Analyzing Vibrations in Space Launch Environments

Analysis of vibrations, temperature, and pressure to predict payload performance.

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A Project Report for the Nasa Techrise Competition

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Abstract

Our experiment for the NASA Techrise Challenge aims to study vibrations and extreme launch environments on space launch vehicles. The purpose of our experiment is to gather data for vibrations for the UPA Spaceloft XL rocket, connect them to different factors of causation, and make conclusions which will allow engineers to accurately model the performance of payloads and prepare for spaceflight. We will use a variety of sensors like accelerometers, piezoelectric sensors, etc... to gather vibration data and specific frequency and amplitude values as well as other general launch sensors to achieve our goal. Our specific design has 9 electrical components taking up 101 mA and weighing a total of 40g.

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1 Introduction

Harsh deep-space conditions have damaged rockets and payloads for years and have caused some of the biggest catastrophes to spacecraft in the last few decades. Vibrations play a major role in this, contributing to the majority of failures early on in the space race, and are still incredibly difficult to predict or correlate to, especially with other factors like velocity, pressure, and temperature. Additionally, many different types of vibrations can severely damage a payload, for example, the Russian Proton Rocket failure in May of 2015, where the craft went out of control due to excessive, unpredictable engine vibrations.

When our team heard about the NASA Tech-Rise competition, we immediately started brainstorming different issues and problems with rockets, and rocket vibration was one of the first topics we researched. We found how little data there was analysis and prediction, which was one of the major reasons we decided to base our experiment on them. The purpose of our experiment is to gather data to analyze these vibrations and correlate them with different factors of motions, pressure, and temperature, to further our understanding of the rocket launch and in-space environment, which will allow engineers to accurately model the performance of payloads and prepare for spaceflight.

Figure 1: An image of vibration testing.

2 Background

2.1 Aerospace Vibrations affecting flight

From our research, we learned that vibrations have been a problem in past launches and can cause severe damage to structures. Vibrations can start out as unnoticeable but as they increase in magnitude, formations of cracks and fatigue in the main framework or reinforcing structures of the aircraft can be created. PCBs may break from reaching max strength (delamination of the board, fatigue of lead wires, or breaking completely). Air turbulence increases as the rocket ascends; unmanned aircrafts can usually withstand 15-30 Gs, while astronauts experience at most around 3 Gs. Components that are soldered on may also break due to the factors such as the source, intensity, and quality of the solder joint. Electrical wiring throughout the rocket is also vulnerable to wide vibrations and extreme motion. An example of this is the Japanese SS-520-4 which failed to reach orbit after a wire was worn out through abrasion due to excessive vibrations.

Figure 2: An image of the Japanese SS-520-4 rocket failure.

Vibrations also affect many payloads, especially sensitive ones like telescopes or other precise machines. Mirrors can be misaligned, sensors damaged, mechanical components compromised, or decoupling mechanisms misfired. In the aerospace industry, most payloads go through rigorous testing through a vibration-simulating machine. NASA uses many of their machines to test out their scientific payloads, such as the James Webb Space Telescope (JWST). By collecting more accurate measurements, especially on unknown vehicles like the UP Aerospace Spaceloft, we could further our understanding and make these simulations more accurate, precisely to solid motor sounding rockets.

2.2 Main Sources of Vibrations

The two main sources of detectable vibrations are:

1. (Engine) Thrust Oscillations
2. Aerodynamic Vibrations

2.2.1 Thrust Oscillations

Thrust Oscillation occurs by the burning of the rocket propellant in the boosters that come in the form of sinusoidal waves that travel up and down the rocket. These waves are a combination of different frequencies of vibrations that can change the predicted smooth liftoff of the rocket and can cause serious damage to the control system of the craft during liftoff to burnout. We predict to detect these vibrations from 0 to 200 seconds after liftoff at around zero to a hundred hertz with the max amplitude of these vibrations being around 1g.

2.2.2 Aerodynamic Vibrations

Aerocaustic Vibrations are caused by the turbulence that is generated when the rocket moves upward. This turbulence makes the rocket vibrate in chaotic ways. Usually, as speed increases, the rocket vibrations become more stable, leading to easily-detectable vibrations. This is because the rocket tends to be less affected by sudden speed/pressure changes at such high velocity. Our general prediction for these vibrations is to stay low and erratic during the rocket's subsonic period, stabilize and become larger from transonic to supersonic. We can't formulate a good conclusion on the hypersonic period because there isn't much experimental data in that period.

2.3 Other Factors of Vibrations

There are many other possible factors that could influence vibrations.

2.3.1 Pogo Oscillations

For example, Pogo oscillations are caused by combustion instability that causes the rocket to experience oscillating acceleration. This effect is significant in hybrid rocket motors, various solid motors, and large-scale liquid engines (ex. Rocketdyne F1, Saturn V S-IC).

2.3.2 Turbulence

Turbulence affects the vibrations because of disorderly movement of the rocket. It is when the airflow makes sudden shifts. Wind, storms, and objects near the rocket can cause this. There are different types of turbulence that can affect the rocket with these being wake turbulence, which is created behind the aircraft, clear air turbulence, which happens above 15,000 ft MSL from strong wind shear due to the jet stream (and other upper-level winds), thermal turbulence, which is when pockets of warm air descend as it cools down, frontal turbulence, which occurs when warm and cold fronts meet, mechanical turbulence, the process of air flowing over objects, mountain wave turbulence, when air flows down the leeward side of a mountain causing strong winds, and finally storm turbulence, which causes updrafts and downdrafts.

2.3.3 Propeller Noise

Propeller noise happens when the propeller rotates at high speeds which can make unsteady flow field pulsations. Our flow field is the distribution of density/velocity of the air around the rocket. These unsteady pulses cause vibrations because naturally the air wants to be uniform with the nearby surroundings, so it shakes the area around it causing the air molecules to shake around and vibrate the rocket. Engine noise is similar in concept to how it causes vibrations. The noise travels in waves that pass through the rocket and shakes the molecules and causes vibration.

2.3.4 Pyroignition

Pyroignition is used to ignite materials that are more difficult to ignite, such as thermites, gas generators, and solid-fuel rockets. When rockets use solid fuel rather than liquid fuel, something called ignition overpressure happens. This leads to vibrations that can damage nearby equipment on the launch pad, as well as the rocket itself. This shock is so powerful that it can cause fractures and can lead to failures in the launch. Ground vibrations due to the launch are caused by the exhaust steam which gets transmitted structurally to parts of the building near the ground and thus increasing the energy of the structure causing vibrations.

2.4 Predictions

We expect our data to reveal some key findings in the relationship between velocity, air pressure, flight phases, and vibration, the factors that influence these vibrations, the types of vibrations, and finally the frequency and amplitude of the oscillating vibrations. We expect vibrations to peak during the transonic region of flight due to aerodynamic forces shifting from subsonic to supersonic behavior. As is commonly known, the aerodynamics during transonic speeds are highly variable and unpredictable - air density and compressibility varies highly due to shock waves, expansions, and choked flow.

For the lower atmospheric flight phase, we expect vibrations to be substantially higher than it would be in the upper atmosphere, and we also expect vibrations to decrease once the rocket transitions to the coast phase. We're interested in finding out how increased velocity affects vibration levels + frequency, especially in high mach numbers.

We also want to investigate what will happen to the vibrations of the rocket at Max Q, the point at which the rocket is experiencing the maximum dynamic pressure. Based on documents from previous rockets, we believe that during Max Q, the rocket will experience greater than normal vibrations. For example, the Falcon 9, which experiences Max Q shortly after reaching supersonic speeds, has exacerbated vibrations during that region.

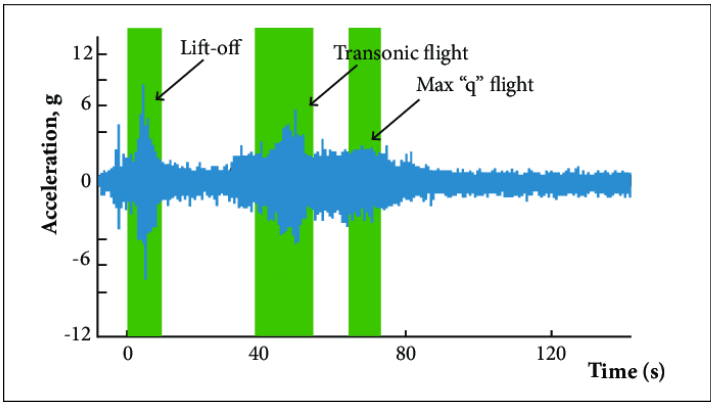

Figure 3: Vibration data from past flights.

Based on NASA data from past flights of common orbital launch vehicles, we expect vibration frequencies of sinusoidal oscillations (of acceleration) to be in the range of roughly 10-150 Hz, while random and shock vibration events to have frequencies in the kHz range. Therefore we will attempt to implement sensors for low and high frequencies, such as a condenser microphone as well as the vibration sensor.

3 Satellite Build

3.1 Sensor List

For our sensors, we chose:

- Adafruit BMP388 barometer to measure altitude at low altitudes (which is not imperative due to rocket telemetry backup)
- Adafruit LSM6DS33 + LIS3MDL 9-axis IMU to measure acceleration up to 16g, angular velocity in the x, y, and z directions, and magnetometer absolute orientation data
- KX134 3-axis accelerometer which has a +/- 64 g range to measure vibrations
- Teensy 4.0 development board as the processor
- SD Flash Memory Breakout Board for data storage
- TMP36 sensor to measure the temperature on four sides of the box

3.1.1 Sensor Info Sheet

Information from our Finalized BOM.

Item	#	Voltage	Amps	Dimensions	Weight
Total		3.3V	101 mA	4” by 4” by 8”	40g
Adafruit BMP388	1	3V - 5V	0.0034 mA	0.9” x 0.7” x 0.1”	1.2g
Adafruit LSM6DS33 + LIS3MDL	1	3 - 5V	1.7 mA	1.0” x 0.7” x 0.2”	2.3g
KX134 (Qwiic)	1	1.7 - 3.6V	0.148 mA	1.0” x 1.0”	2.33-5g
Teensy® 4.0	1	3-5V	100 mA	1.4” x 0.7”	10g
SD Flash Memory Breakout Board	1	3-5V	0.05 mA	0.8” x 0.7” x 0.1”	5-10g
TMP36 Temp Sensor	4	2.7-5.5V	0.05 mA	0.14” x 0.18” x 0.74”	0.2g

Table 1: Sensor specifications for our build.

3.2 Build Diagram

The sensors which are the IMU: LSM6DS33 + LIS3MDL. 9-axis, BMP388, and TMP36 along with the Teensy 4.0 Development board and Breakout board are placed onto the Breadboard inside of the box. This is connected to the middle using a horizontal plate. The flight simulator will be at the top of the box. The dimensions of the box are 4 by 4 by 8 inches. Here our are diagrams:

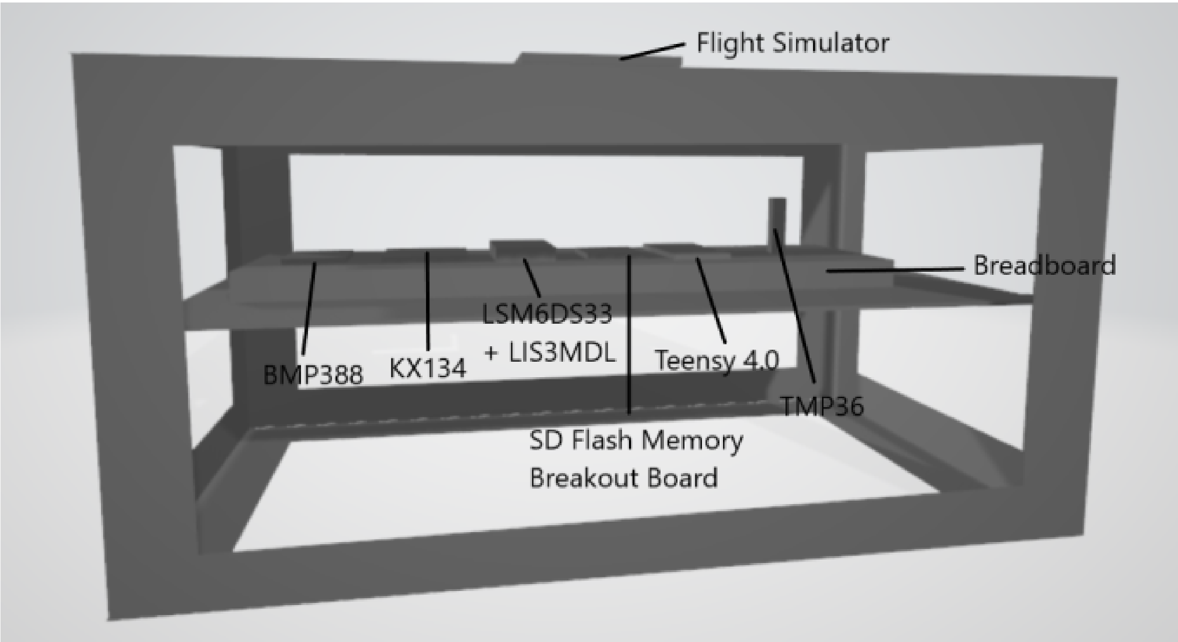

Figure 4: 3-D View.

3.3 Circuit Diagram

These are our wiring diagrams for our sensors, created with Autodesk EAGLE:

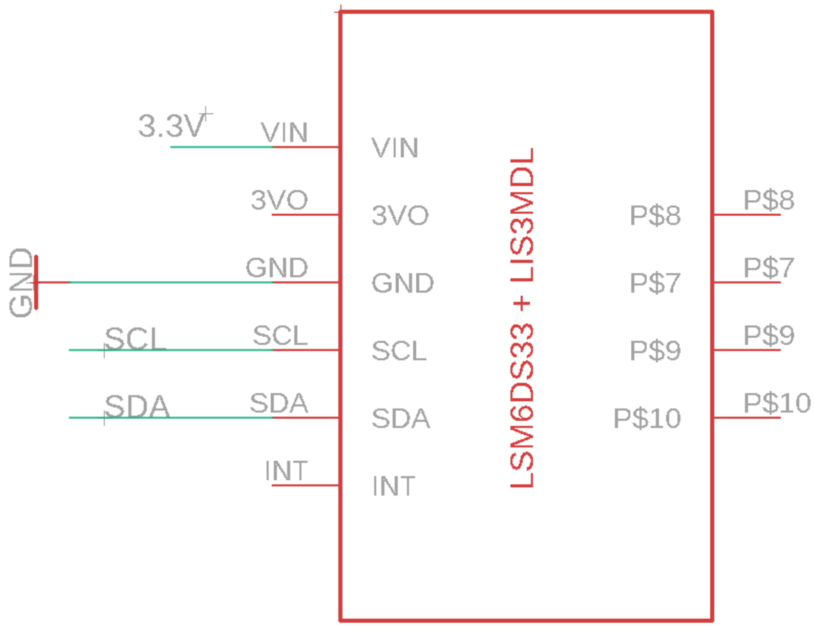

Figure 5: Our IMU.

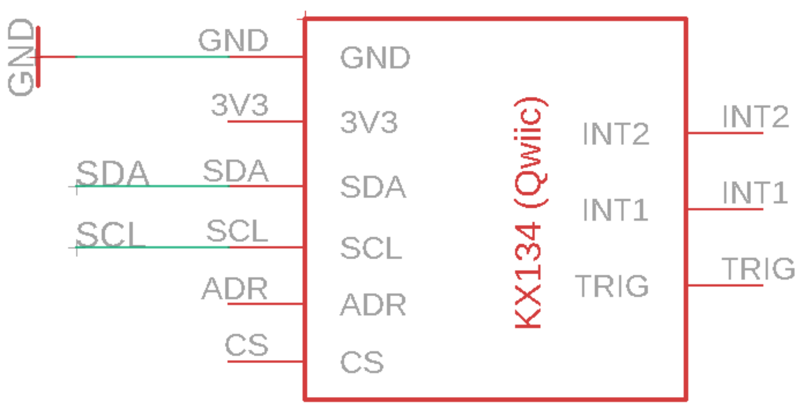

Figure 6: Our other accelerometer that has a sensing range of 64g.

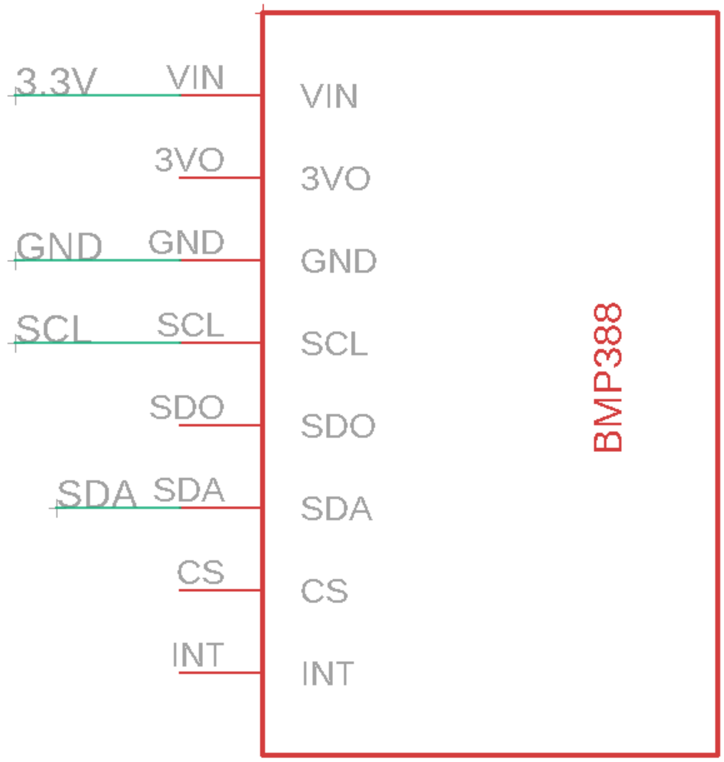

Figure 7: Our Altimeter.

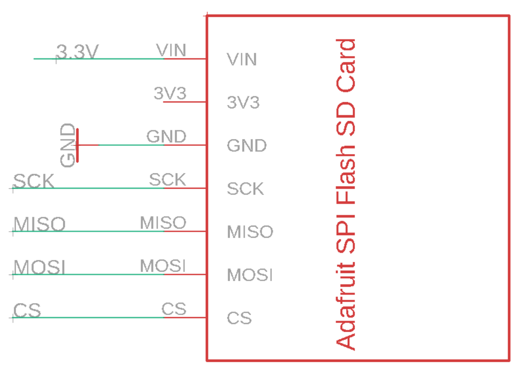

Figure 8: Our SD card.

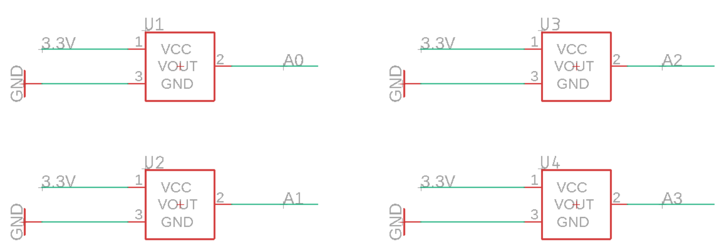

Figure 9: Our temperature sensors.

4 Data Analysis

Our methods of analysis consist of explaining how we plan to analyze the raw data collected and stored into our SD card by the sensors after the launch. As seen in the finalized BOM, the TMP36 (our temperature sensor) uses voltage outputs to transfer data, thus we found that the formula for converting these voltages into celsius was Temp in °C = [(Vout in mV) - 500] / 10. On the other hand, the majority of our breakout boards that we are planning to buy use I2C to communicate with the processor.

4.0.1 Brief I2C Explanation

I2C communication works by having 2 main pins one could connect - SCL (Serial Clock) and SDA (Serial Data), the SCL (Serial Clock) is the one which synchronizes data transfer between the devices on the I2C bus and its generated by the master device. In contrast the SDA (Serial Data) line carries the data. The data signal is transferred through 8 bit sequences, after a special start condition occurs, the first 8 bit sequence indicates the address to which the data is being sent. Following that sequence comes an acknowledge bit, after the first acknowledge bit in most cases comes another addressing sequence but this time for internal registers of the slave/periphral device. After that 8 bit sequence, follows another acknowledged bit. From that bit comes 8 bit sequences of data until the data is completely sent, then it ends with a special stopping condition.

4.1 Getting Data from Sensors

We would use I2C to communicate with the breakout boards containing the sensors, as pictured below on eagle we would connect each pin to the respective line and the breakout board would be sending data.

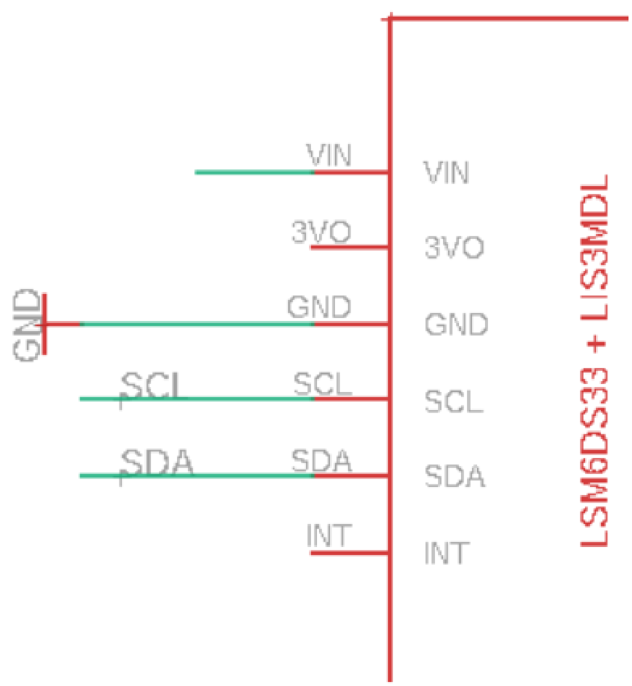

Figure 10: Example Connections

To use and collect this data, we would also need to use libraries provided from the public on github. Moreover, our team would be using Arduino IDE to code this.

To specify on collection vibration data, we would be using the method described above to communicate with the KX134 (our accelerometer that has a greater sensing range than the other one listed in the BOM) with I2C and use an existing library compatible to code with on Arduino IDE to communicate with it.

4.2 Analyzing Sinusoidal Vibrations

Sinusoidal vibrations oscillate in a wave-like motion, so what we really want isn't the vibration over time, it is the frequency of the vibrations. To do this, we can use something called a Fourier Transform; it will take in an acceleration vs time graph and output a frequency graph. We will probably use a Fast Fourier Transform for this task, because it can quickly discretely compute a frequency spectra from a given acceleration vs time function.

4.2.1 Fourier Transforms

Fourier transforms are a way to get a frequency distribution/spectra from an acceleration-time graph. It can transform a graph from the time-domain to the frequency-domain. For this, we will be using MatLab's Fast Fourier Transform calculator on various parts of our data. But how do Fourier Transforms' work?

To convert a time-domain to a frequency-domain, we must utilize a special property with circles. If we wind a sinusoidal time-graph around the center point of a circle, the average, center of mass point of the curve will mostly be close to the origin. However, when the curve is winded to the exact frequency of the sinusoidal, the average point moves farther away from the center significantly. Using this knowledge, we can take any graph and decompose the frequencies by winding it out on a graph and checking the "spikes" in the distance the average point is from the origin. This way, we can create a frequency spectra graph and see how the frequency of different vibrations change with respect to time, velocity, altitude, and other factors.

5 Project Timeline

Our current project timeline all the way until Apr 21, 2022

5.1 Mar 3, 2022

Bill of Materials The expectations we have for our bill of materials include the voltage, the current, the mass, and the dimensions of the component. In addition to these basic quantities, we expect the team members to link the webpage/provider that we can find the component(s) on, if the component is currently out of stock, the team member(s) would report back immediately. The bill of materials is absolutely imperative to our team's success.

5.2 Mar 8, 2022

Finish Project Report Paper Expectations of the research paper include concise and clear writing of the main points listed here. We expect the team members to accordingly finish their assigned roles for writing this paper by this time. This project report will serve to help team members better understand the entire project and help communicate our project plan with our NASA mentors.

5.3 Mar 10, 2022

Meeting with NASA and format paper with LaTeX We expect the team to finish the latex of the paper by the meeting and prepare a presentation for this meeting. This presentation will include what we have achieved so far (according to the timeline given by NASA), clarifications on the last meeting, and questions. Not finishing this by this date will be really disastrous, including a bad/unclear meeting leaving our NASA mentors really confused and misled.

5.4 Mar 13, 2022

Breadboard and Fritzing The team should by now be starting with ordering the parts, and understanding the breadboard basics with a youtube video or in person meeting. We should also be continuing to follow the milestones NASA set out for us.

5.5 Mar 18, 2022

Updating the report We expect team members to be finished updating the report with the current team status and what we expect in the future.

5.6 Apr 1, 2022

Making the board Finish the board with the materials we listed out in the BOM.

5.7 Apr 21, 2022

Present first prototype (breadboard) The expectations of this prototype include a working breadboard with all the ordered components from the BOM on it. We expect everyone to contribute to this prototype. The small milestones that we take to get here include to build the prototype on the Fritzing App and to make everyone understand how to use a breadboard.

[Cor02] [AWH+13] [you05] [AM05] [Aut21] [Bha22] [CMN] [Con09] [CFB+02] [epi22] [Har17] [HFS70] [Jai16] [WAZ+19]

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