometer on the board itself, and only indicative of direction of motion relative to the accelerometers.

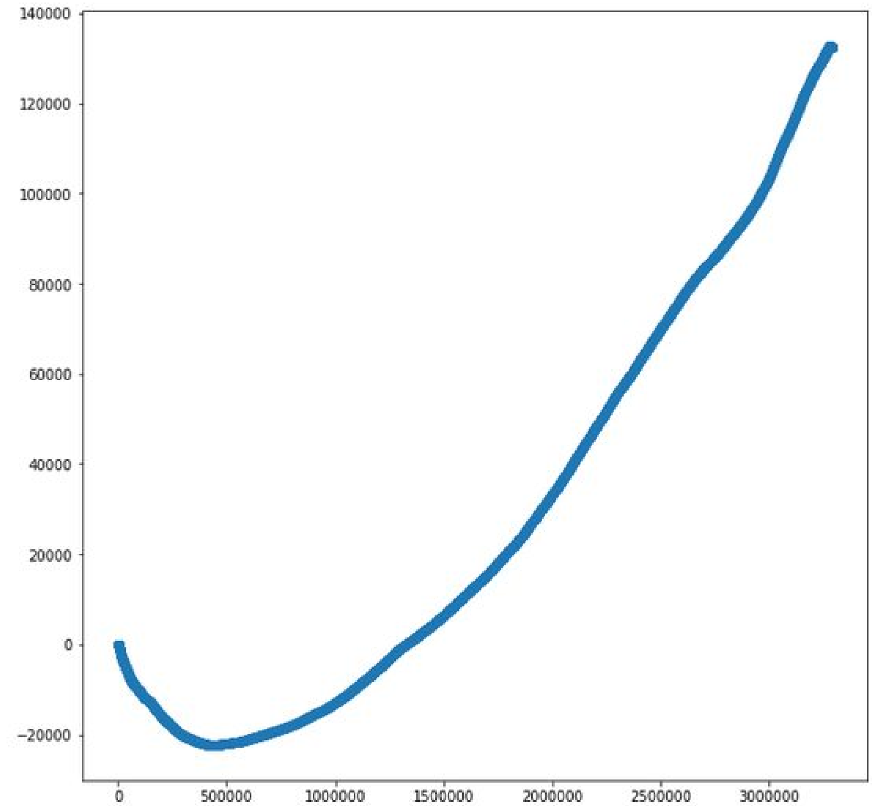
Control Displacement Graph



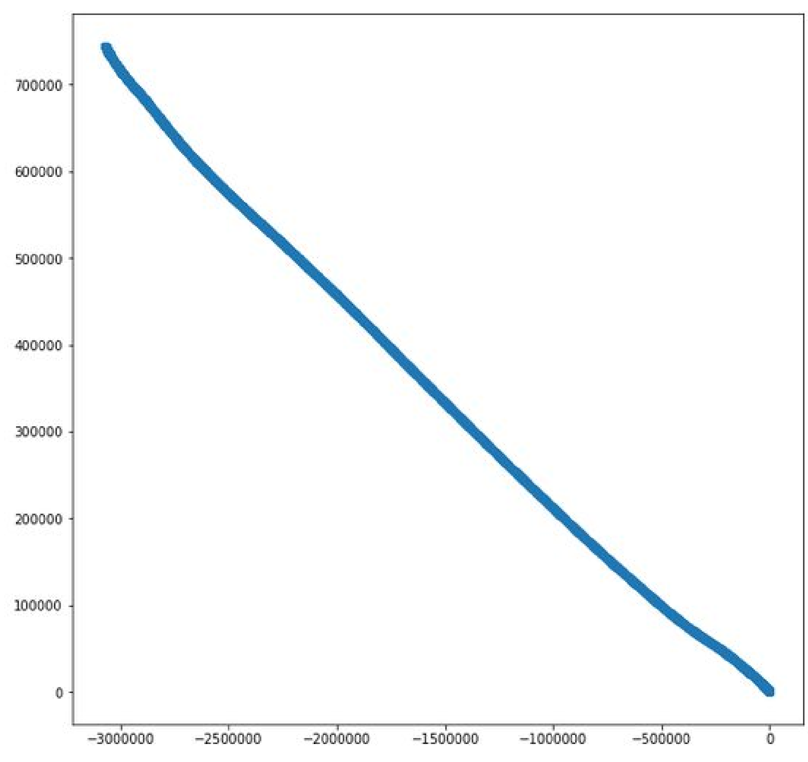
Neoprene Displacement Graph



Cable Displacement Graph

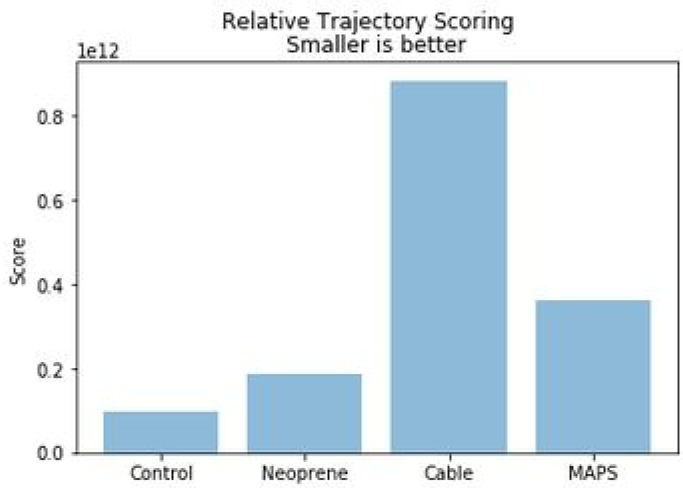


MAPS Displacement Graph



These are the relative scores as determined by a root mean square error equation.

	Score
Control	96459978365.5505
Neoprene	188955937544.19083
Cable	883909016743.6768
MAPS	362248043935.52435



7.0 Conclusions

In a rather unexpected result, the control ended up resulting in the best overall result, giving the lowest error score. It was expected that vibration dampening would assist in giving better readings on the accelerometers, as the extra acceleration added by the vibrations would have added in error.

Since control is the most accurate of the tested materials, it shows that this is very easily doable on our commodity hardware while maintaining a very low cost. The only upfront cost comes from printing or construction of mounts in order to hold the accelerometers. In addition, with proper hardware that can thread faster than once every millisecond, it is not outside the realm of possibilities to build a Kalman filter for position in real time.

8.0 Potential Follow-on Work

Potential future work could be done in order to find proper hardware that can do this in real time. The obvious goal would be to create a system that works during the actual launch, but a more ambitious goal would be to do one which examines how these materials function in a launch environment. The post launch analysis can only give so much data, and more realistic values would go a long way towards finding a proper base for a custom positional system.

Looking for ways to improve read accuracy or otherwise lower the sampling speed needed would also be a good way to reduce the needed amount of samples, thus allowing for other hardware which can calculate the position in real time.

9.0 Benefits to the Scientific Community

While IMUs today are tried and true, that does not mean that new ways to accomplish the task should not be explored. As such, we strove to attempt new ways to construct an IMU from readily available hardware. The accelerometer breakout boards were known to be good for calculating acceleration values, and using them led to results which demonstrated different methods for creating an IMU system, and one which requires very little dampening on top of that.

10.0 Lessons Learned

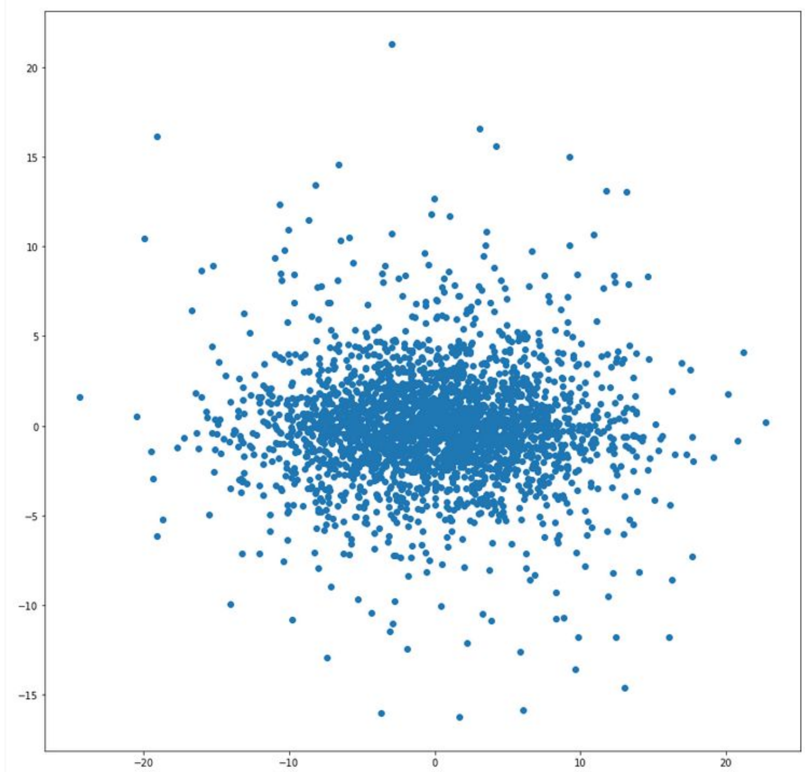
The main thing that ought to be considered if this experiment was flown again is an increase in available manpower. Unfortunately with two members, not a lot of time was had to be spared on the experiment. As such, the panic crunch near the end of the experiment, lack of time to work on the project during the main portion of the year made the project rather difficult, and some last minute emergencies made the project struggle, especially near the end of the year.

In addition, more research into stronger hardware should be researched before purchasing. The low computational power of the STM32F407VET6 makes it unideal for a high frequency data acquisition unit, and a microcontroller more suited for that application should have been selected. The additional power would have made it possible to do the Kalman filter in real time.

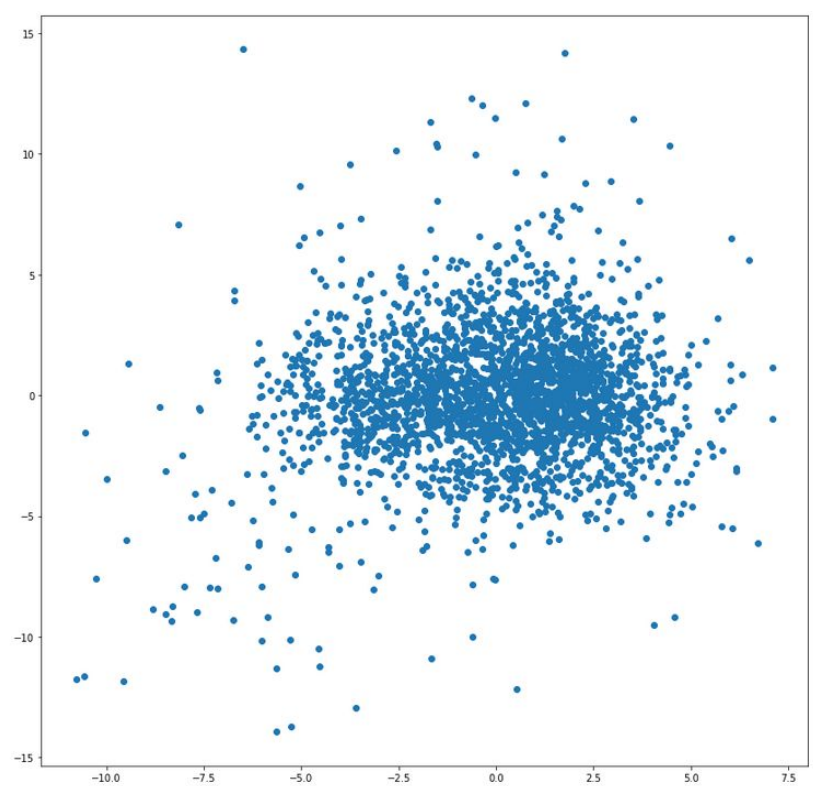
11.0 Appendices

Acceleration Plots

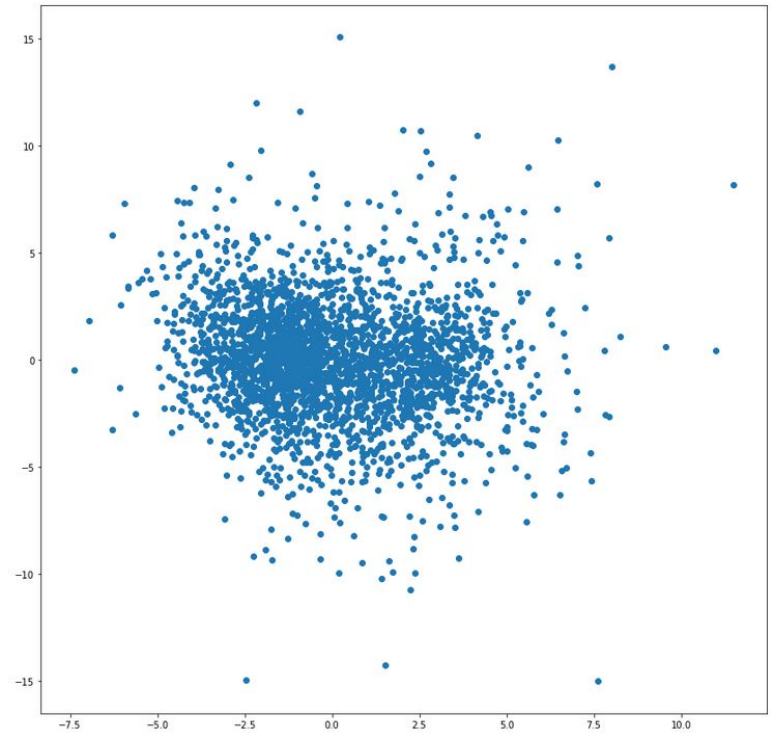
Control Acceleration Plot



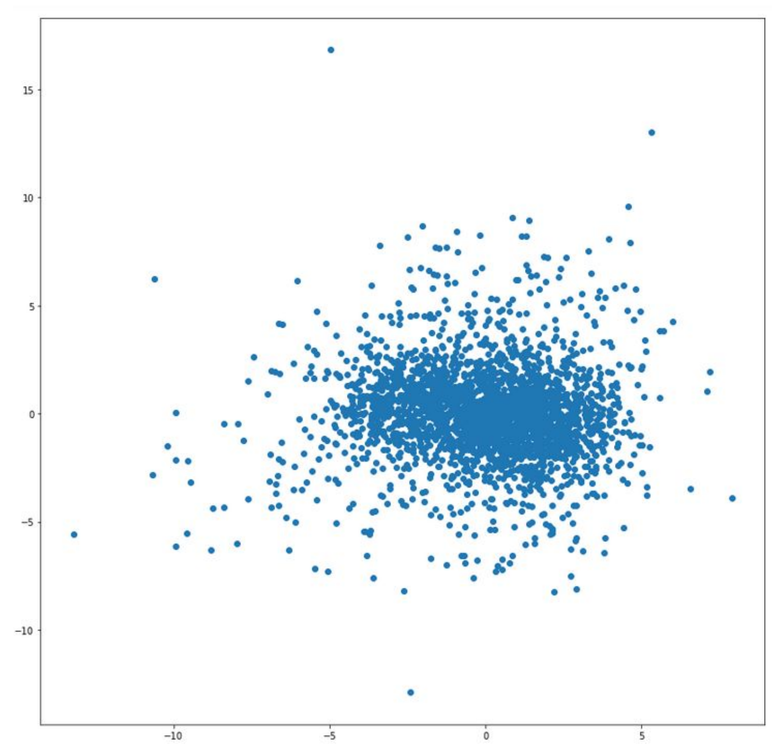
Neoprene Acceleration Plot



Cable Acceleration Plot

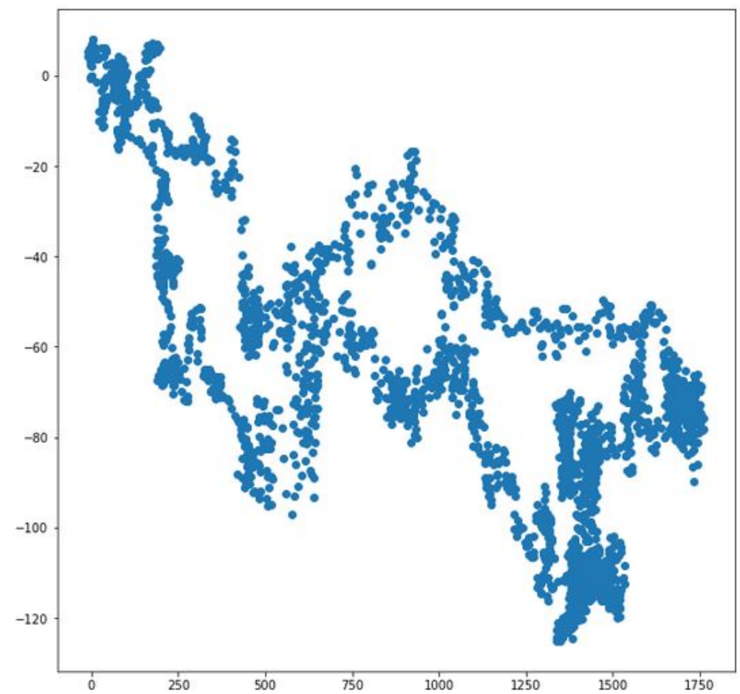


MAPS Acceleration Plot

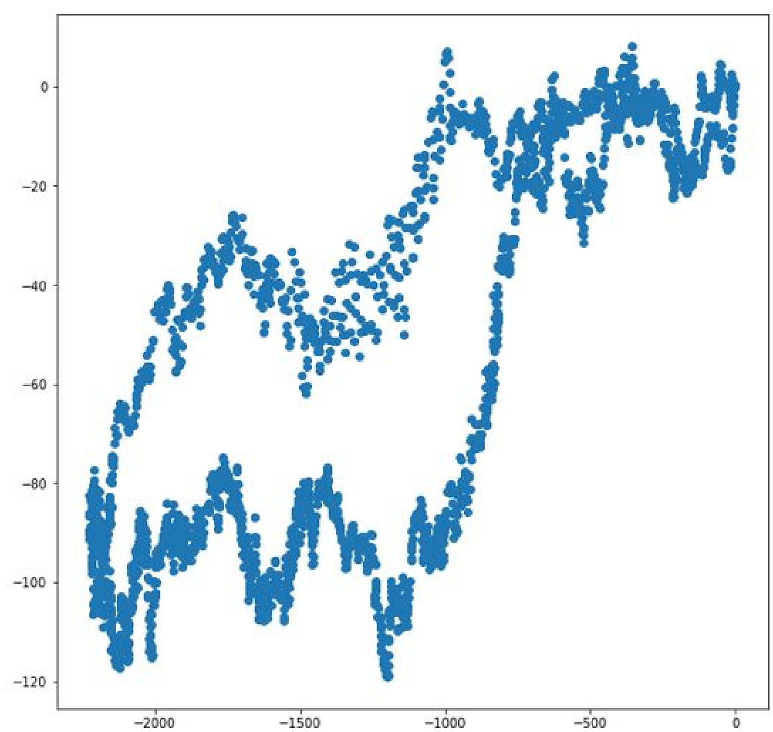


Velocity Plots

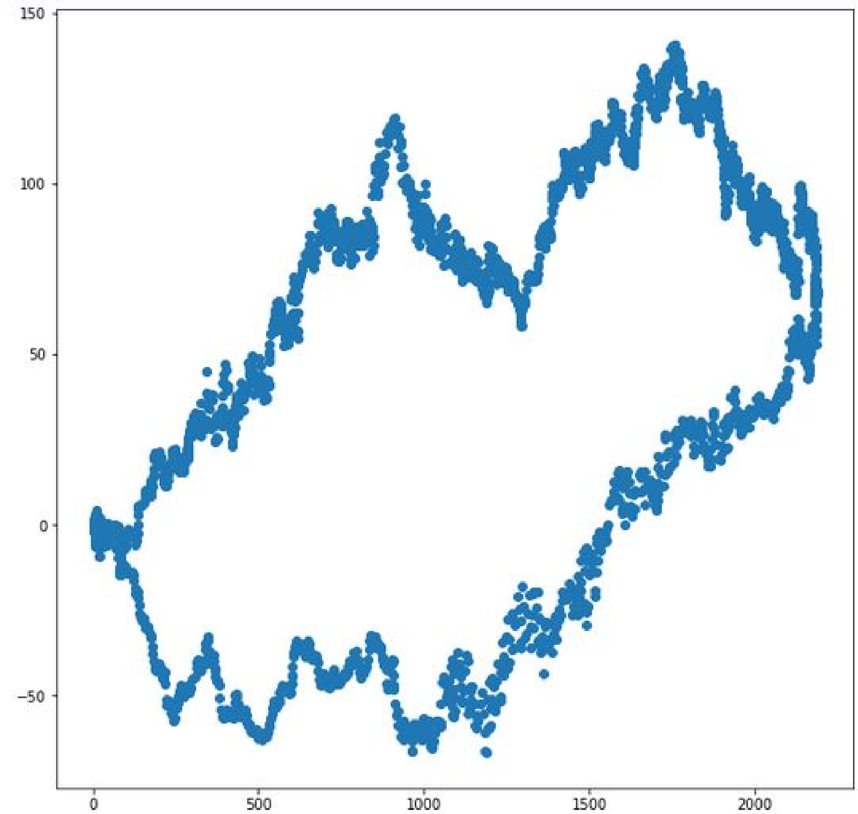
Control Velocity Plot



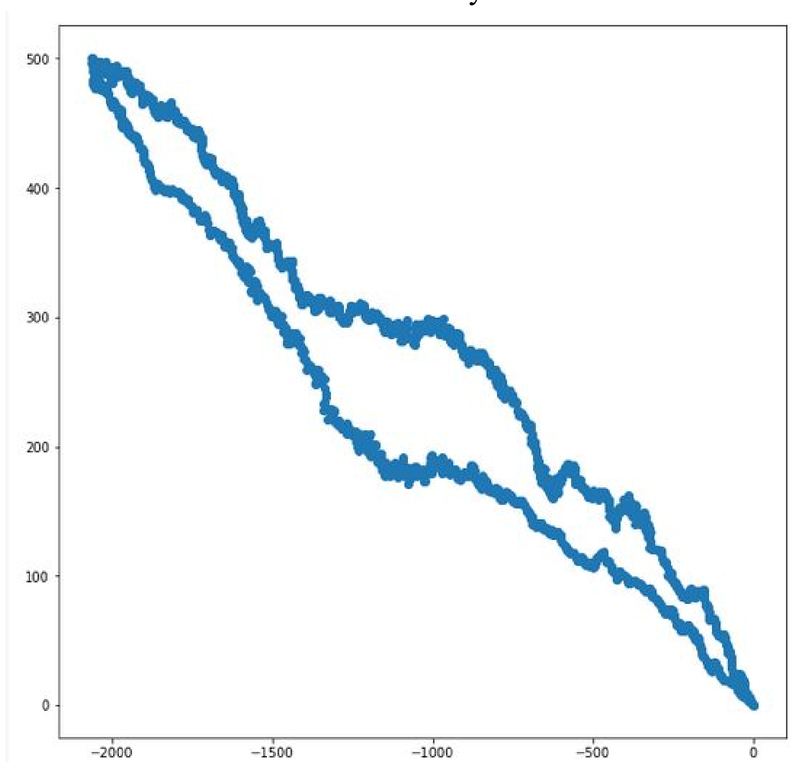
Neoprene Velocity Plot



Cable Velocity Plot



MAPS Velocity Plot



Power Management Board

1.0 Mission Statement

This project aims to integrate the power needs of all of the experiments in our payload and ensure all experiments can co-exist with the same battery. In previous year's experiments, the power supply and integration was performed after the payload was completed and was always an afterthought. This project aims to fix that.

As our payload became more complicated with more experiments it is critical to ensure that no one component of an experiment can cause the entire payload to fail or short. In addition it is useful to have a record of any power events that occurred to the payload for debugging an integrated system and performing post-launch analysis to figure out what may have gone wrong.

Space is a premium on our payload as the soldering experiment takes up the majority of the canister volume so individual power boards for each project is not practical. The power management board combines the switching, monitoring, and regulation of seven voltage rails on one board saving a lot of space in the canister.

2.0 Mission Requirements and Description

First and foremost, the power board should be able to supply every other component in our canister with regulated power. The board should be able to measure the current draw and voltage supplied to each individual project, and in addition should be able to disable a malfunctioning project if necessary.

The power board itself should have minimal current draw, and be able to enable itself and the other projects when the t-3 activation line is triggered. After the experiments have completed, it should shut down dangerous components such as the hearer as an additional failsafe.

A main requirement of the power board is the logging of power data to an SD card and over tethered USB for debugging and post-mortem analysis. The rate shall be fast enough to pick up any significant spike or dip in voltage that may affect an experiment.

It should be as easy as reasonably possible to integrate and de-integrate the power system with the rest of the components, facilitated through the use of power-poles and db9 connectors. The board should also be as easy as possible to debug, and aid in debugging other projects as necessary.

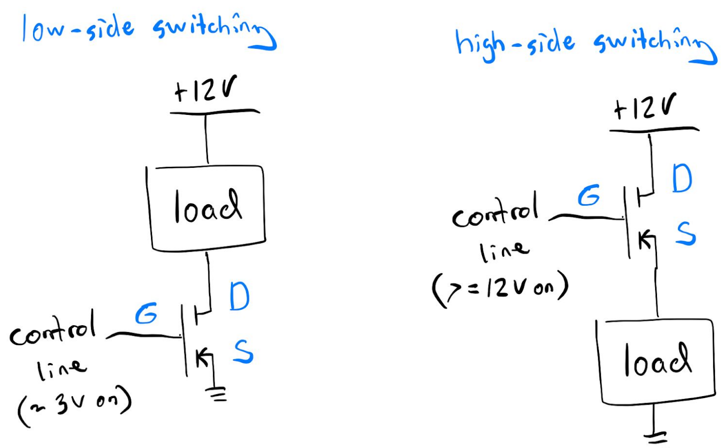
The required power rails for the experiments include the following:

1. 5V @ 1.5 A - Vibe Iso
2. 5V @ 1.5 A - Soldering
3. 5V @ 1.5 A - Pressure Sensor (reserve)
4. 12V @ 10+ A - Soldering Team Heater
5. 12V @ 1 A - Soldering Team Fan
6. 12V @ 1 A- Pressure Sensor Team Main Bus
7. 36V @ 0.25 A - Pressure Sensor Team Sensor

3.0 Payload Design

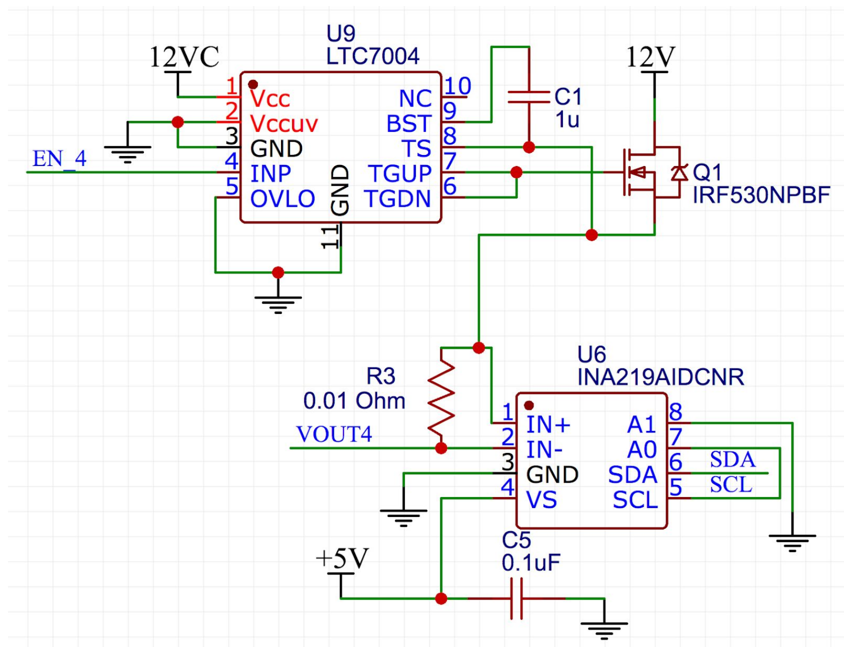
Very early in the design process, it was realized that we were dealing with many unknowns. It was therefore decided to design, order, and build a V1 prototype board, test and debug with that board, then proceed with a final V2 board.

One challenge faced in designing this power board is switching each voltage rail from the high-side (aka the + side of the battery). The team chose to use MOSFETS to switch the voltage rails for each project as they are solid state, are not affected by vibration, small, and inexpensive. The simplest MOSFET circuit is to use an N-Channel MOSFET to switch the current from the GND side as shown below. The MOSFET turns on when the gate voltage is raised above the source voltage. This makes it easy to drive the gate directly from a microcontroller or activation line as the source voltage is ~ 0V.



Comparison - High-side vs Low-side Switching for N-Channel MOSFETS

Low-side switching is a problem for projects that require several voltage rails that have a common ground as connecting those grounds will cause current to flow through the system in an undesirable way. So high-side switching is a requirement. However the circuits for high side switching are often more complicated due to the nature of MOSFETs. One solution is to use an N-channel mosfet with source connected to the 12V voltage rail. However in order to fully turn on the MOSFET the gate voltage needs to be raised above the 12V voltage rail which is challenging to control from a microcontroller. To get around this the team chose to use a dedicated MOSFET driver chip (LTC7004) that includes a charge pump circuit that is able to raise the gate voltage in excess of 5V above the gate voltage to ensure that the MOSFET is fully turned on and will conduct current efficiently. The LTC7004 is controlled using low voltage signals that are easy to control from a microcontroller but has internal circuitry to switch a high voltage on the gate of the FET which simplifies the analog design and meets the requirements.



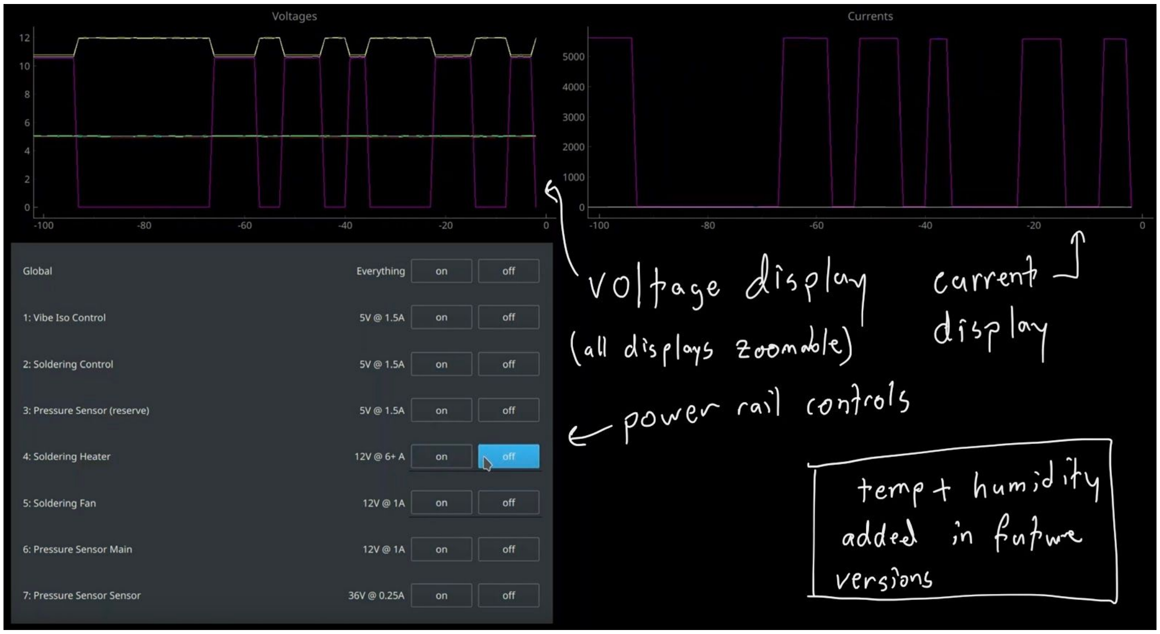
High-side Switching Using the LTC7004 + Power monitoring using INA219

P-channel MOSFET circuits were also considered as they would be easier to implement using discrete components but was decided against on due to their higher internal resistance and inverted logic.

The team chose the Adafruit Adalogger M0 for the microprocessor to control the power board because it has built in sd-card writing, a compact size, and has plenty of speed to run quick loop cycles for fast responses to changing conditions.

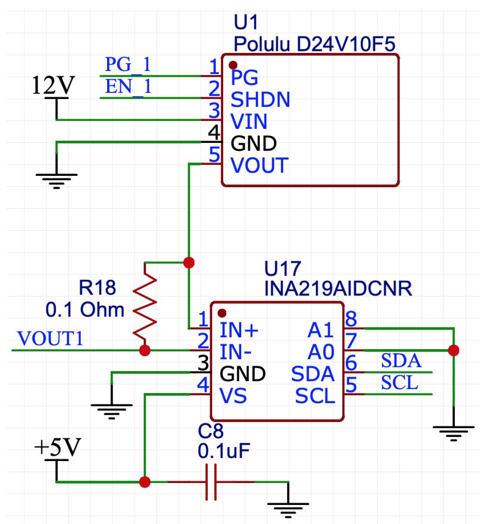
For current and voltage monitoring, the team chose the INA219 as it has an I2C interface making it easy to interface to the microcontroller and handles the filtering, A/D conversion, and scaling of the results all in one small chip.

For testing the board and verifying the readings a Python Qt GUI was developed to visualize the data in real time and provide an interface for controlling each rail. The encoding format chosen was Google's Protobuf. Protobuf was used for both the live streaming and data storage. The nanopb implementation is used on the microcontroller.



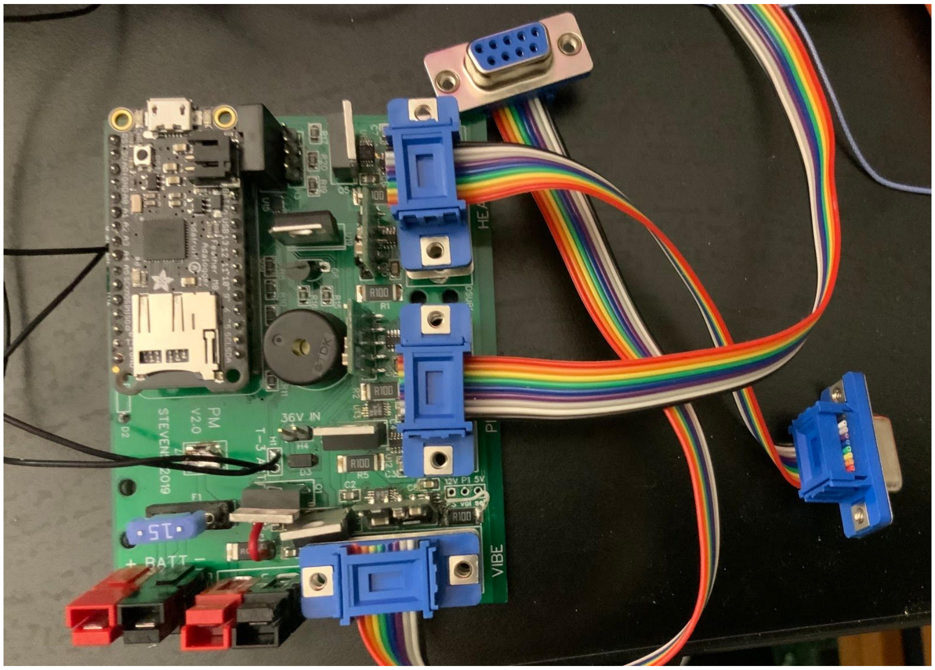
Python Qt GUI for Real-time Debugging

All 12V rails were unregulated, all experiment 5V rails were regulated using Polulu 5V switching regulators for efficiency. These regulators can also handle short-circuit conditions themselves without heating up, and the enable line from the microcontroller.

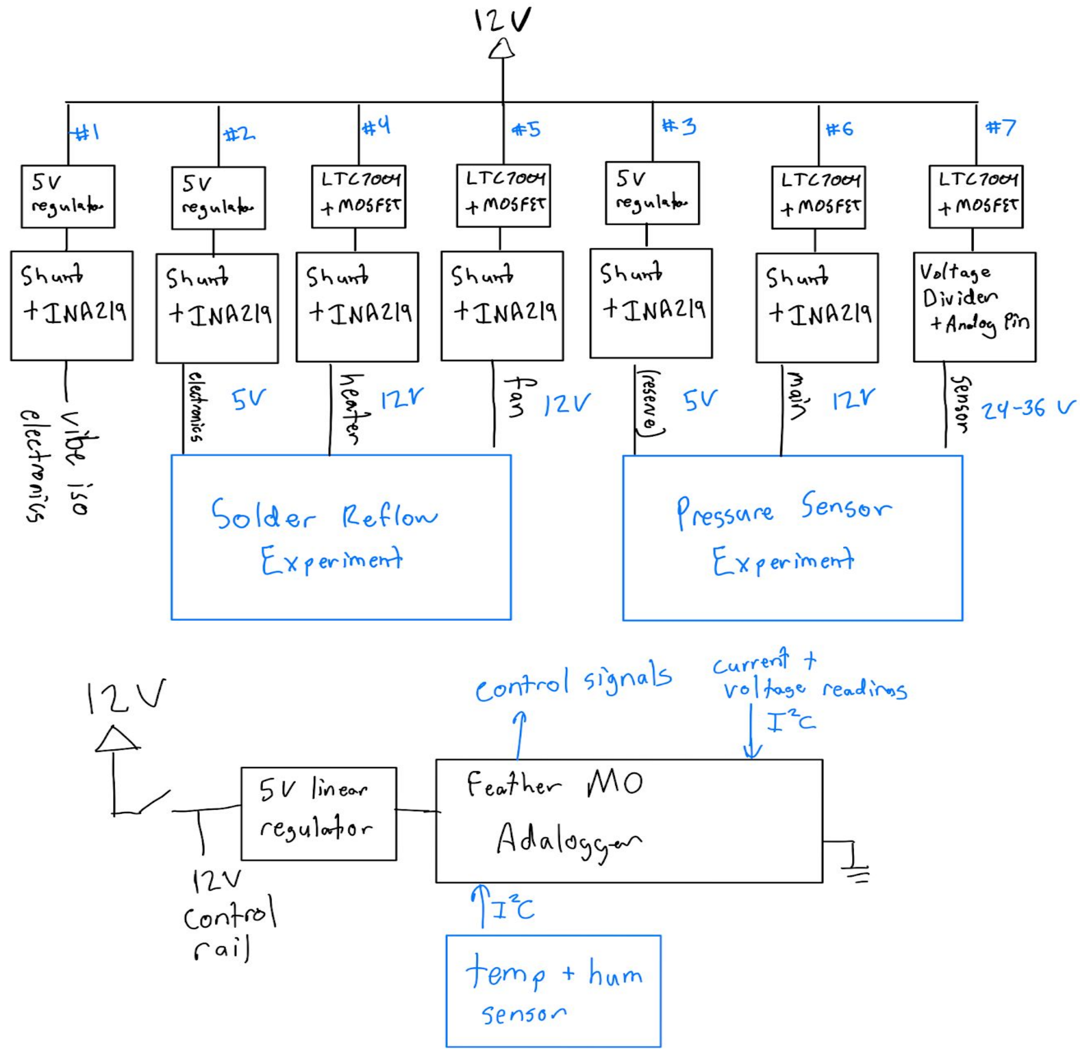


Typical 5V Regulated Power Rail

To connect each project to the power board, the team chose a ribbon cable terminated on both ends with insulation displacement DB-9 connectors. This setup made it easy to make the cords to any length required just by snapping the connector over the ribbon cable in the right location and trimming the extra. This was significantly less error prone than manual crimping and soldering used in previous years payloads. If necessary, the connectors can also be screwed down to prevent them from loosening during launch.



DB-9 IDC Cables to Connect Experiments to Power Board

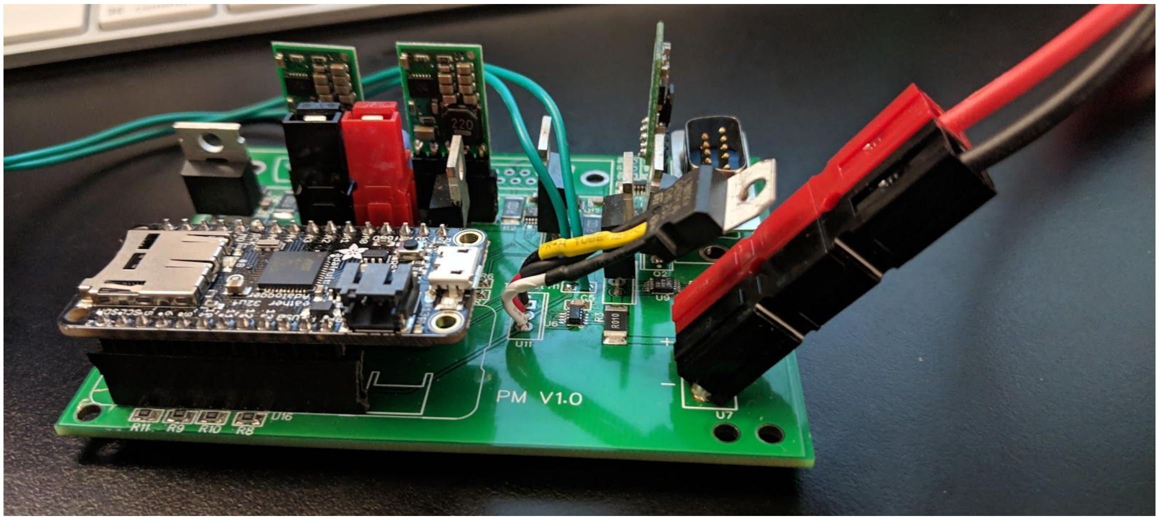


Power System Block Diagram

4.0 Student Involvement

The two main members of the team that worked on the power board include Jesse Stevenson (Electrical Engineer + CS Minor) and Jack Hymowitz (Computer Engineer). Jesse Stevenson was mainly responsible for leading the project, design decisions, sourcing components, and programing. Jack routed the PCB, helped with the schematic design, and v1 board assembly.

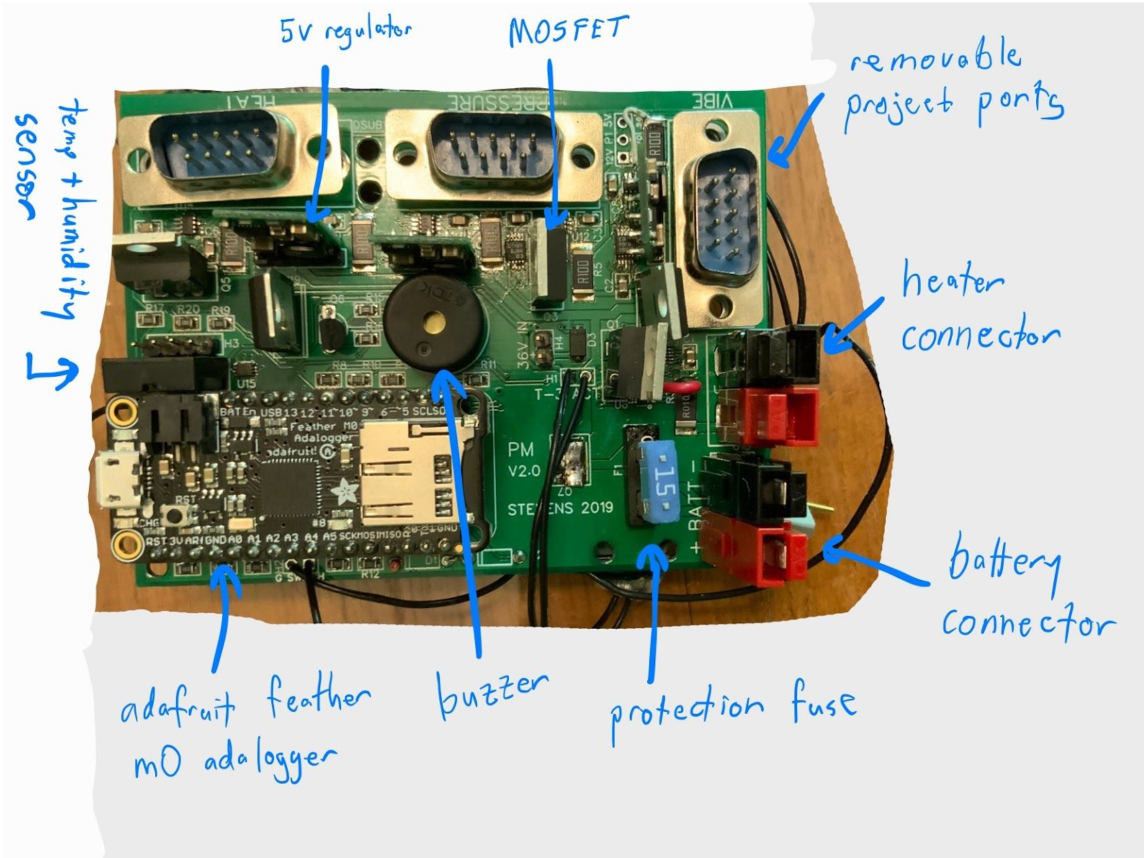
5.0 Testing Results



V1 Power Board - Connector Bent for USB Cord to Fit

Initial testing results were positive for the V1 board. Testing was performed using a digital load on each rail. Tests included comparing the voltage and current for each rail against the digital load and checking the switching for each rail.

For the final board, several issues discovered from the prototype power board had to be addressed. One problem that arose from the first revision include a ~40 mA draw when the power board was deactivated. This draw would be present before the T-3 activation line was enabled, and would significantly deplete the battery prior to launch. This was caused by the MOSFET driver chips that were connected to the 12V continuous rail instead of the 12V activated rail. Another issue that arose was the voltage drop from the battery to the 12V voltage rail. This was caused primarily by an inefficient reverse polarity protection diode on the board and was remedied by a more efficient MOSFET circuit in revision two. The high current traces were also shortened to further reduce the voltage drop to the heater rail to provide more power. In addition the microcontroller's usb port was not on the edge of the board but faced inwards. This was similarly fixed in revision two. The 5V linear regulator that was used to regulate the voltage for the microcontroller and other control logic had an incorrect pinout as it was designed for a negative voltage regulator. A buzzer was added to the revision two board to assist in quick debugging.



On revision two the new reverse polarity protection MOSFET circuit didn't work and the team decided to cut it out so we could focus on ensuring the other parts of the board were working correctly as it was getting close to launch.

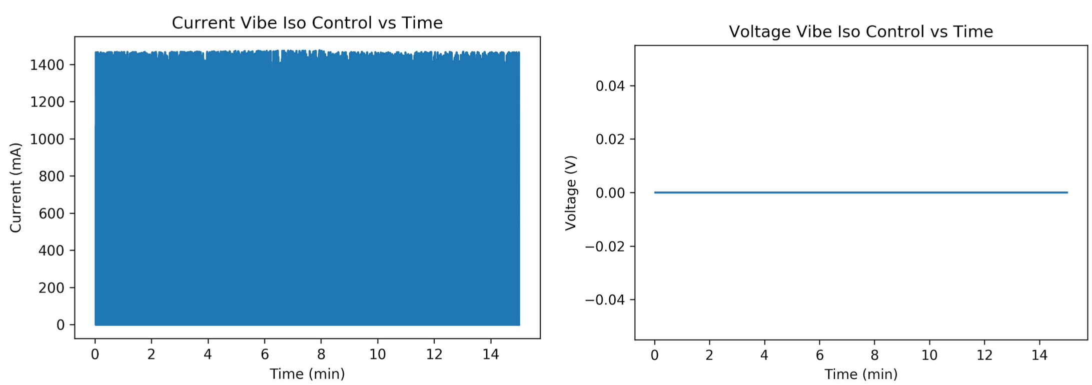
For revision two the solder paste was dispensed onto the board using a stencil. Then the chips were soldered using a reflow oven. This worked well for all components besides the LTC7004 MOSFET drivers. The driver chips have a very small component pitch (0.5 mm) which is difficult to solder without bridging pins. Also the chips start to fail if they are heated too long which caused problems for the team during assembly. Over-soldering breaks the chip and it no longer turns on that voltage rail - but sometimes does not show symptoms until later. This was particularly frustrating as the power board that went down to Wallops had some failures with this chip even though it was fully working before heading down.

Another contributing problem that caused the LTC7004 chips to fail is a mistake in board design. A trace that carries the majority of the current to the heater was mistakenly routed as a thin trace under the LTC7004 and INA219. During operation of the heater for longer periods the MOSFET driver chip on the other side of the board would get hot and stop working. A jumper wire to carry more current was added to fix this as there was no time between when this was discovered and launch.

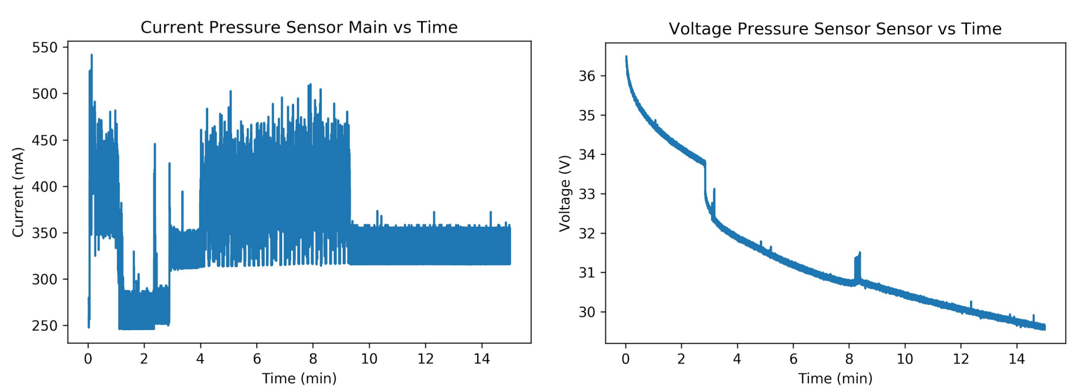
6.0 Mission Results

Overall, the power board functioned well during launch. Voltage and current measurement on some of the lower power rails were not working (likely from overheating those chips from replacing the LTC7004 chips too many times) but the power board was not a limitation for any of the experiments during launch.

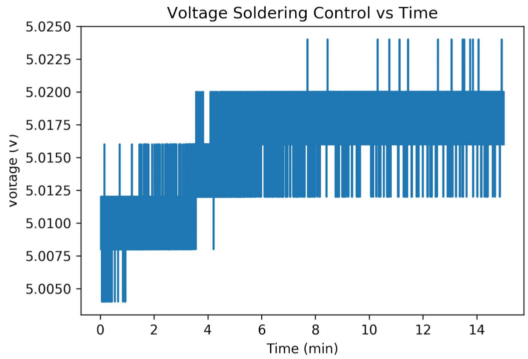
For each of the experiments, the following occurred from the power board's logs. The pressure sensor team's experiment looks like it recorded data as it shows a clear difference in the current graph indicating when the beaglebone booted, waited for the region of interest, recorded, then went back to idle. The accelerometer filtering experiment had a short on the 5V rail and the power regulator limited the current effectively turning the rail off. The reflow soldering experiment was fully turned on and remained on for the launch drawing very little current and never turning on the heater. From further post-launch analysis, it appears that the reflow experiment's microcontroller has a bug software bug as it exhibited similar symptoms in other test runs, mainly writing a small log file for the first few minutes then stalling.

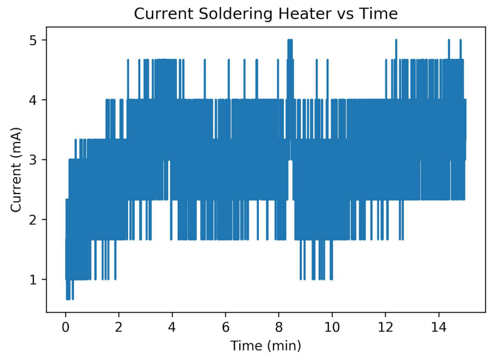


Vibe Iso Current + Voltage Graphs - Shorted But Tries to Turn On



Pressure Experiment Main + Sensor Rails Working as Expected





Solder Reflow Experiment Control Rail On, No Heater Current

Many of the graphs from the power system's debug log during launch are also included in the specific experiment's reports listed previously in this document, and have aided in determining what occurred during the launch. A complete listing is included in the appendices section

7.0 Conclusions

Although the power board came across some hiccups with soldering the LTC7004 chips, it functioned as intended and gave valuable insight to help the post-analysis for the payload. The experience gained from designing and producing the power board this year will be used to improve next year's payload as well.

8.0 Potential Follow-on Work

The power system was a worthwhile addition to the canister, protecting and debugging the rest of our projects. In the future, the continued use of this system or a similar one would be worthwhile, especially with high current draw projects like the heater.

9.0 Benefits to the Scientific Community

The power management board is primarily an engineering project but did provide a framework for future experiments and payloads to use to ensure high power experiments are kept safe. The design used for this board can easily be modified and repurposed for another payload and benefit from the live-debugging capability, programmatic control of all power rails, and monitoring provided by our project.

10.0 Lessons Learned

Several of the smaller surface mount chips were challenging to solder or even place accurately for a reflow oven to solder. In future experiments the team recommends having the board assembled by machine and possibly making the board more modular so components can be switched out easier in the event of a failure.

Part inventory was also a challenge during board assembly because of the number of surface mount chips required. Using inventory software or assigning someone to keep track of the parts would be useful as a lot of time was spent figuring out how many we had left, what we needed to order, and what part is associated with what part on the board. We did eventually have a spreadsheet of parts but it was hard to keep up to date when parts are used. Wherever possible it is best to use common parts even between experiments to ensure we have spares and to make it easier to inventory and locate replacements.

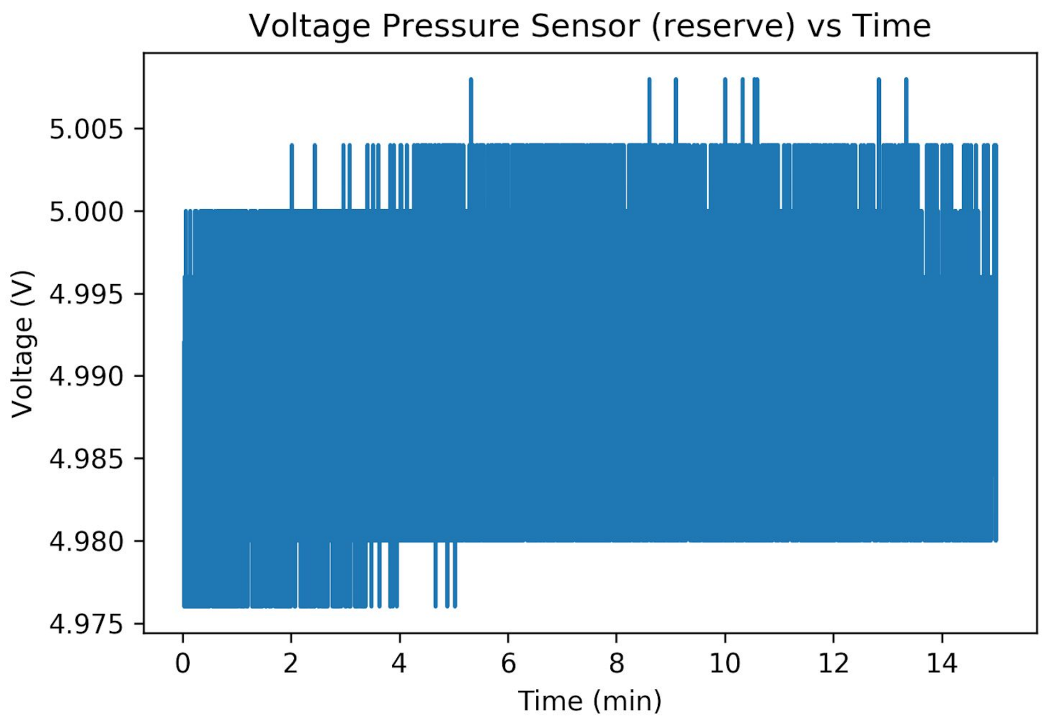
Before sending out a design be sure to double check any traces carrying a substantial amount of current to ensure they are wide enough and short as possible. It can be frustrating to skip over this step when trying to get a board made, but a few minutes spent checking them could save hours of frustration after the board is produced.

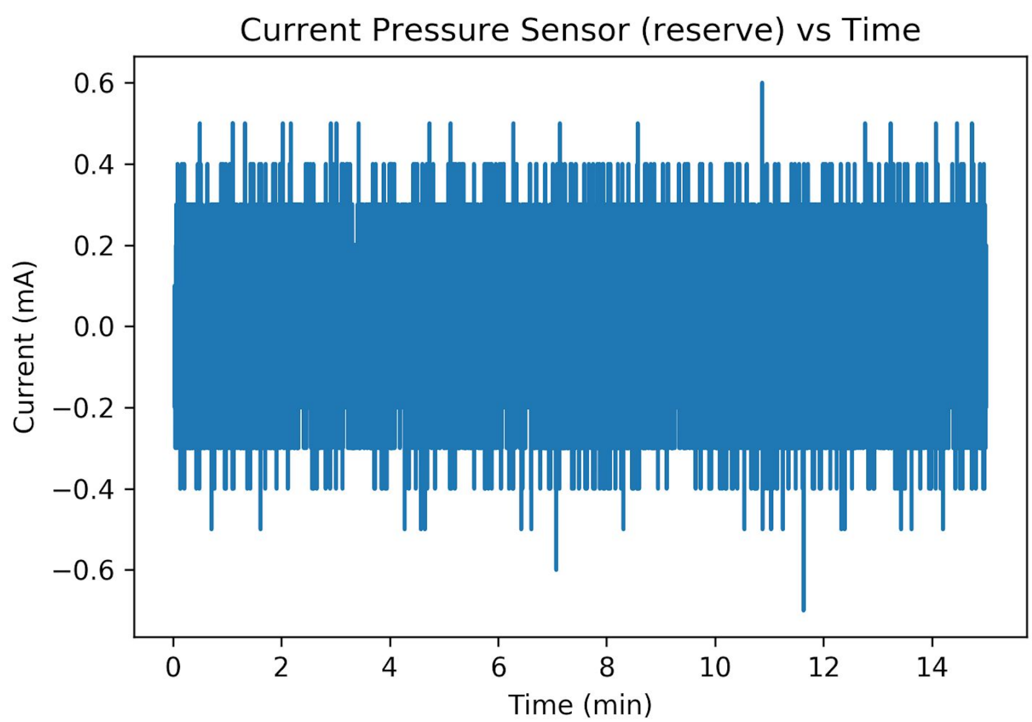
Extra pads around critical components would also be useful for quick fixes after assembly, especially when a pad has lifted from desoldering a surface mount component too many times.

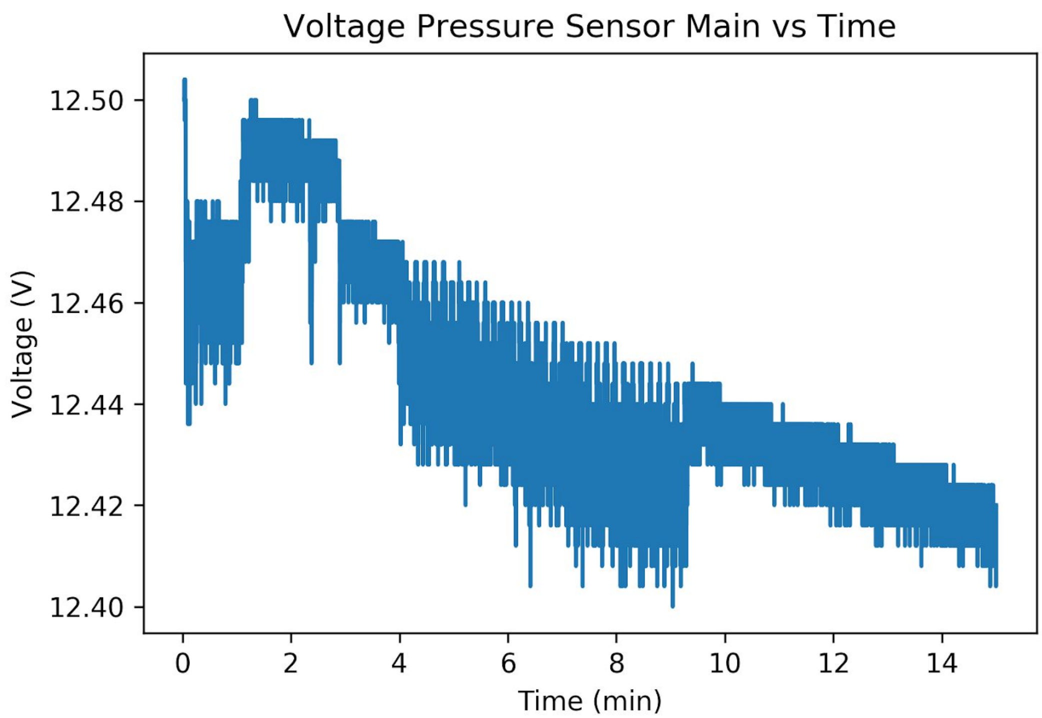
The power poles and db9 connectors worked well and should be used again, but their use and interface between projects should be clearly set up as early as possible. This year, the interface was designed relatively early, but it was not communicated well to one experiment that resulted in some last minute wiring.

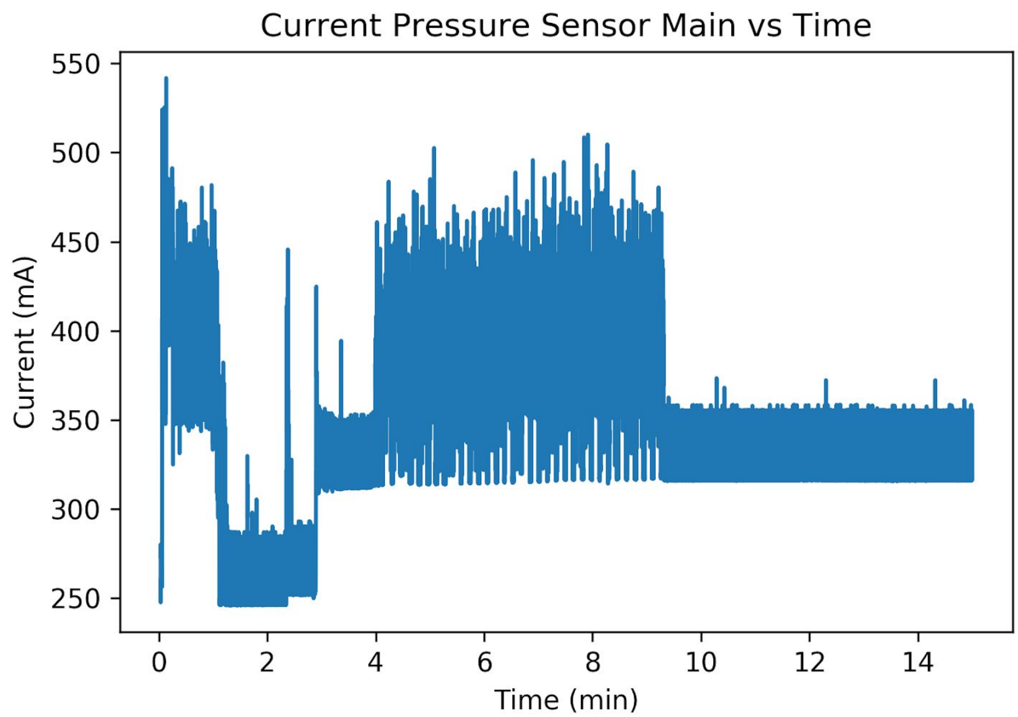
The usage of lights and different beep noises on the power board were really useful and we highly recommend it to future experiments as it lets you tell instantly whether something is wrong in the payload after fully integrating.

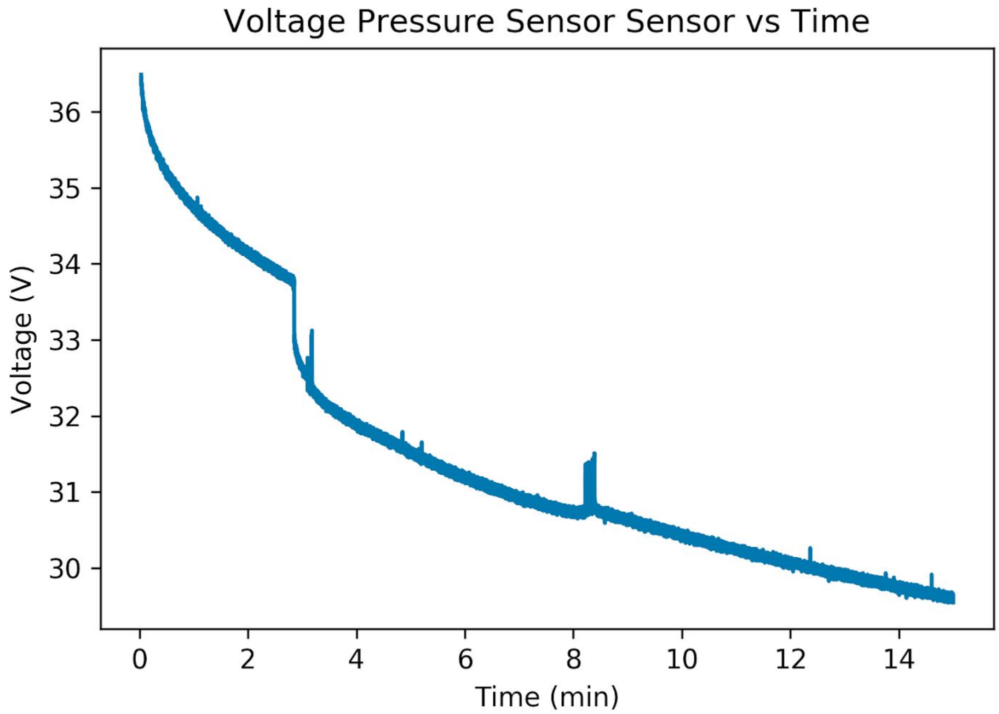
11.0 Appendices



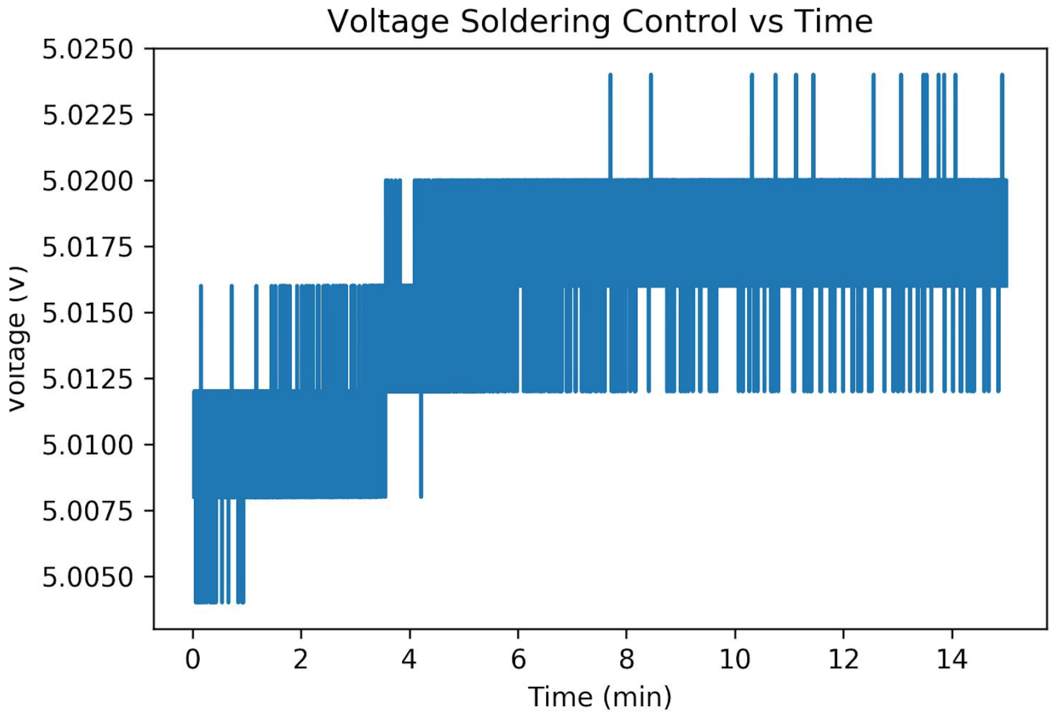


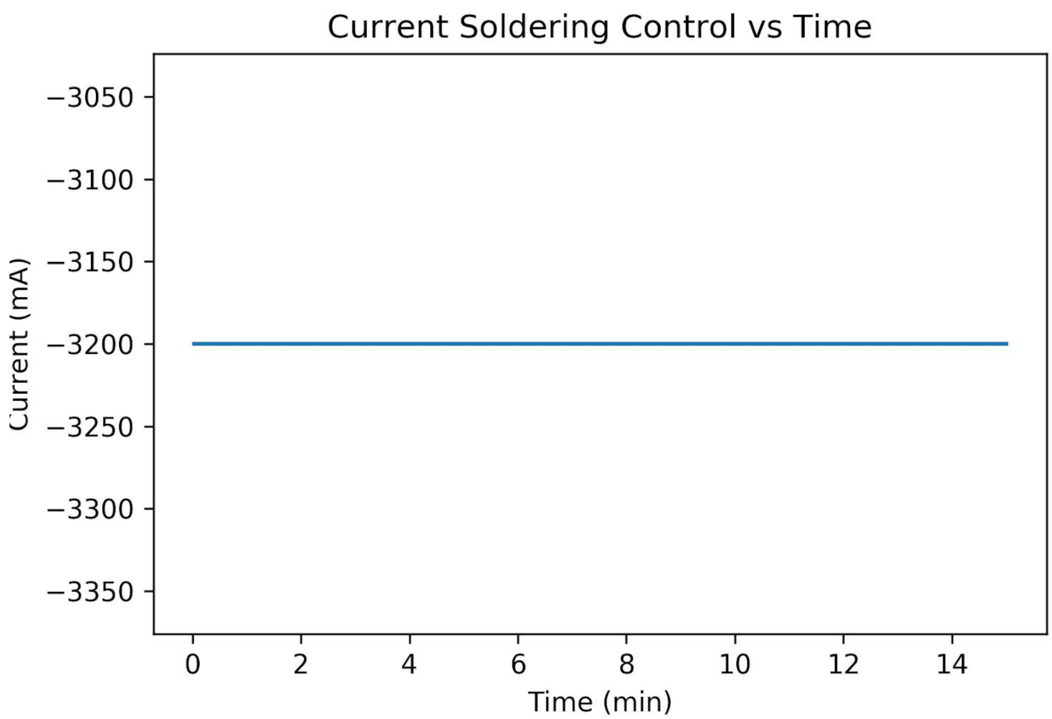

Voltage Pressure Sensor Main vs Time
Voltage (V)
12.50
12.48
12.46
12.44
12.42
12.40
0
2
4
6
8
10
12
14
Time (min)


Current Pressure Sensor Main vs Time
Current (mA)
550
500
450
400
350
300
250
0
2
4
6
8
10
12
14
Time (min)



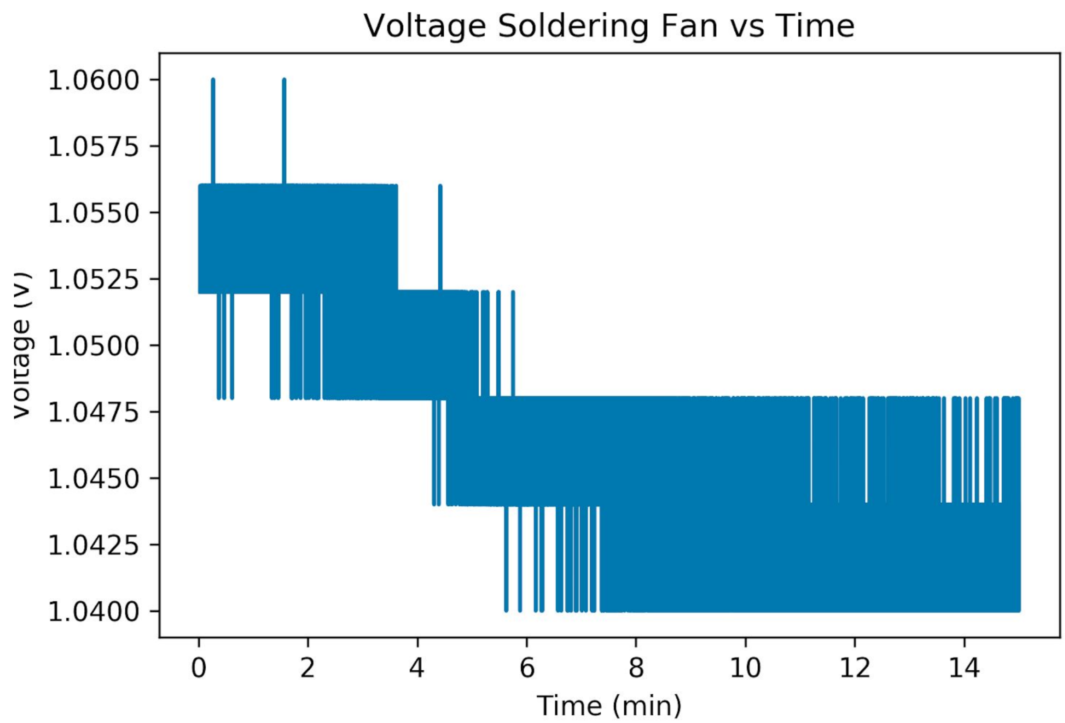
(no current measurements were possible on the pressure sensor 36V rail)

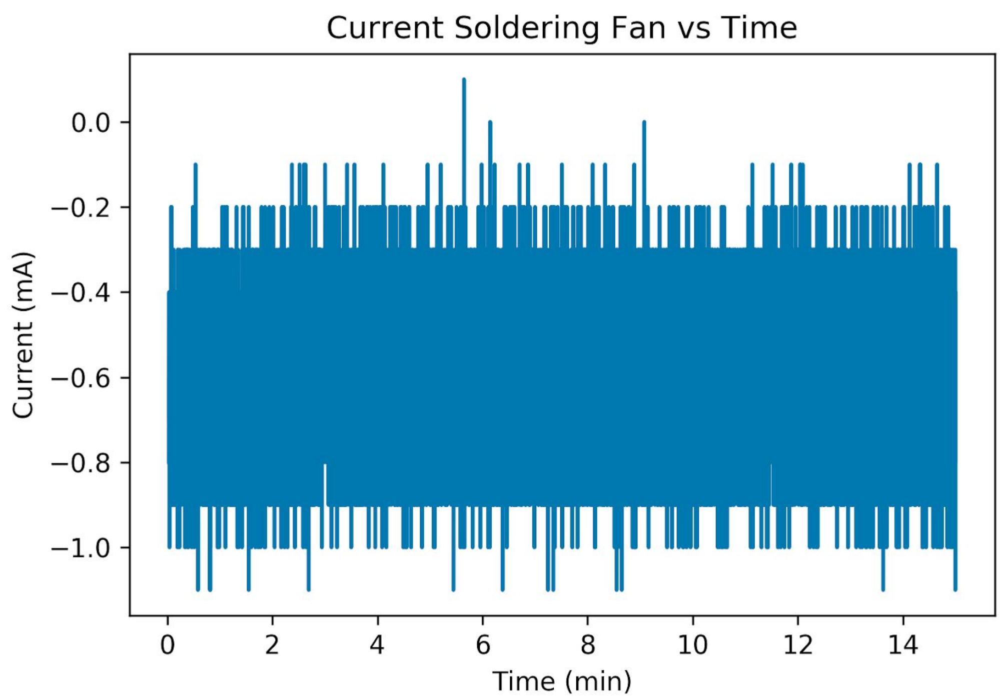


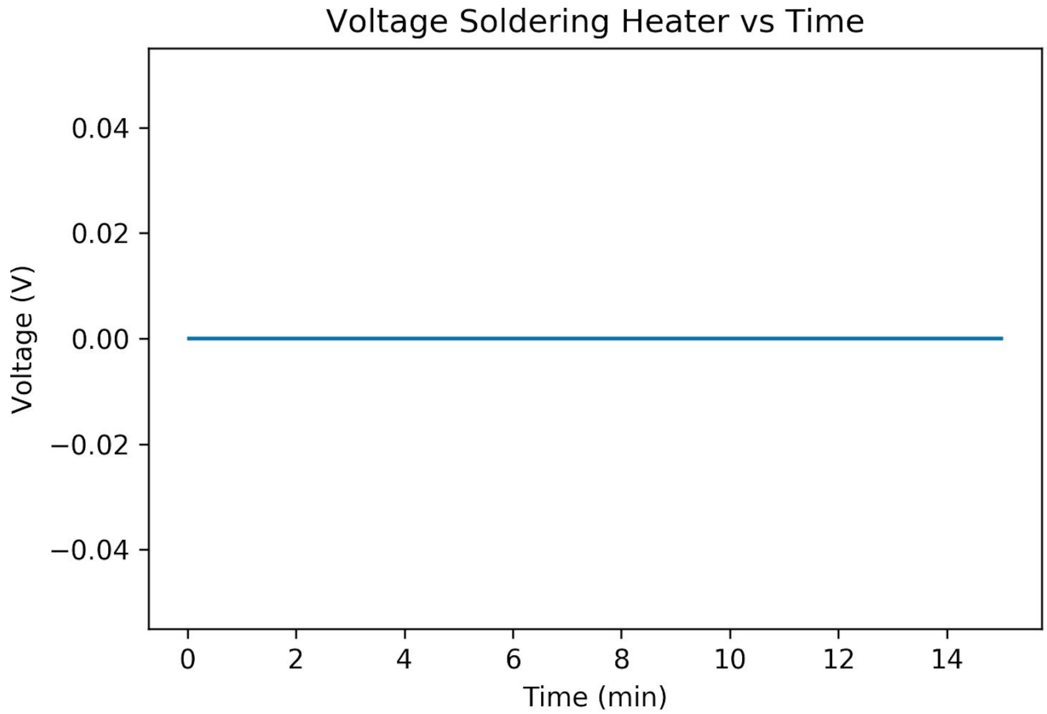


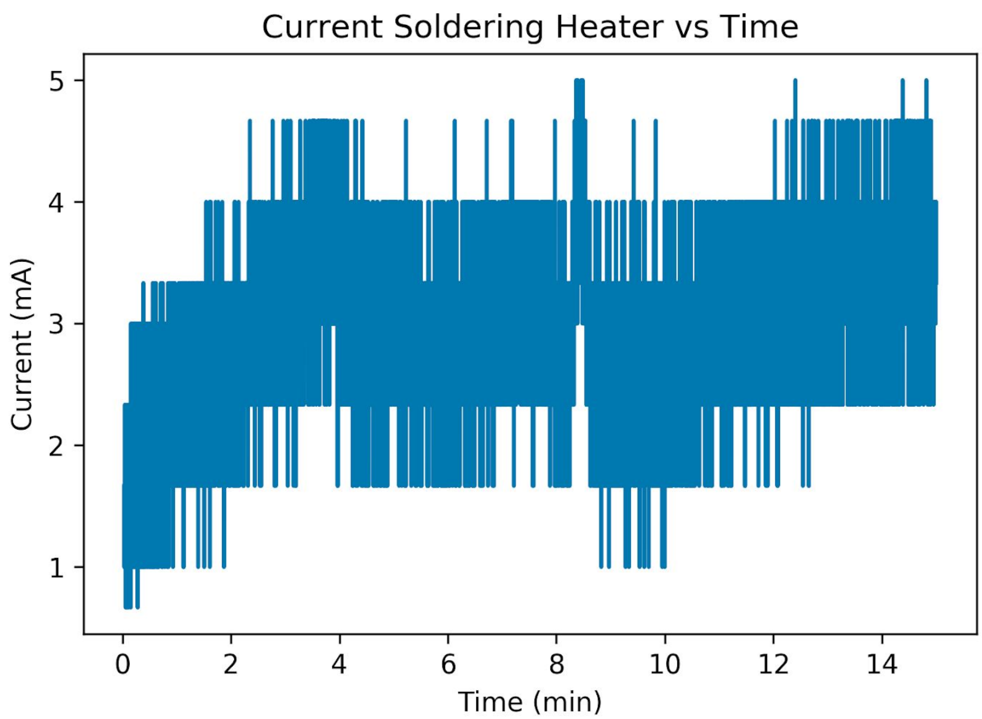
^ The Soldering Control current measurement is not working correctly - also reads a large negative current when the output is floating. Likely due to a lifted pad for the current sensor that was temporarily fixed with thin wire.

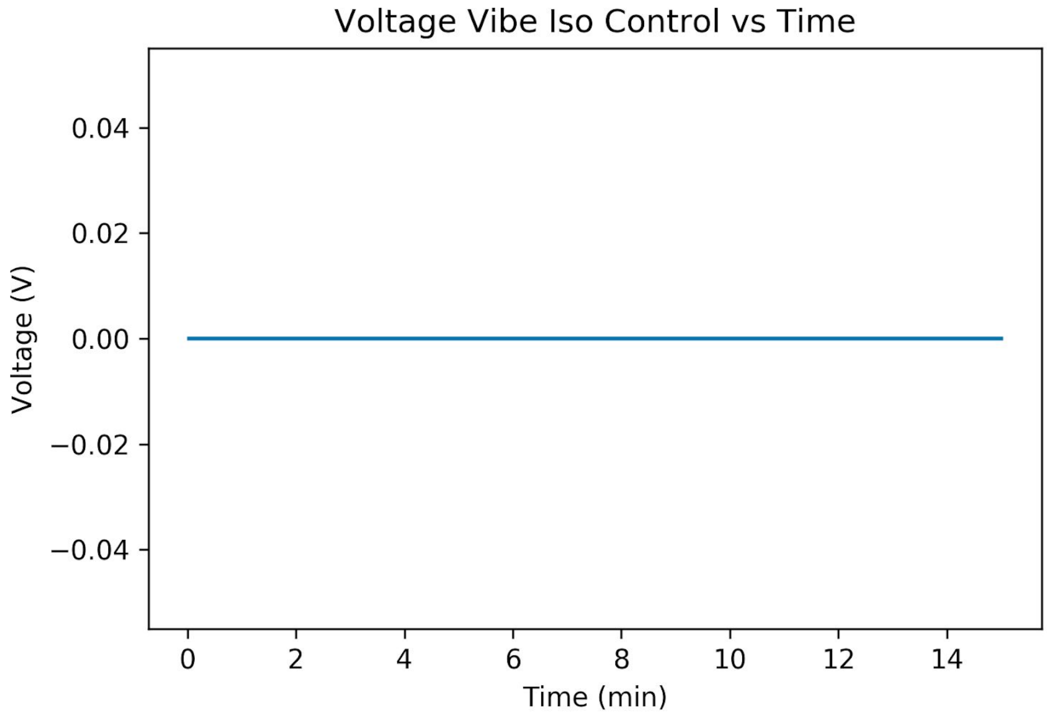
The Reflow Soldering Team's Fan was fried after the connector was made incorrectly so the LTC7004 from this rail was used to fix another rail, so the power rail is "off" right now. The residual voltage and current are because the output is floating.

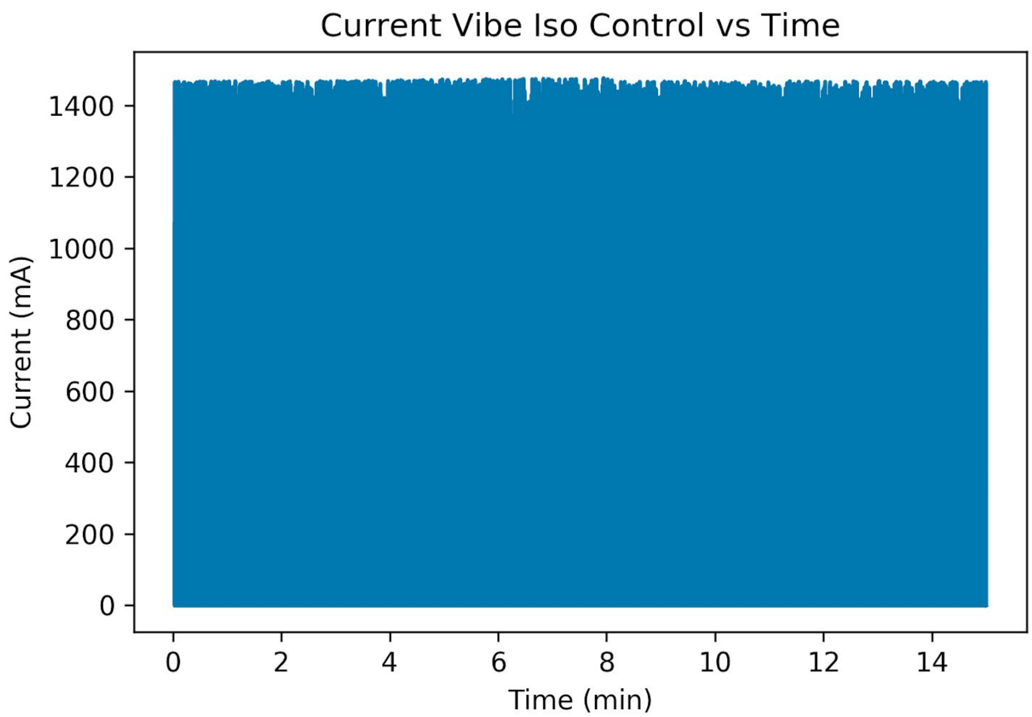





Voltage Soldering Heater vs Time
0.04
0.02
0.00
−0.02
−0.04
Voltage (V)
0
2
4
6
8
10
12
14
Time (min)


Current Soldering Heater vs Time
5
4
3
2
1
Current (mA)
0
2
4
6
8
10
12
14
Time (min)


Voltage Vibe Iso Control vs Time
Voltage (V)
0.04
0.02
0.00
−0.02
−0.04
0
2
4
6
8
10
12
14
Time (min)


Current Vibe Iso Control vs Time
Current (mA)
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
Time (min)

The environment sensor is very particular about it's I2C signals and fails if it gets confused - it stopped reading new values after 7 minutes of flight.