Preliminary Design Report

University of Wisconsin - Platteville

Pioneer Rocketry

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Executive Summary

This year's challenge involves creating a roll control system that is capable of both holding a specific orientation, and orienting roll to any requested heading. This challenge has brought the team to looking at different airfoil designs, along with advanced feedback linearization control algorithms. A lot of the design aspects required going to professors for help, this is where we got the idea of putting airfoils on the control fins, instead of having normal control flaps.

A professor suggested the use of NACA00** airfoils. These airfoils do not produce lift unless the angle of attack is more than 0 degrees. Taking advantage of the lift generated from airfoils allows our design to be more agile than simply using fins with square cross sections. These fins are then connected to high torque HiTech metal gear motors. These motors allow us to be confident in their ability to orient to the desired positions.

The student developed electronics payload consists of a Teensy 3.6 development board. The sensors present include a 9 Degrees of Freedom sensor, an altimeter, and 2 pitot tube pressure sensors. One pitot tube sensor is tuned for low pressures to accurately measure slow speeds all the way to apogee. The Teensy 3.6 was chosen because of its fast processor speed at 180 MHz. This speed is more than enough to run all of the various tasks the avionics need to manage.

Grant Oberhauser, 2018 MRL Student Lead

Rocket Design

Airframe Specifications

The airframe of the test rocket was designed to be rugged to allow for “snappy” active roll control, and spacious for the various electronics packages needed (servo control, microcontroller processing Pitot tube, accelerometer, and barometer data, and power). In accordance with this, a 4” body diameter was chosen to mount servos without spatial conflict at the base of the rocket between the fins and motor tube. The servos are mounted via four bolts each through the body tube. A symmetric control horn attached to the servo protrudes through the side wall and attaches to the control fins via two 2.5” bolts going through the fins parallel to their axes of rotation. There are only two control surfaces and two static fins alternating around the rocket’s bottom section.

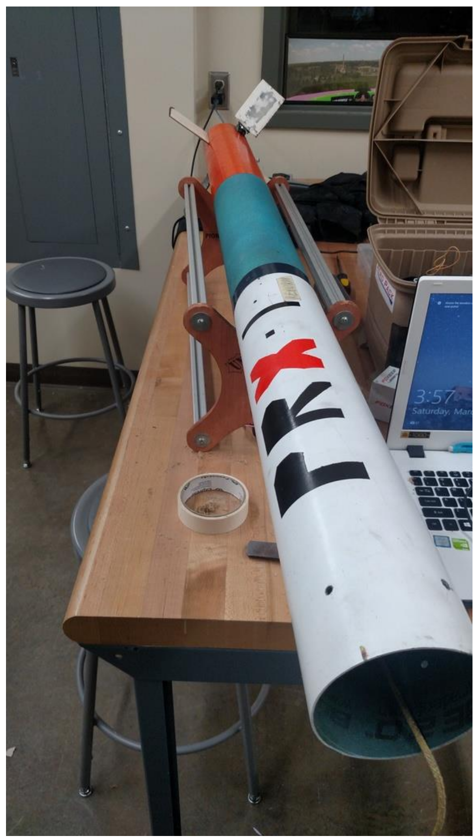

Figure 1: Completely assembled rocket (except for the nose cone). Note there are only two control fins present.

It is worth noting that the rocket is purposefully heavy to keep altitude low at our test launch site (limited to 3500 ft), and to keep speed relatively low (< Mach 0.7) to reduce forces on the servos and maximize effectiveness of our airfoil shape. The airfoil shape is NACA-16-012 with a 100 mm cord. This shape is symmetric and will only produce lift when it has an angle of attack greater than 0 degrees. To prevent the rocket from stalling, the angle of attack is limited to ± 5 degrees from the central axis of the rocket. Each airfoil was made by taking 1/4 inch–thick sections of maple wood, laser cutting sixteen identical airfoil shapes with alignment holes, and epoxying them together to form a 4 in (100 mm)-wide airfoil.

There are coupler sections of the rocket, as it was designed to be dual-deploy, which will be explained in detail in the recovery system section of this report. The forward-most coupler will house all the electronics mentioned above. The bottom coupler will simply contain the wires running from the servos to the main electronics bay. Upon ejection, the servo connections will also easily separate.

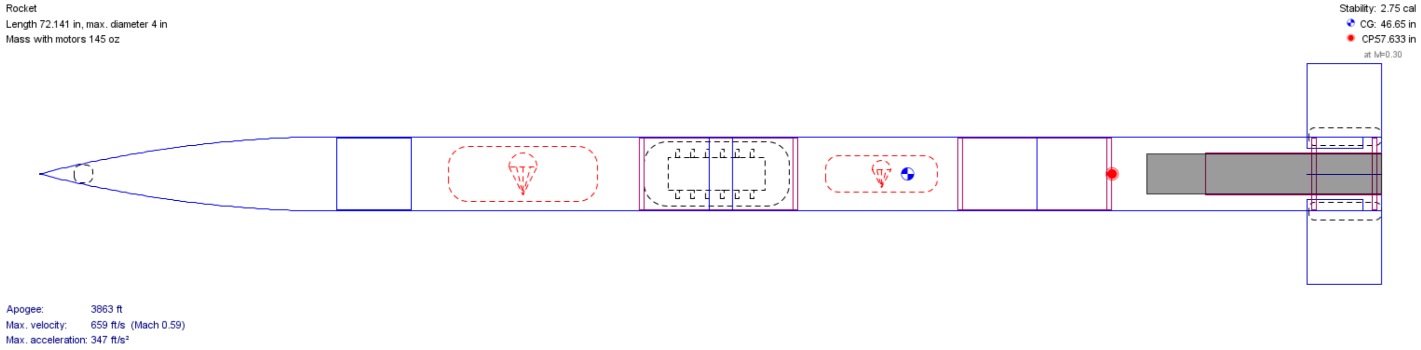

Figure 2: The design of the test flight rocket. CP and CG are at 46.65"and 57.63", respectively. This leads to a high stability of 2.75 Cal with the J360 loaded. The rocket is 72" long and has a mass of 4.1 kg.

Fin Construction

While brainstorming ways that symmetrical airfoil fins can be constructed, many ideas came to mind. These included CNCing nylon, injecting fiberglass into a mold, and even wrapping a plywood skeleton in fiberglass. However, the simplest approach won over. The fins on the initial test rocket are comprised of 16 slices of 1/4 inch maple epoxied together. This is the strongest, lightest, and fastest way found to fabricate fins. The other methods failed in the end due to either being too weak, or too slow to fabricate. In every airfoil, there are two small holes used to align the slices before epoxying. The slices are then epoxied and clamped until they are dry. After the epoxy has completely hardened, the fins are sanded to a smooth finish.

Figure 3: Freshly epoxied fin.

Propulsion Specification

The propulsion system required for this competition has a very strongprominent focus towards maximizing the amount of time between burnout and apogee. In the past, Pioneer Rocketry has employed the use of a K2045 Vmax motor because of its excellent burn time, at only 0.7 seconds, coupled with its outstanding impulse. However, this competition limits teams to a maximum of J-Class motors. So, the obvious choice is the J1520, another Vmax motor. Logistically, however, using this motor is nearly impossible because of the ridiculously short supply. Therefore, the next best motor is the CTI J360 Skidmark, not only because of its sparky goodness, but also because of its relatively short burn time of 2.8 seconds. Open Rocket simulations indicate a 14.6 second time to apogee. This allows a maximum of 11.8 seconds of control time. The J360 also far exceeds the flight limit imposed by the competition, soaring to 3860 feet. We also did not want to use an Aerotech motor, because we have more experience with, and parts for, CTI based propulsion systems.

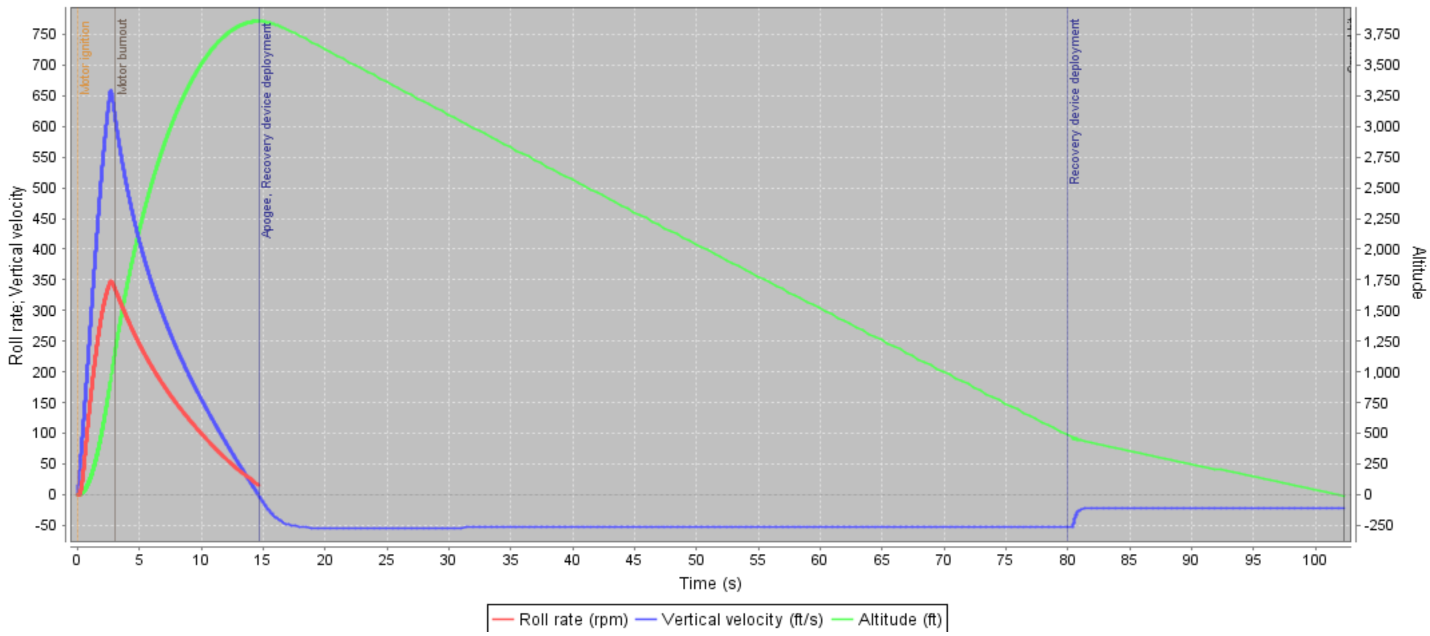

Figure 4: Open Rocket simulation of Roll Rate, Altitude, and Vertical Velocity vs Time. The fin cant is set to a fixed 5 degrees in this simulation. The rocket can spin up to 350 RPM.

For the initial test flight, the J280-SS motor has been chosen because it provides enough thrust to get us close to 3000 feet of altitude in about 14 seconds with a relatively short burn time of 2.5 seconds. The difference between apogee and burnout is key, as it will allow us to have ~10 s of orientation control before the rocket slows down and our airfoils cannot produce enough lift to generate a torque to overcome the inertia of the rocket. The motor will also propel the rocket no more than Mach 0.5, which, again, will allow our airfoils to be effective without generating too much force on the fins and servos themselves.

Recovery System

The rocket has a dual deployment recovery system. Deployment is controlled by two PerfectFlite StratoLogger SL100s. The first separation will be a 24 inch drogue chute deployed from below the central electronics bay. The primary StratoLogger will deploy drogue at apogee, and the secondary

StratoLogger will deploy one second later. The second separation will be a 52 inch main parachute that will deploy from the nose cone. The primary StratoLogger is set to deploy main at 700 feet with the back-up deployment at 500 feet. The chute combination used for this rocket ensures a touch down speed of 21 feet per second.

Avionics Specifications

The avionics section is responsible for managing the active roll system, interfacing with sensors, and sending and receiving telemetry data. A system was needed that could fulfill all those requirements elegantly. Extra space was also needed for the commercial altimeter, which is treated as a separate entity with its own power source. This determination was made to be in compliance with internal safety codes of Pioneer Rocketry. Non-commercial flight computers and commercial altimeters should have separate power sources, in case of unforeseen electrical problems that might jeopardize the safety of the rocket.

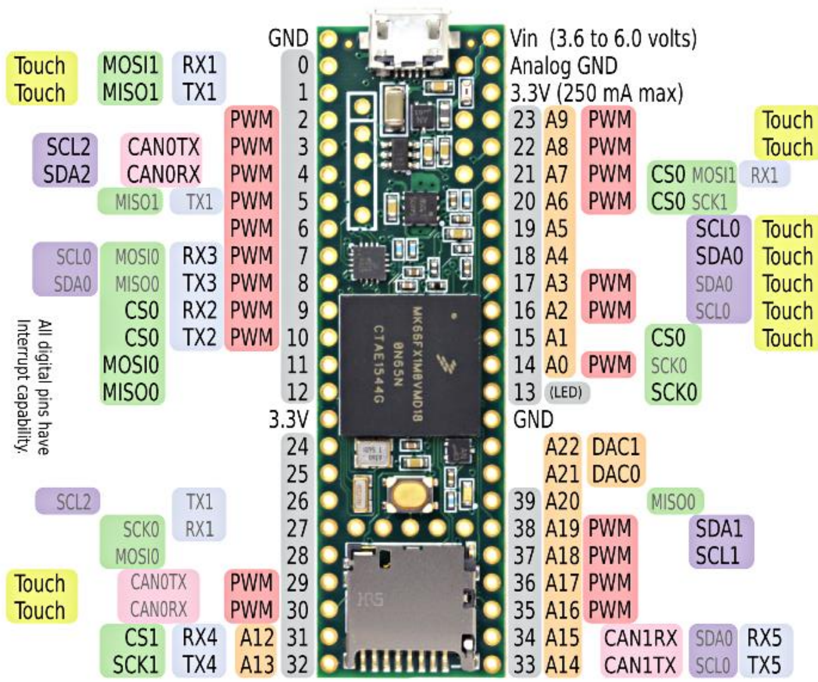

Figure 5: Pin configuration of the Teensy 3.6

The board chosen for this year's competition is the Teensy 3.6. Thanks to its computational capabilities, sporting a 32 bit 180 MHz ARM Cortex-M4 processor, and relatively small footprint, it has proven to be more than capable of handling all of the tasks this year's competition requires. On top of being computationally superior, the Teensy 3.6 also supports a myriad of inputs and outputs, with six UART ports, 3 SPI ports, 4 I2C ports, 25 analog input pins, and 58 digital I/O pins. Teensy supporting all of these inputs and outputs lets the team feel confident in using any external peripherals required for the competition.

This year’s competition requires a lot of data to be collected. The more data collected, the more accurate the model can be during flight, which naturally leads to the rocket being more accurate in its roll control. Due to this, the number of sensors incorporated into this rocket design, exceeds that of any of Pioneer Rocketry's previous rockets.This includes using two pressure sensors for pitot tubes, one 9 degrees of freedom sensor, and one altimeter. To save this data, the onboard SD card reader is used on the Teensy 3.6. Currently, sensor data is being fetched at ~30 Hz. However, this is before major optimizations have been performed. Future iterations will take full advantage of interrupts to speed up sensor data readiness speeds.

Avionics Spatial Layout

The avionics section, from here on referred to as the E-bay, is designed to be very easy to work with. A custom sled was designed to accommodate the components required for the E-bay, while also being easy to slide in and out of the rocket. A top down diagram for the sled can be seen in Figure 6. A 2200 mAh battery was chosen for initial testing, and a properly sized lower section was created to carry the battery during flight. The battery can be inserted and removed through either a hole in the top of the sled, or through the sides. This sled design also accommodates the initial proto-board used for electronics testing, along with two stratologgers and a radio for telemetry.

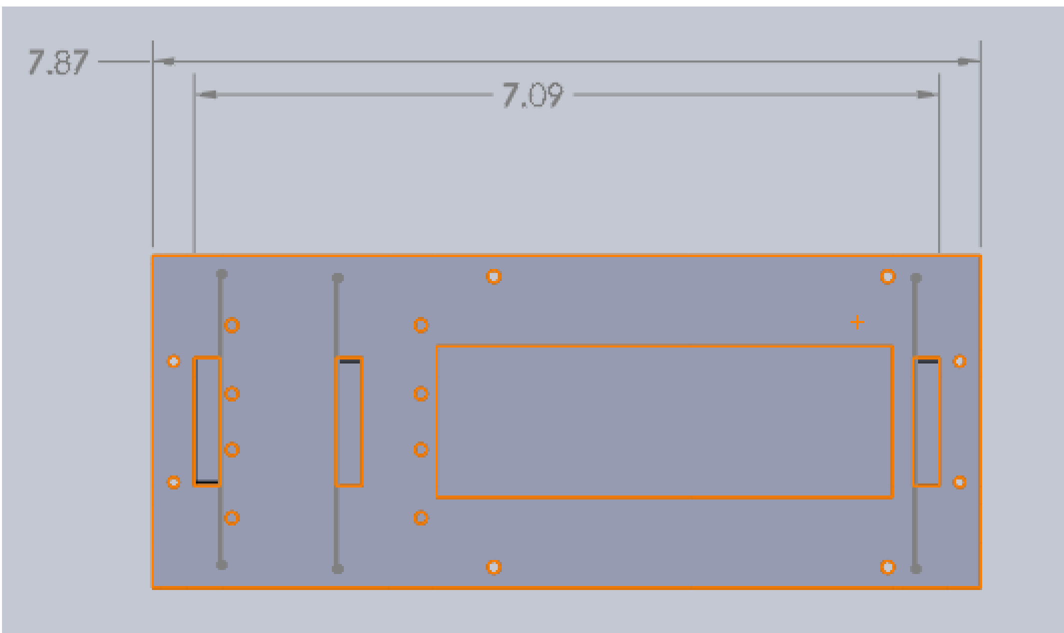

Figure 6: Top down view of the main E-Bay sled. This sled is designed to hold one protoboard, a 2200 mAh battery, a radio, 2 StratoLoggers, and a battery for the StratoLoggers.

Bonus Challenge Consideration

Pioneer Rocketry has years of experience with telemetry systems. For the last two MRL competitions, the teams have used various radio systems to retrieve information and send information to the rocket. During the 2015-2016 season, the team heavily used XBee radios. However, during the 2016-2017 season a search for new radio systems was launched due to high prices of XBee radios, and their finicky nature. The radio system that was decided upon are the Hope RF HM-TRP based radio systems commonly used in multicopters. These radios, while limited in features, offer a very easy to use platform for communication at 915 MHz. These are the radios that we will implement in the bonus challenge. Space and compatibility are being left open to allow for the physical layer of the network protocol to be switched over to any radio system we desire, including XBees.

The control system software on the rocket is being designed to have full dynamic capabilities in terms of control parameters. However, the device on board is also an embedded system, which does not play well with dynamically allocating memory. The control positions are internally represented via structs. Structs are an easy way to *structure* data in C++. Every struct only has two parameters currently: the angle of heading expressed as a floating point number, and the time to hold the orientation expressed as an unsigned 64-bit number with millisecond resolution. These structures are placed into a first in first out (FIFO) data structure. This allows the operator to send the commands via XBee in the order rocket should execute them.

Sending commands to and receiving commands from the rocket will be done via function pointers. Function pointers are a very nice way to rapidly swap out a function's task efficiently and elegantly. It can even be done at runtime. This will allow us to quickly implement any functions when we are told what they need to do, and tell the system to run them without changing an implementation anywhere else in the code.

Sensor Data Collection System

As stated previously, a driving force for the avionics system is having a lot of sensor data that can be used for better filtering. This naturally leads to a better in-flight model of the rocket, and a better model of the rocket leads to a more accurate control system. The sensors this system is comprised of are the pitot tube, the nine degrees of freedom (9 DoF) sensor, and an altimeter.

Pitot Tube

Part of the sensor suite is a pitot tube in the nose cone. The nose cone is designed to be hollow and have a 1/4 inch hole through the tip. There, a hose fitting will be put for the differential pressure sensor. One side of the hose fitting has a barbed tip to attach the polyethylene tube that leads to two pressure sensors. The other side has “1/4”-28 female threads. We will remove the head of a “1/4"-28 bolt and bore a 1/8 inch hole through the center. This will fit through the tip of the nose cone providing a strong yet easily replaceable pitot tube. Further inside the nose cone is an electronics sled that will house two differential pressure sensors. The sensor will be wired through a bulkhead at the bottom of the nose cone and connected to the main electronics bay via two 4-wire cables which are designed to easily disconnect when the nose cone is separated at deployment of the main parachute. Figure 7 shows a cross section of the pitot tube attached to the nose cone.

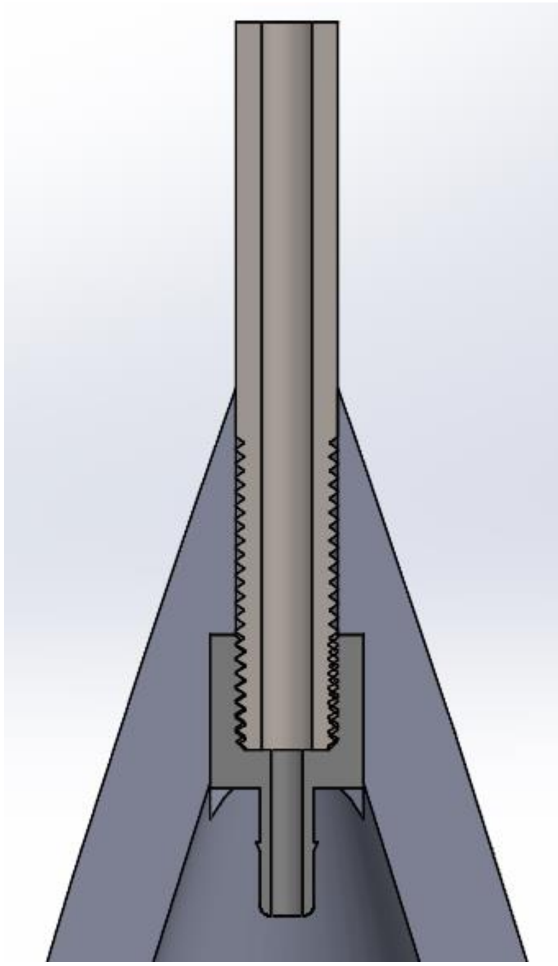

Figure 7: Cross-section of the pitot tube fitting in the nose cone. The barbed hose fitting leads to 2 differential pressure sensors. The threaded pitot tube is meant to be easily removed and replaced if necessary.

Nine Degrees of Freedom Sensor

In addition to speed, the control system also requires orientation. This is where the 9 DoF sensor steps in. The 9 DoF sensor is actually comprised of three different sensors: an accelerometer, a gyroscope, and a magnetometer. By applying special filtering techniques, these three sensors provide a full model of the rocket's orientation at any time.

Altimeter

Starting with the altimeter, the system has more sensors than strictly necessary. An altimeter would be required if the system considers the current air density at an altitude and its effects on the force being applied to the airfoils. However, this consideration has been deemed unnecessary because of the negligible difference in atmospheric pressure between ground level and ~3500 ft above ground level. Now, the altimeter is simply being used as another source of velocity by taking the derivative of the vertical position over time to get vertical velocity. This extra data, in conjunction with the pitot tube, will help converge on the exact velocity of the rocket. The altimeter is also used to detect apogee and stop all control algorithms once apogee is detected.

Cameras

For visual confirmation of the control system, two cameras are being included on this year's rocket. One camera will be used for judging and will have LED output to signal the control system's determination upon the direction of effort coming from the control system. Only two LEDs are used in this system for rolling right or rolling left. A "holding" LED will not be used, because holding is not a concept the control system recognizes. When it holds, it sets the setpoint at the current heading, and tries to achieve that setpoint. The second camera will be a Foxeer Legend HD camera. This camera will be for presentation purposes, and will not be fitted with LEDs. Both cameras are mounted within "camera pods", on the exterior of the rocket above the control fins, near the E-bay. They are positioned near the E-bay in order to allow easy connections to the electronics.

Active Roll System Design

This year's main challenge is implementing an active roll/orientation control system. The system needs to be able maintain a given orientation for any given time during flight. The active control system will consist of two control surfaces controlled by HyTech servos. The servos will be controlled by a control system implemented on the Teensy 3.6. The current state will be estimated using a Kalman filter which will then be fed into a feedback linearized control system to determine the required control effort for the current time step.

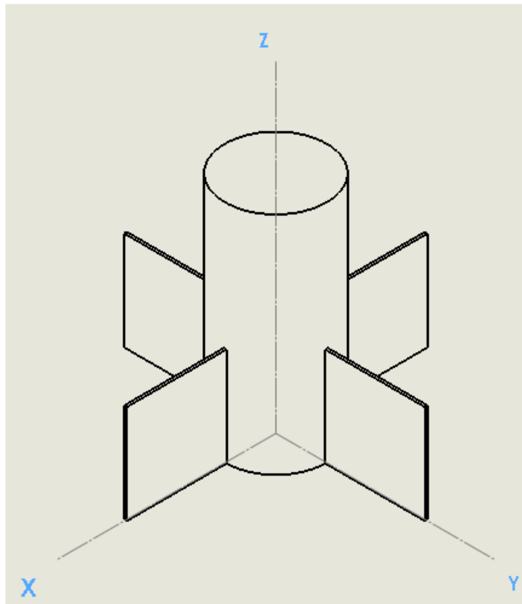

Figure 8: Basic model on 3-dimensional axes

The first iteration of the control system looks at only roll control. The basic model shown in Figure 8 shows the base coordinate system used. The angle θ is measured off the positive x-axis toward the positive y-axis. For the equations of motion the rocket is reduced to a disc with a moment of inertia J and mass (m_r).

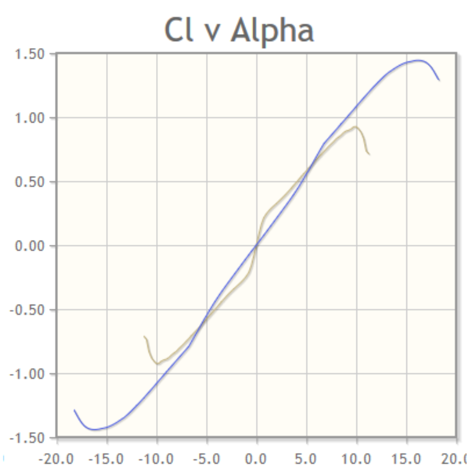

Figure 9 The coefficient of lift for a symmetrical air foil, for a high and low Reynolds numbers.

Since the control surfaces are symmetric air foils, we can find a lift coefficient to use to describe the force created. Figure 9 shows a typical C_L curve for a symmetrical NACA00** air foil. It can be seen that there is a linear region for the C_L. We can use this as a max restriction of our angle of attack, α. This linear region is valid for a wide range of Reynolds numbers; two extremes are shown. This will allow to write the lift equation in terms of the angle of attack and a fin characteristic k,

$$F_L = \frac{k\rho A_p}{2}\alpha\dot{z}^2$$

where $\dot{z}$ is the velocity of the rocket, ρ is the air density, and A_p is the area of the airfoil. The air foils can also be seen as a damping component while rotating. This coefficient of drag (C_D) will be assumed constant at all times. Take the distance between the effective lift forces to be d_1 and the distance between the parallel drag forces to be d_2. The force of drag on each fin can be written as:

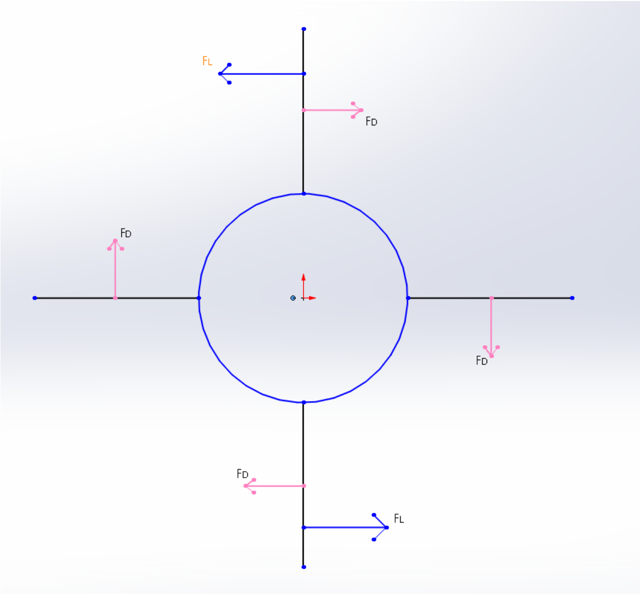

Figure 10: CL curve for a symmetrical NACA00** air foil.

$$F_D = \frac{C_D \rho A_p}{2}\left(\frac{d_2}{2}\right)^2 \dot{\theta}^2.$$

Using the torque equation $J\ddot{\theta} = T$, the moments about the z-axis, see Figure 10 for force diagram, are

$$J_R\ddot{\theta} = d_1 F_L - 2d_2 \mathrm{F}_D \ .$$

From the above definitions, the equation of motion is

$$J_R\ddot{\theta} = -2d_2\frac{C_D \rho A_p}{2}\left(\frac{d_2}{2}\right)^2 \dot{\theta}^2 + d_1\frac{k\rho A_p}{2}\alpha\dot{z}^2.$$

If we let $x_1 = \theta,\ x_2 = \dot{\theta}$ and $\alpha = u$, the system can be written in state space form:

$$\dot{\boldsymbol{x}} = \begin{bmatrix} \mathrm{x}_2 \\ -a_1 x_2^2 \end{bmatrix} + \begin{bmatrix} 0 \\ b_1 \end{bmatrix}\boldsymbol{u}$$

$$y = x_1$$

$$a_1 = 2d_2\frac{C_D \rho A_p}{2J_R}\left(\frac{d_2}{2}\right)^2$$

$$b_1 = d_1\frac{k\rho A_p}{2J_R}\dot{z}^2 \ .$$

Taking the first two derivatives of y, it is easy to see that the relative degree of the system is equal to the degree of the system:

$$\dot{y} = \frac{\partial y}{\partial x}\begin{bmatrix} x_1 \\ -a_1 x_2^2 \end{bmatrix} + \frac{\partial y}{\partial x}\begin{bmatrix} 0 \\ b_1 u \end{bmatrix} = x_2 + 0 = x_2$$

$$\ddot{y} = \frac{\partial \dot{y}}{\partial x}\begin{bmatrix} x_1 \\ -a_1 x_2^2 \end{bmatrix} + \frac{\partial \dot{y}}{\partial x}\begin{bmatrix} 0 \\ b_1 u \end{bmatrix} = -a_1 x_2^2 + b_1 u \ .$$

The derivatives of y also reveal that this system is input-output linearizable with a state feedback control of

$$u = \frac{1}{\frac{\partial \dot{y}}{\partial x}\begin{bmatrix} 0 \\ b_1 \end{bmatrix}}\left[-\frac{\partial \dot{y}}{\partial x}\begin{bmatrix} x_1 \\ -a_1 x_2^2 \end{bmatrix} + v\right] = \frac{1}{b_1}(a_1 x_2^2 + v).$$

This analysis shows that the system can be linearized, allowing the use of linear control techniques. This technique requires accurate measurements of the velocity of the rocket and the angular acceleration. To achieve this, a Kalman filter will be implemented to estimate the state and remove noise of the system. The reason we choose feedback linearization is that even with imperfect cancelation of the nonlinear terms the system will be robust enough to remain stable.

The next stage of the control system will be to develop a discrete time Kalman filter and to discretize the above results. The system can then be stabilized, simulated, and implemented. Another step is to form a complete model to ensure that controlling roll will not destabilize the rocket.

Predicted Performance

Flight Analysis

When not taking the roll control devices on the rocket into account, it flies the same as a typical rocket. With a J360 motor, the rocket has a maximum speed of Mach 0.6, and a maximum altitude of 3860 ft. If the rocket encounters high wind speed situations (>20 mph), it begins to tumble if the nosecone is too light. This condition is covered in greater detail in the Stability and Environmental Conditions Analysis section. Maximum acceleration experienced by the rocket with a J360 motor is 110 m/s/s. The estimated descent speed comes in two parts. First, when the drogue is released, the rocket begins falling at a velocity of about 55 feet per second. When the main chute is deployed, the descent altitude drops to ~21 feet per second in order to safely land the rocket. These values were obtained by simulating the rocket in OpenRocket. These values are for a wind speed of ~5 mph.

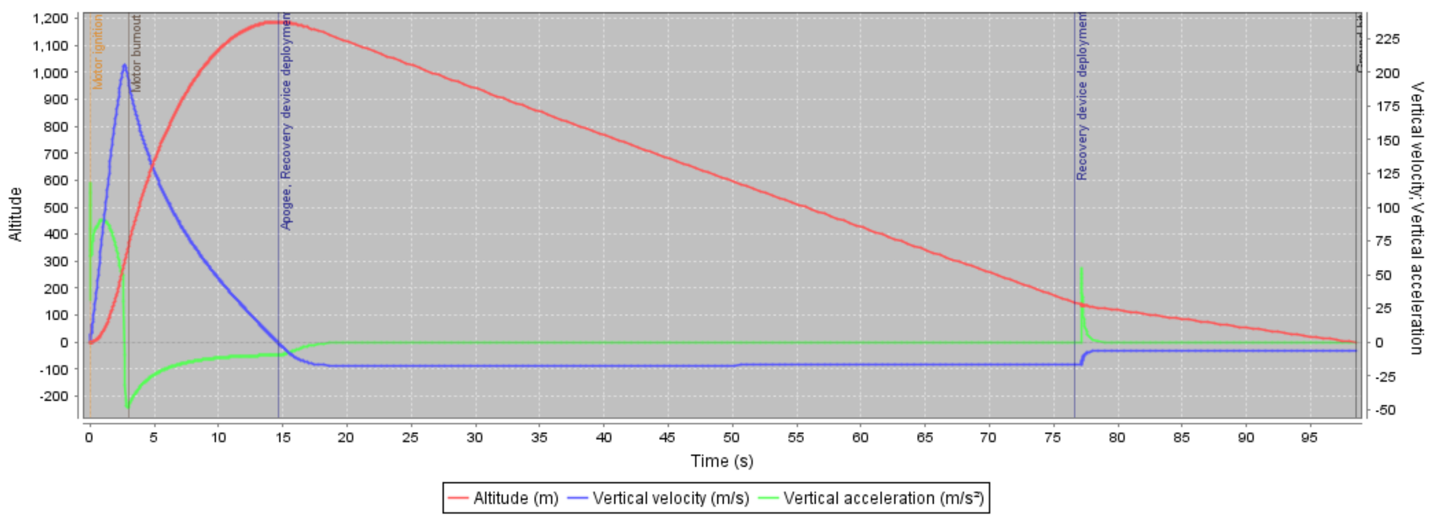

Figure 11: Flight simulation of the prototype rocket using a J360.

Stability and Environmental Conditions Analysis

In the initial simulations of the rocket, it would tumble (“cork-screwing”) under thrust if the crosswind exceeded 5 mph. This was due to the slightly different fin sets (dynamic and static) that slightly offset the center of pressure, favoring rotation of the rocket in a cross wind. This was countered by increasing the mass of the rocket through the doubling of the weight of the nosecone, which increased the inertia of the rocket and made it significantly more resistant to turning in winds exceeding 20 mph. In all other regards, the rocket is stable fully loaded, and after the motor has expended its mass.

Safety Considerations

Safety is a very serious topic to Pioneer Rocketry as a club. Every year we attempt to push the boundaries of what is possible, while being mindful of possible hazards and failures. We perform rigorous strength and safety testing before we allow any experimental design to fly. We stress test custom made parts for compression and tensile strength. We use computational fluid dynamics (CFD) to simulate effects of all control systems in a wide variety of scenarios. Additionally, we have access to a wind tunnel for gathering data on fluid dynamics. All experimental rocket designs are flown as a small scale proof of concept to minimize risk in the event of a failure and extra safety procedures are put in place for test flights.

Pioneer Rocketry has a system of creating checklists for preflight and postflight operations. These steps guide the team through prepping everything on the rocket, bringing the rocket to the pad, running all preflight tests, retrieving the rocket after launch, and performing any data collection activities that might have to be done.

Material handling procedures include storing all flammable materials, such as black powder, motors, and LiPo batteries in fire-hazard storage lockers. LiPo batteries are always stored in PVC battery-bags in the shop and while travelling. While doing any construction activities on the rocket, the team was sure to wear safety glasses, gloves, and filtration masks. This is especially true while working with fiberglass. Consumption of any food within the workspace is strictly prohibited because of the fine particulates that might be floating in the air.

The current team consists of one NAR Level 2 certified member, and one NAR Level 1 certified member. Our high power mentor, Jake Ellenberger is NAR Level 2 certified as well. Pioneer Rocketry as a whole consists of more than five Level 2 certified members, over a dozen Level 1 members, and three members working on Level 3 certifications. All of the certified members are more than happy to suggest safer building strategies, and answer any questions we might have.

Conclusion

This year has been a year of learning and trying many new things. Finding new ways to fabricate fins, and securely attaching them to the rocket has been a process from which new, sought after knowledge has been gleaned. Another important element that has been learned is how to set up a non-linear control system.

The rocket body constructed for this competition was designed to optimize the efficiency and speed. We designed for structural integrity to minimize the potential for dangerous situations to arise during or prior to launch. The materials comprising the external structure of the rocket and the construction techniques used were decided upon to allow for a light weight design without compromising the strength and durability required of the rocket to perform while under the stresses produced by the two airfoil control surfaces. The Teensy 3.6 was chosen for its fast processing power, and its quantity of input and output pins, both digital and analog, being large enough to support the large assortment of individual electronic components. The programming used to process the data and derive an output to control the servos, was created from scratch by members of our team using C++, taking into account fluid dynamics calculations and mathematical models.

Overall, every aspect of the rocket; the design, construction materials and techniques, programming, and electronics components, have been thoroughly planned and researched, while the design and implementation of each component is juxtaposed with every other, so as to optimize the safety and efficiency of the rocket's ability to perform its required tasks.

Ad Astra

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Garry Stroick, Off We Go Rocketry

Budget

Item	Quantity	Cost per Unit	Total Cost
RocketPoxy Epoxy (2 Quart)	2	$65.00	$130.00
75 mm G12 Fiberglass Tube (Cost per foot)	8	$20.51	$164.08
75 mm G12 Fiberglass Coupler	2	$20.78	$41.56
54 mm Motor Mount	1	$17.63	$17.63
54 mm Retainer	1	$32.00	$32.00
StratoLogger Alitimiter	2	$58.80	$117.60
Teensy 3.6	1	$29.25	$29.25
PLA Filament (1 kg)	2	$25.99	$51.98
Xbee Pro 60mW Antenna	2	$37.95	$75.90
Xbee Pro 60mW Connection	2	$37.95	$75.90
Servo Motor	2	$42.00	$84.00
G10 Fiberglass Sheet	2	$28.00	$56.00
GPS Antenna	2	$15.95	$31.90
GPS Adapter	2	$4.59	$9.18
Radio Reciever	1	$249.99	$249.99
Radio Tracker	3	$89.99	$269.97
Fruity Chute Parachute	3	$45.00	$135.00
DC-DC converter	2	$20.00	$40.00
9 DoF sensor (digital)	1	$15.00	$15.00
Altimeter sensor	1	$10.00	$10.00
Differential pressure sensor	2	$10.00	$20.00
PCB fabrication	3	$50.00	$150.00
CTI J360	2	$93.00	$186.00
CTI J280	1	$71.25	$71.25
Registration fee	1	$400.00	$400.00
Travel	1	$600.00	$600.00
Total			$3,064.19

A total of $3,064.19 is expected to be spent on this project, including $600 for travel