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# Hybrid Rocket Engine Ignition and Control

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# Hybrid Rocket Engine Ignition and Control

Honors Thesis for Electrical Engineering

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## Introduction:

In order to successfully launch and control a rocket, accurate timing and system performance measurements are necessary. To make these measurements, a control system is required to take input data and execute its commands to accurately guide the rocket to the targeted location. Utilizing altimeters and Inertial Measurement Units (IMUs), a projected apogee can be determined by using kinematic equations relating to the current state of the rocket. The flow regulation system within the rocket is used to control the flow of a fuel through the combustion chamber allowing for thrust to be produced and the rocket to take off. For this to happen however, the fuel must be released through the combustion chamber at a specific time in order to be successfully ignited and must be stopped at a precise time to reach the desired apogee. Without these factors working in conjunction with each other, the rocket is unable to perform to its peak performance.

For the purposes of this project a control system was designed to allow for a hybrid engine rocket to successfully ignite and accurately target a pre-specified altitude. This rocket was designed and built through the student run organization, Students for the Exploration and Development of Space (SEDS), for the purpose of competing in the Spaceport America Cup in New Mexico. According to guidelines set by Spaceport America, rockets will fall into categories dependent upon their design and propulsion methods. The students at the University of New Hampshire were supposed to be competing in the Student Researched and Designed hybrid engine, 10,00ft. apogee class. Therefore, the rocket is designed to accurately target a height of 10,000ft. However, due to the effects of COVID-19, all actions in regards to the Spaceport America Cup were cancelled and continuing work on the rocket was halted.

The initial project goals that had been identified in order for the UNH team to compete included the design of a flow regulation system that can efficiently toggle between three states; no flow, flow, and emergency abort. In addition, a subsystem that toggles between flow and no flow to adjust the rocket's velocity and alter its apogee needed to be designed. The latter system is to be wirelessly ignited from distances up to 500 ft, as well as be tracked via GPS signal, such that the rocket may be successfully located upon its descent. These goals were in the pursuit of designing a system that is robust and capable of successfully launching a rocket to 10,000ft. at the Spaceport America Cup in June of 2020.

## Background:

A hybrid-propellant rocket engine is a rocket that utilizes two different phases of propellants, one being a solid and the other being either a liquid or a gas. These types of rockets manage to take away some of the disadvantages of solid rockets such as propellant handling. While also decreasing the mechanical complexities that come with liquid fuel rockets. Due to these factors, hybrid rockets have the tendency to be safer during failures than the other two types.  These rockets are designed in such a way that the ignition turns off just before the oxidizer is released, allowing for the pressure within the combustion chamber to build up. Once this happens the oxidizer is sent to the combustion chamber via the nozzle and the injector plate, igniting the solid fuel and creating the thrust required to launch the rocket. The primary focus of this project is to design the system that will allow for a successful launch of the rocket.

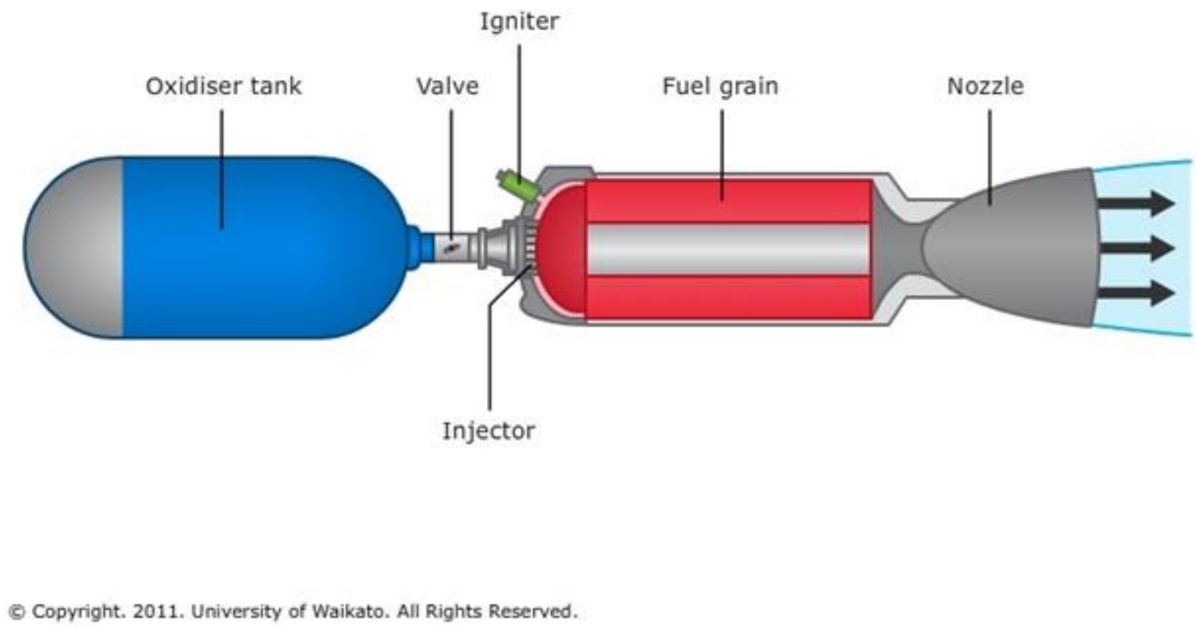



Figure 1: Hybrid Rocket Engine Diagram

In order to accurately control the rocket so that it reaches a specified apogee, (the highest altitude reached by the projectile), sensors will be used on board the rocket, specifically an altimeter, and a 9 degree of freedom (9 DOF) IMU sensor. An altimeter is a device used to determine the altitude of an object. These sensors measure the atmospheric pressure and compare the value to a preset value with a known altitude. This allows for the current altitude of the device to be determined, with its resolution dependent upon the sensitivity of the sensor.

The second sensor being used is an IMU, which combines accelerometers, gyroscopes and magnetometers. These sensors are capable of measuring the device's angular rate and orientation. IMU devices are most often used in aircraft for attitude and heading reference, including in unmanned aircraft, and spacecraft. When used in conjunction with each of the sensors an IMU is capable of measuring how an aircraft is moving through space in reference to the earth. Depending upon the sensor that is used an IMU can have differing degrees of freedom, directions in which it is capable of reading changes, typically this could be 6 or 9 degrees of freedom. For the purposes of this project 9 DOF are used, which include the sensing of up, down, left, right, forward, back, roll, pitch and yaw as shown in Figure 2.

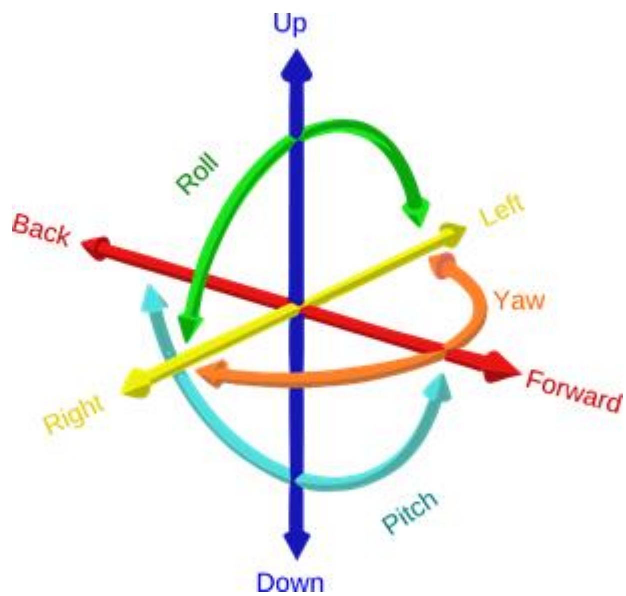



Figure 2: The 9 Degrees of Freedom Measured by the IMU

Within the flow regulation system, 24VDC, pneumatically actuated solenoid valves were used. A solenoid valve is an electromechanical valve that typically has two states, open or closed, with no capabilities to be partially open. They come in two types either normally open or closed and toggle between open and closed via an electrical input. For the pneumatic type of valve, the physical opening and closing mechanism is performed by some form of a pressurized gas, which is controlled by a smaller valve that is opened with an electrical signal. These types of valves are commonly used in situations in which a high-pressure fluid or gas is being run through the main valve.

## **<u>Methods:</u>**

The design of the entire system can be broken down into five separate parts, the ignition system, mechanical-flow regulation system, the apogee-targeting system, wireless communications and the launch control module. These subsystems were each integrated into the main system at differing phases, to allow for testing of the combustion chamber and nozzle, specifically to determine the thrust capabilities for the hybrid engine. This also allowed the prioritization of the ignition, mechanical flow system design, and wireless communications testing over the apogee targeting system, as ignition and the control of the flow system are considered mission critical for the launch. Whereas, the apogee targeting system is designed to be used only during a firing of the rocket and not for testing the thrust capabilities of the rocket. As this project is being conducted through UNH SEDS, this project is dependent upon other teams for its successful operations.

## <u>Design Documentation:</u>

The design of this project took place in multiple stages. The first being utilizing the system that was in place over the 2018-2019 year, for the control of the rocket. During this stage, research was being done into improvements that needed to be made from the previous system as well as running the old system to try and get thrust data from the rocket engine.

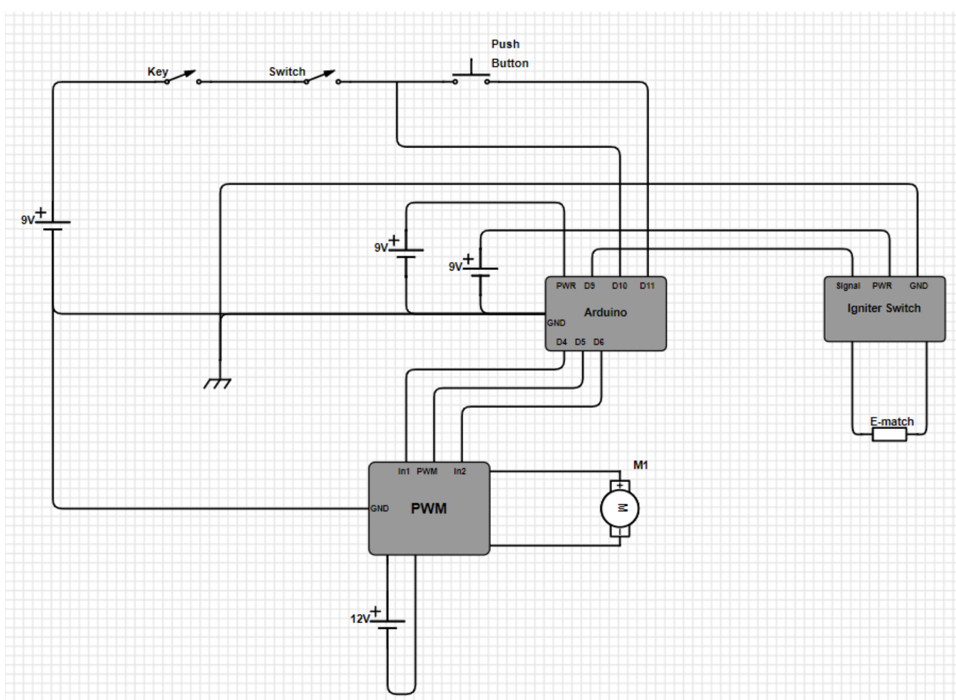



Figure 3: V1 Hardwired Flow Regulation System Block Diagram

The next stage of the design process was developing the new system with increased range, and reliability. This stage was implemented into testing procedures for the hot fire testing and the old system was phased out.

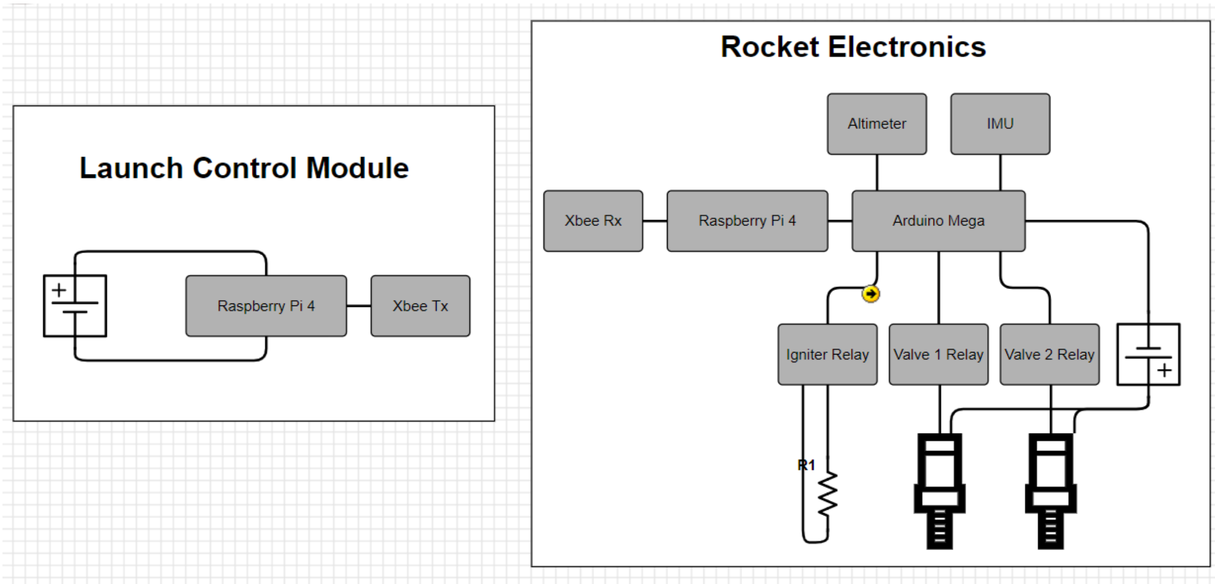



Figure 4: Wireless System Block Diagram

## Tests and Results:

Each component in the rocket was tested in isolation before being added to the larger system. The XBEE wireless transmitters were tested to ensure that they could transmit the 300 meters needed for competition requirements. The XBEE transmitters were first tested while connected to computers via a USB cable and reached about 300 meters before running into issues with line-of-sight. When line-of-sight was lost between the two transmitters, the order in which the bits were sent did not correspond to the order that the bits were received. The transmitters were tested again when connected to the raspberry PI 4 and the PI 3. The distance was measured with a rangefinder. There were no transmission errors up to 350 meters.

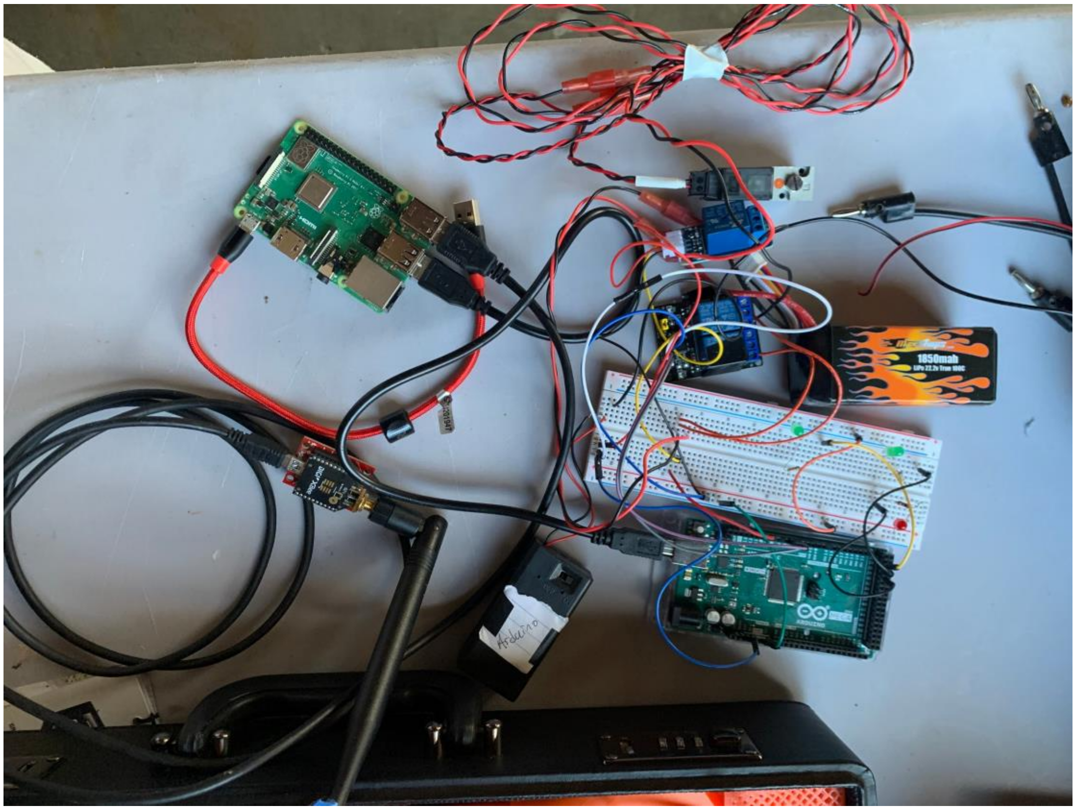



Figure 3: Current Flow Regulation Electrical Systems

The flow regulation system was designed using 24VDC pneumatically actuated solenoid valves, supplied by Swagelok. These valves were used to control the flow of oxidizer from the nitrous oxide tank to the combustion chamber as well as to dump the fuel, should a launch be aborted. These valves were powered by a 24V Lipo battery with an 1850mAh capacity and were actuated by using a pressurized gas.  The valves were opened whenever a 24V supply was run through the valve, thus requiring an electrical switch to be used to prevent the valves from being constantly open. For this problem, relay switches were utilized for their ease of use and low weight. These relays were then controlled to close the circuit with the valves upon receiving a signal from an Arduino, which controls all actions that will be within the rocket.

An Arduino Mega is being used as the control center on the rocket, due to its open source foundation and ease of use. The Arduino was coded to receive a signal from the wireless communication system, through a serial port connection. The Arduino was set up to receive three separate commands and run through different sequences dependent upon the command. The most commonly used command was the Launch command, which will through the ignition sequence, including firing the igniter and, then after 1s sending a signal to open the valve through the combustion chamber. The second command is the Abort Launch command which opens the valve that did not go through the combustion chamber. This command is only used if the launch of the rocket needs to be completely aborted and is done to prevent any misfire while launch pad personnel are at the rocket, by dumping all of the oxidizer out of the side of the rocket. The final command is, Halt, this command will override the Launch command and shut all valves and stop all oxidizer flow within the rocket.

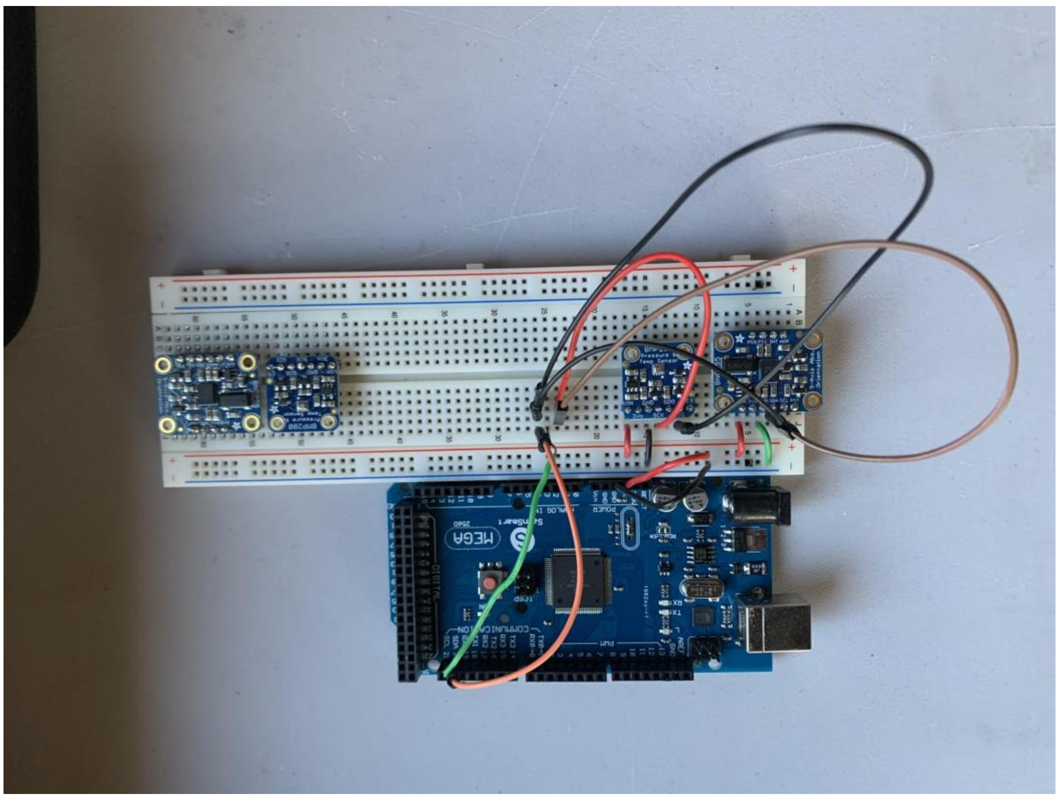


Figure 4: Apogee Prediction Hardware

Within the apogee prediction system, two sensors are being used in conjunction with an Arduino Mega. This system is currently capable of reading the current altitude, orientation, and acceleration. This data is used to determine the approximate apogee of the rocket, should all thrust be stopped at that exact moment. However, before this set-up is fully implemented within the rocket, it should be tested in a launch of a rocket with a consumer grade, altitude logger, such as the Telemega. Therefore, this system cannot be fully implemented into the rocket until after a full-scale launch next year.

A Raspberry Pi 4 is used as the primary computer within the launch control module. This processor runs the Altus Metrum software, to generate the GPS location of the rocket, such that its location will be known during its flight, and aid in the recovery process of the rocket. The launch control module is also the home to all wireless transmission to the flow regulation system and is capable of performing all commands within that system through the use of switches as well as a software-based back-up ignition method.

Figure 5: The Launch Control Module

The system was tested extensively during live hot fire and cold fire tests of the engine. Due to issues with propulsion sometimes not reaching ignition, a halt feature was implemented such that the flow of the propellant through the chamber could be halted after it had been opened. This feature was added as a cost saving measure in case a test needed to be stopped by saving fuel. Every hot fire worked flawlessly for the avionics system. The system was always tested minutes before the hot fire to ensure the system worked. During the March 12 hot fire, an issue with the impinging plate caused an aluminum fire where the side of the engine ruptured. After a few seconds of runaway, the halt button was pressed, flow was stopped, and the fire subsided. The halt function saved components and some NOS.

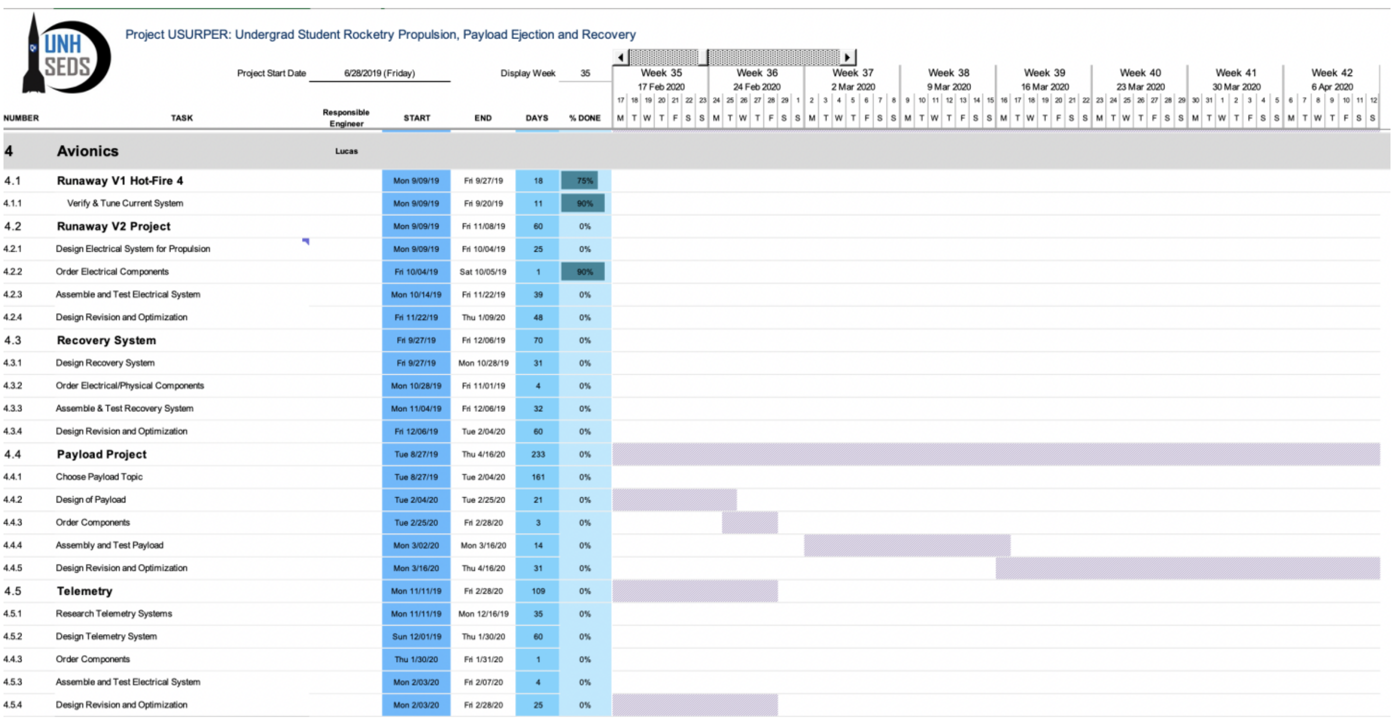
## Bill of Materials:

| Part | Manufacturer | Part# | Supplier | Quantity | Cost |
|---|---|---|---|---|---|
| Relay Module | Tolako | | Amazon | 6 | 37.72 |
| Screen | | | Adafruit | | |
| Cord | | | Adafruit | | |
| Keyboard | | | Adafruit | | |
| Zigbee Modules | | | Mouser Electronics | 2 | 73.11 |
| Switchkey | | | Digikey | | 42.03 |
| Raspberry Pi 4 | Raspberry Pi | | Amazon | 1 | 61.70 |
| Briefcase | Solo | | Amazon | 1 | 54.67 |
| Xbee Explorer USB | SparkFun | | SparkFun | 2 | 58.56 |
| Indicator Valve Switch | SwageLok | | SwageLok | | 116.46 |
| Flow Regulation | Swagelok | | SwageLok | | 991.22 |
| IMU | | | Adafruit | | 77.73 |
| 2.4 GHz Antennas | ChangHong | DA-24-01 | Adafruit | 2 | 25.73 |
| HDMI Cable | Tartan | | Amazon | 1 | 5.94 |
| 22.2V Lipo Battery | MaxAmps | | MaxAmps | 1 | 109.99 |

| | | | | | |
|---|---|---|---|---|---|
| Altitude Sensor | Bosch | | Adafruit | 1 | 24.40 |
| Xbee/Arduino Shield | Sainsmart | | Sainsmart | 1 | 30.99 |

Due to the sponsorship of this project by UNH SEDS, most of these costs were covered through the funds of the group.

## Gantt Chart:




| NUMBER | TASK | Responsible Engineer | START | END | DAYS | % DONE |
|---|---|---|---|---|---|---|
| 4 | **Avionics** | Lucas | | | | |
| 4.1 | **Runaway V1 Hot-Fire 4** | | Mon 9/09/19 | Fri 9/27/19 | 18 | 75% |
| 4.1.1 | Verify & Tune Current System | | Mon 9/09/19 | Fri 9/20/19 | 11 | 90% |
| 4.2 | **Runaway V2 Project** | | Mon 9/09/19 | Fri 11/08/19 | 60 | 0% |
| 4.2.1 | Design Electrical System for Propulsion | | Mon 9/09/19 | Fri 10/04/19 | 25 | 0% |
| 4.2.2 | Order Electrical Components | | Fri 10/04/19 | Sat 10/05/19 | 1 | 90% |
| 4.2.3 | Assemble and Test Electrical System | | Mon 10/14/19 | Fri 11/22/19 | 39 | 0% |
| 4.2.4 | Design Revision and Optimization | | Fri 11/22/19 | Thu 1/09/20 | 48 | 0% |
| 4.3 | **Recovery System** | | Fri 9/27/19 | Fri 12/06/19 | 70 | 0% |
| 4.3.1 | Design Recovery System | | Fri 9/27/19 | Mon 10/28/19 | 31 | 0% |
| 4.3.2 | Order Electrical/Physical Components | | Mon 10/28/19 | Fri 11/01/19 | 4 | 0% |
| 4.3.3 | Assemble & Test Recovery System | | Mon 11/04/19 | Fri 12/06/19 | 32 | 0% |
| 4.3.4 | Design Revision and Optimization | | Fri 12/06/19 | Tue 2/04/20 | 60 | 0% |
| 4.4 | **Payload Project** | | Tue 8/27/19 | Thu 4/16/20 | 233 | 0% |
| 4.4.1 | Choose Payload Topic | | Tue 8/27/19 | Tue 2/04/20 | 161 | 0% |
| 4.4.2 | Design of Payload | | Tue 2/04/20 | Tue 2/25/20 | 21 | 0% |
| 4.4.3 | Order Components | | Tue 2/25/20 | Fri 2/28/20 | 3 | 0% |
| 4.4.4 | Assembly and Test Payload | | Mon 3/02/20 | Mon 3/16/20 | 14 | 0% |
| 4.4.5 | Design Revision and Optimization | | Mon 3/16/20 | Thu 4/16/20 | 31 | 0% |
| 4.5 | **Telemetry** | | Mon 11/11/19 | Fri 2/28/20 | 109 | 0% |
| 4.5.1 | Research Telemetry Systems | | Mon 11/11/19 | Mon 12/16/19 | 35 | 0% |
| 4.5.2 | Design Telemetry System | | Sun 12/01/19 | Thu 1/30/20 | 60 | 0% |
| 4.4.3 | Order Components | | Thu 1/30/20 | Fri 1/31/20 | 1 | 0% |
| 4.5.3 | Assemble and Test Electrical System | | Mon 2/03/20 | Fri 2/07/20 | 4 | 0% |
| 4.5.4 | Design Revision and Optimization | | Mon 2/03/20 | Fri 2/28/20 | 25 | 0% |

The team at UNH SEDS closely adhered to the timeline above in order to meet all competition and academic deadlines.

## **Ethical Consideration:**

Throughout this project the team has upheld the Engineering Code of Ethics within the design and construction processes. First, and most importantly, the safety, health, and welfare were kept in mind to ensure a design that would not put any individual at risk. When working through the design process electrical components were chosen and implemented with safety checks such as switches, LED lights, and keys, in order to supply users with knowledge of the status of the rocket. Prevention of unauthorized or premature launches was a major consideration when designing the avionics bay and launch control module in order to maintain the safety of the public.

To make certain the design and construction processes were completed properly, and within the scope of the team member's competences, components and programs were chosen based on research done. Programs and components used were within the scope of education for individual team members. In cases where some concepts needed more clarification, outside resources such as research databases, university educators, and other professionals to guarantee the design and construction was consistent with the skill level of team members.

Team meetings were held open to the public in which updates were accurate and objective. All team members were informed of any issues and successes to make sure all announcements regarding the progress of the project were truthful in the status of its design and completion. Lastly, team members maintained responsibility and professionalism throughout the progress of the project. All purchases were recorded and confirmed with the advisor to prove financial responsibility and avoid unnecessary purchases. The team treasurer also maintained a record to regulate the spending of team funds. Workspaces, such as the lab and launch areas, were acquired lawfully and ethically with proper permissions from owners.

Engineering Code of Ethics

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.

5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

## Safety:

Due to safety standards that were put in place by Spaceport America Authorities, the rocket was designed in order to meet these guidelines. This includes the use of three distinct actions to be taken in order to launch the rocket. Adding safety features, such as LEDs or buzzers to the rocket and launch control module that show when the certain parts of the launch sequence are live and capable of being fired.

Other safety precautions are needed to be put in place for testing of the rocket engine. These include going to a designated site in Lee, NH to test the engine, working in partnership with the UNH police department to ensure safety guidelines are met at each hot fire test. As well as all personnel at launch maintaining a distance of over 150ft from the rocket engine during the test fire, being under protective cover, and wearing suitable personal protective equipment (PPE) during set up.

## Contribution of Group Members:

Thomas Pham - For the project Thomas has been focusing on the ignition system of the Hybrid Engine Rocket as well as the power sources of the flow regulation system and launch control module. This portion of the overall project is about the remaining 10% of it. The ignition system is about 95% complete as there is still testing that needs to be performed to ensure that it is operating correctly for launch day. Although this portion is a small factor in the overall project, it is one of the most important parts and relies on all the other electrical components such as the launch control module and flow regulation. If the overall ignition system fails, then the whole project fails as the rocket would not be able to launch. Work for this section of the project has been in close affiliation with the flow regulation and wireless communication projects.

The work on finding the correct amount of power needed to supply the launch control module, as well as the flow regulation while referencing the restrictions and requirements for the competition. The work done in this section was primarily research based and focused on finding the correct power supplies to be used for the project.

Megan Johnson - Megan's contributions to the SEDS project have largely revolved around the Launch Control Module, which was completed and 30% of the overall project. This includes physical construction of the module (installing 3D print for base, installation of screen, LEDs, and manual switches) and connecting inside components. A cold fire test was run to ensure the wireless communication coming from the control module was working correctly as explained previously and ensured the communication could work across 350 yards using the XBee's and a rangefinder. Work was done to integrate the XBee communication into the Launch Control Module to ensure all control is centralized from the module. The next step was finalizing the placement of components and wiring inside the module in order to gain a better idea of placement for a wiring diagram and to ruggedize the system. Work with the real time feedback would have been recorded with the use of TeleMega and Altus Metrum software that has been downloaded onto the Raspberry Pi if not for the effects of COVID-19 halting testing.

Ben Letourneau - So far this year work has mainly been focused on the flow regulation system of the rocket. This entails the design of the circuit that will control the solenoid valves to regulate whether or not the oxidizer is going through the combustion chamber. The work done on this section of the project included wiring the solenoid valves and Arduino together, as well as coding the Arduino to open and close each of the relays at appropriate times. This system is currently operating and is wirelessly controlled through the use of the transmitters. The current flow regulation setup is being used to conduct hot fire tests to determine engine data. As of this point the system is capable of igniting the engine and beginning the flow of oxidizer through the combustion chamber and venting the oxidizer, per competition regulations, out the side of the rocket, without having oxidizer going through the combustion chamber. Within the flow regulation system, an Arduino is acting as the brain, dependent upon the signals that it receives from the Launch Control Module. The script that is running on the Arduino has been completely finished and can be modified depending on the needs of the testing. This portion of the project is approximately 25-30% of the project on the whole.

The other portion of the project that has been worked on is the altitude projection algorithm that will be running in real time on the rocket to determine what the apogee of the rocket will be, as well as simulating the rocket's flight in MATLAB and Simulink. This system is composed of a pressure sensor and IMU, to determine the altitude, velocity and orientation of the rocket. This system is dependent upon thrust data that comes from the upcoming hot fire tests. The work that has been conducted on this section includes the wiring of the sensors to the Arduino and the corresponding coding to read the altitude and acceleration of the sensors. Other work that has been completed in this section is the derivation of an equation with the inputs, altitude and velocity, to calculate the highest altitude that the rocket will achieve. Currently, the two sensors are reading the current altitude and the orientation of sensors.  These sensors will soon be integrated into the whole system allowing the rocket's thrust to be controlled by its projected altitude. This project is about 5-10% of the total project.

Trevor Blampied - Trevor has worked primarily on the launch control module with regards to the Xbee wireless communication aspect of launching the rocket. The wireless communication begins when the circuit is closed with a key turn and a switch flip or a button press to abort. This connection goes to the IO pins of our raspberry PI 4 which then goes to the transmitter Xbee then to the receiver Xbee to a RaspberryPi 3 in the rocket and finally to an Arduino to activate the Swagelok valves which Ben was primarily working on. The Xbees were not functional out of the box so a new firmware had to be flashed onto them in order to achieve functionality. Additional roadblocks were reached when the Xbees were discovered to have a 4 foot range without the antennas attached. After antennas were purchased, the Xbee range was tested in an ideal scenario using XCTU, the Xbee software, with two computers. The Xbee range was later tested with the Raspberry Pi's and no difference was identified. In addition to the physical launch system, a virtual one was also built that can be operated via the Raspberry Pi with a mouse and keyboard.

Avionics Team Contribution - This portion of the project accounts for roughly 30% of the overall project and has many overlaps with the work of others. Overall accomplishments include:

- Completion of Raspberry Pi set up

- Launch, halt, and abort system design and construction
- Xbee wireless communication
- Flow regulation through the Arduino and solenoid valves with use of relays
- Launch Control Module design and construction
- Altitude projection algorithm with a pressure sensor and IMU

## Conclusions:

The electrical engineering team of 2019-2020 SEDS was able to successfully design and build a working wireless ignition and flow regulation system for the hybrid rocket. However, the effects of COVID-19 have prevented the completion of the project and as a result, final implementation of the electronics into a fully operational rocket were not achieved. Though there is significant room for improvement, the wireless ignition system worked flawlessly in every cold fire and hot fire test to date. The system is straightforward to set up, so someone with minimal electrical engineering experience would be able to launch the rocket.

## Recommendations for Future Efforts:

Due to the effects of COVID-19, efforts on the completion of this project were suspended, as well as the cancellation of the Spaceport America Cup. This is primarily due to the inability to access the necessary equipment to continue progress upon the majority of the project. This in turn means that there is significant amounts of work to be completed in the future in order to be able to compete in the future at Spaceport America.

The main areas that will need to have work done will be in the ruggedization of all systems throughout the rocket as well as the launch control module. Other areas that have the potential for growth would be in the development of a payload within the rocket, as well as advancements in the apogee projection system, and overall improvements within the electronics on board the rocket.

Another area for future efforts is the connections within the rocket from the PI3 to the Swagelok valves. A custom 6-conductor cable with varying gauge sizes was briefly sketched up but was never formalized and requested from New England Wire.


## Acknowledgements:

We would like to say thank you to all those who have helped in the development and construction of these electrical systems. Especially to the members of the University of New Hampshire's SEDS organization, and to the Electrical and Computer Engineering Department. We would also like to thank Dr. Chamberlin for his help and input on this project.

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