Utilizing NACA Ducts and an Inner Turbine System in a High-Power Rocket to Generate an Electric Current

Kathryn E. Lenz*, David A. Juckem
University of Wisconsin-Fox Valley
Menasha, Wisconsin, USA

*Corresponding Author (lenzk7373@students.uwc.edu)

Abstract
During the 2016-2017 Collegiate Rocket Launch (CRL) competition, teams were required to design and construct a high-power rocket that would complete a safe flight that would reach as close as possible to a target apogee height of 3,000 feet, as well as generate an electric current during the pre-apogee portion of the rocket's flight. The UW-Fox Valley team, the Rocketeers, designed a three-inch diameter, thin-walled fiberglass airframe at a final length of 188cm that was able to achieve safe flights. In order to generate electricity during the flight, the team used a ducting system that allowed air through an inner turbine system. On competition day, three safe flights were completed, with altitude, velocity, and acceleration data recorded. Electric generation data was recorded during the first flight, but due to environmental factors data was not recorded for voltage generation on the second and third flight.

1. Introduction

The Wisconsin Space Grant Consortium (WSGC) CRL competition challenged participating college students to achieve two main goals: reach as close as possible to a target apogee height with a high-powered rocket, as well as generate an electric current during the pre-apogee portion of the rocket's flight. Reaching a specified target apogee would require the consideration of many design components, including the motor chosen in conjunction with the final weight of the rocket, and the rocket's drag. When considering which electric generation method to use, reliability of the system needed to be considered, as well as the location of the system and how it might affect the stability of the rocket. In addition to the design goals, WSGC encouraged teams to participate in educational outreach, as well as develop their project management skills with various deliverables that were also scored for the competition.

2. Design and Construction

Approach. Early in the planning stages, it was decided to make the design for the electronic systems modular. Creating a modular electronics system meant that it could be designed independent of the rocket airframe, provided the outer diameter of the designed system didn't exceed the inner diameter of the rocket frame.

Having decided this, the team then moved on to basic airframe design considerations, and electric generation methods. In order to decide which generation method should be used, the team brainstormed various ideas and created a decision matrix. When deciding what materials should be used for the airframe and general electronics components, various options were researched, and

the team discussed which option would work best for the rocket. After design and construction were completed, multiple test flights were planned to be completed in order to confirm that the rocket would meet the requirements of the competition.

Airframe. The rocket was designed in three main sections, as shown in Figure 1. The top section was the nose cone section, the middle section the electronics bay, and the bottom section was the tailfin section. The nose cone section housed the GPS tracker, as well as the main parachute and the main parachute deployment charge. The middle section housed the altimeter bay, as well as the electronic generation bay. The altimeter bay contained the two altimeters used for the competition, as well as a 7.4-volt LiPo battery and a 9-volt battery used to power the altimeters. The electric generation bay housed the electric generation system, as well as the data recording system. The tailfin section contained the drogue parachute, as well as a deployment charge.
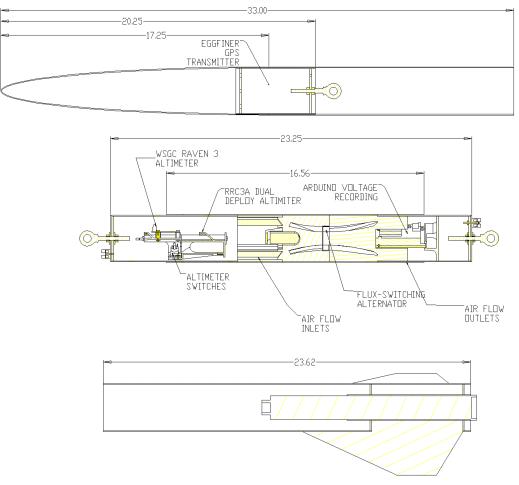

Figure 1: Diagram of components in rocket frame

Initial design of the airframe started with which material to use for the rocket build. The two primary materials available for high-powered rocket frames were cardboard tube or composite. Consideration was given to strength, unpredictable conditions at the launch site, ease of construction, cost, and adaptability to a fluid design process. The decision was made to start with a DX3 kit from Madcow Rocketry. The kit provided all the major construction materials required for the design. The tubes were three-inch diameter, filament wound, vinyl ester tubing with

appropriately sized connection tubing and bulkheads. Additional tubing to extend the fuselage and construct the avionics bay was also acquired. A G-10 sheet for the fins and additional bulkheads from Wildman Rocketry where obtained as well.

Once the G-10 sheet components were designed, they were cut using an X-Carve CNC router. Hand cleanup and shaping was accomplished with sandpaper. Slots for the fins were cut using a Dremel tool with an abrasive disc. The 38-mm motor retainer was obtained from Aero Pack and bonded to the fiberglass motor tube with epoxy paste. Epoxy paste was also used to attach the fins, with smooth fillets between the fin and rocket for reduced drag. To join the upper body tube to the nose cone, rivets were used. Shear pins were used on either side of the electronics bay to create separation joints for chute deployment. Finally, holes were cut into the rocket to allow for ducting, which was divided into two identical sections 180 degrees from each other to cancel the effect on the flight path.

Recovery system. The altimeter used in the rocket was a RRC3 altimeter from Missile Works, located in the electronics section of the rocket. The altimeter recorded the altitude of the rocket, and was additionally programmed to set off deployment charges to eject the parachutes from the rocket. The team decided to use a RRC3 altimeter because it met requirements set by the competition, as well as fitting within budgetary constraints. Along with this altimeter, the altimeter provided by WSGC, a Raven III Featherweight Altimeter, was also placed in the electronics section of the rocket.

The rocket was designed with a dual deployment parachute system. Nomex parachute protectors and parachutes where obtained from Wildman. A 24-inch drogue parachute was designed to deploy at apogee, with two grams of 4F black powder set up as the charge for deployment. The main parachute was 60 inches, and was set by the RRC3 to deploy with a 1.5 gram charge at an altitude of 500 feet. These sizes were chosen based on an estimated maximum flight weight of 10 pounds at. To tether the parachute to the rocket, 3/8-inch Kevlar tubing was used, attaching the nose cone, avionics bay, and motor housing using swivel connectors and screw links for reliability.

Electrical generation design process. Generation of electrical power during the ascent of the flight was one of the main requirements of the competition. This became a major design consideration because of its impact on the airframe structure and the avionics required to implement it. The brainstorming session determined a number of possible methods to obtain this goal. Peltier tiles, a Stirling engine, piezoelectric crystals, and a turbine driven by airflow during flight were the main methods explored. After much deliberation and the use of a decision matrix to facilitate the decision process, a turbine driven generator was chosen as the method that would be pursued.

Once the decision was made to go with a turbine design, the focus shifted to methods of accomplishing this while affecting the flight dynamics of the vehicle as minimally as possible. It became apparent that housing the turbine and the associated duct work internally offered the least impact to the stability of the rocket in flight and also provided a challenge to the group in the design, implementation and testing of the system. Centering the ductwork as much as possible to

the center of pressure (CP) of the rocket was crucial to the airflow through the turbine system not having an adverse effect on the flight path of the rocket.

A NACA duct was used to provide inlet airflow to the ductwork while decreasing the amount of drag as the air entered the rocket. The ducting then directed the air through the turbine, which was a repurposed 12-volt cooling fan. From there, the ducting directed the airflow out of the side of the rocket through a basic round hole.

Avionics and electrical generation hardware construction. The entire avionics bay sled and nose GPS mount were designed and constructed in house using primarily 3D printed components made with polylactic acid (PLA) filament. All wiring, switches and battery connections were soldered for reliability and are incorporated in the avionics bay design.

An Arduino unit was selected to monitor and record the electrical generation. Cost, relative ease to program and troubleshoot, along with its modest power requirements all entered into the decision process. An expansion SD card recorder was used to provide in flight storage of the turbine output voltages and current levels. A custom circuit board was designed and fabricated to support the acquisition of power generation data from the turbine. This housed the rectifier, voltage divider and noise suppression capacitors.

The electronics system was designed and modeled in PTC Creo. Initially, the system attempted to use flexible ducting that would interlock with the body tube. However, the PLA wasn't flexible enough, and the design for this system had to undergo iterations. In the final design, the ducting was separate pieces that were bolted to the frame. The ducting section was split into two separate sections after multiple iterations. The top ducting section was designed with a relief for the turbine to be placed in. The bottom ducting section houses the Arduino, with a strap to hold the Arduino's battery. This was all held together by the pressure applied by mounting nuts on both sides of a pair of 2-foot avionic bay rods that run the length of the electronics section. The final print of the housing was modified to have a 20% interior infill to reduce weight, as well as the cost of the material.

3. Testing
Predicted Performance. In order to predict the initial performance of the rocket, it was modeled in OpenRocket. From the original simulation, data obtained from test flights was used to make more accurate predictions. Simulation parameters, to match actual flight conditions during testing, included: 5 mph winds, 10% wind turbulence, 55° Fahrenheit, 1013 mbar atmospheric pressure, a 2-meter launch rod, 800-foot launch altitude, and GPS coordinates of 42.6 N, -88.2 E for the launch site. This gave the predicted results seen in Figure 2. The final simulation before the competition showed an expected apogee of 3,073 feet.

Additionally, a predicted voltage as a function of time was found. It was predicted that voltage peak would be reached early in the rocket's flight, remaining at this peak voltage for the remainder of the pre-apogee portion of flight, returning to a zero voltage gradually as the rocket slowly decelerated. The predicted voltage function is shown in Figure 3, with the flight reaching a peak voltage of 4.5 volts at about 0.275 seconds, and decreasing gradually until twelve seconds into the flight, where it decelerates more quickly.
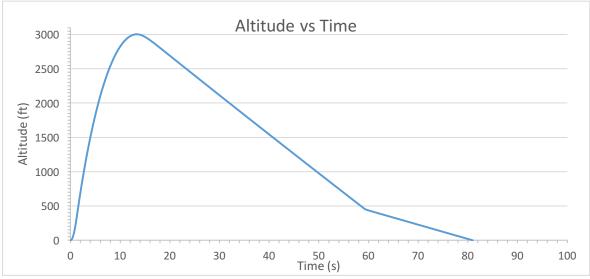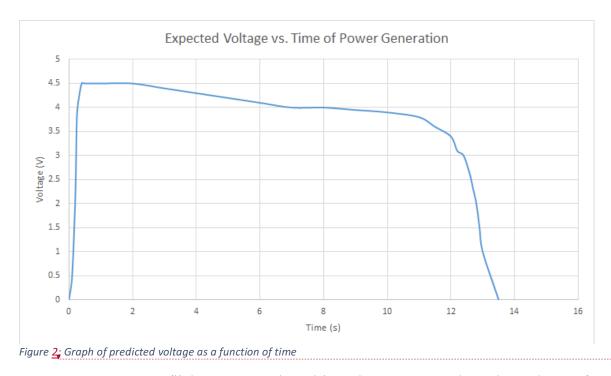
Figure 2: Flight altitude shown as a function of time

Figure 2: Graph of predicted voltage as a function of time

Test Flights. Test flights were conducted in order to compare how the rocket performance compared to the simulation performance. During the first test flight, the rocket reached an apogee of 3,384 feet and voltage data was recorded. However, the data received from the Arduino showed voltage reading with no trend lines. Due to this inconsistency, the Arduino code was modified to retrieve the time data, as well as sample at a higher frequency. In addition to failing to properly retrieve voltage data, the rocket also failed to complete a safe flight at the first test launch. Initially, the shock cord was partially wrapped around the bottom of the rocket with no method of retaining the cord. During the flight, the cord slipped into the motor exhaust, separating the cord between the tailfin section and the rest of the rocket. This caused the tailfin section to descend back to the

ground in free fall at ejection of the drogue parachute. Despite this failure, the tailfin section was recovered with minimal damage. After the first test flight, the Kevlar was retained within the rocket to prevent this problem.

On the second day of test flights, the rocket was launched twice. The Arduino code corrected the original problems seen in the first test, however the code stopped recording data points before the Arduino was turned off. On the first flight, 12.4 ounces of removable weight was added, along with the weight due to the paint on the rocket. The apogee height of this flight was 2,780 feet. In order to see how much of an impact the paint had made on the difference in apogee, the 12.4 ounce weights were removed. The apogee height of the second flight was 3,112 feet

4. Results
On the day of the competition, the Rocketeers were the first team to fly their rocket, sending it on its first flight within the first hour. On the first flight, voltage was generated and recorded, but the altitude was above the target altitude. In order to lower the altitude, weight was added to the rocket and it was launched a second time. On the second flight, the rocket landed in water and no data
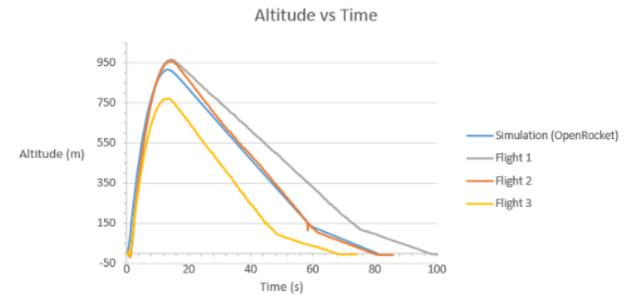

Figure 4: Graph of altitude versus time for each of the competition flights

was recovered from the Arduino. However, the altimeters still worked, and it was shown that the rocket's apogee height was still too high. On the third and final launch of the day, more weight was added to the rocket. However, the altitude on the final launch was much lower than was calculated by the team. The flight data is shown in Figure 4. It can be seen that the flight data matched the prediction quite well, within 94 percent in the best case.

Reaching target apogee. To try to reach the competition target apogee of 3000 feet, the team modeled their rocket in OpenRocket, which output a precise weight of the rocket to hit this goal. According to the simulation, the team needed to add 4.4 ounces to reach an apogee height of 3,005 feet. For the first launch, the 4.4 ounces were added, and the apogee of the flight was recorded to be 3,168 feet. Due to this considerable difference in predicted height, the team decided for the second flight to add an additional 2.4 ounces to the rocket. During the second flight, the rocket reached apogee at 3,143 feet. The team had been expecting the height to go down by a greater amount, so the difference in height of only 25 feet was not as close to the target as the team was comfortable with. The Rocketeers decided to launch one more time, using a linear relationship to predict that a total weight of 12.7 ounces added to the rocket would bring the height down to a value closer to 3000 feet. However, the apogee height of the final launch was 2,534 feet. The altitude of each flight, along with its velocity and acceleration, can be found in Table 1.

	Simulation	Flight 1	Flight 2	Flight 3
Altitude (ft)	3005	3168	3143	2534
Altitude (m)	916	966	958	772
Acceleration (m/s^2)	153	195	209	175
Velocity (m/s)	172	190	159	159

Table 1: The altitude in feet and meters, acceleration, and velocity for each of the flights

Voltage Generation. As stated earlier, an inner turbine system was used for electric power generation. Before this system was ever launched while inside a rocket, it was tested at a lower wind speed to ensure the fan would operate in a way that wouldn't destabilize the rocket's flight. Seeing that the fan withstood lower speeds, the electric generation system was put in a rocket for a test flight before competition. Early test flights were successful, and the electric generation system underwent a few minor changes before the competition flight.

At the competition, voltage was recorded during the first flight of the day. The data points read by the Arduino resulted in a curve that increased from the rocket's launch to its apogee height. While the Arduino recorded a voltage of 4.5V, the true voltage peak was at 11.63V. Since the Arduino had a maximum voltage read of five volts, this higher voltage needed be stepped down in order to be recorded by the Arduino. Once getting the raw data, it was then possible to convert the data to the correct voltages. After the rocket landed from its second flight, it landed in standing water, which entered the electronics bay. While the altimeters continued to work after this flight, the Arduino was unable to retrieve data for the second flight, as well as record or retrieve data from the final flight. The voltage recorded is shown in Figure 5.
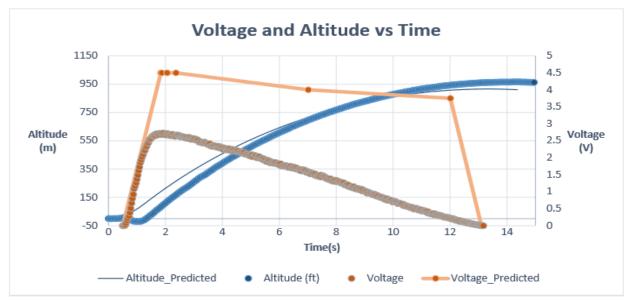
Figure 5: Graph of voltage and altitude versus time predicted and for the first flight

5. Discussion

Altitude inconsistency. During the last flight of the competition, the team saw a discrepancy between what they were expecting from the weight added in comparison to the apogee height. When the team was predicting what the change in weight would result in for a change of apogee, linear interpolation was used. It is possible there are other factors that the team didn't consider during the competition that would have a greater impact than the weight of the rocket on the apogee. Additional test flights may have helped in determining what various contributing factors may have been. One possibility discussed was an anomaly with the rocket motor. In the third flight, there is a spike in acceleration just after the .06 second mark, followed by a sharper decrease in the average thrust after that point, as compared with the previous two flights, shown more closely in Figure 6. There is another anomaly near the 0.8 second mark. These differences lead the team to believe the motor to be one of the contributing factors in the significantly decreased apogee.
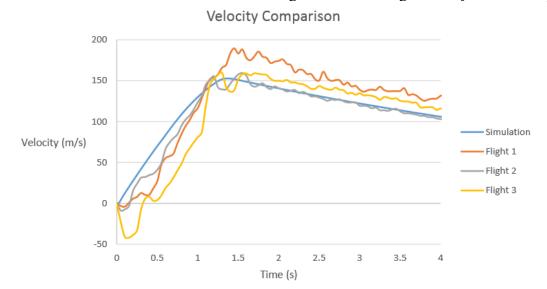

Figure 6: Detail of velocity comparison of simulation and flights

Obstacles. As this was the first year that a team from University of Wisconsin-Fox Valley competed, many obstacles had to be overcome. The group discovered the lack of tools and equipment to be a setback during the construction phase of the project. While some funds where available to purchase what was needed, some members brought tools from home and many of the more expensive items were borrowed.

Successfully managing a large, multiple-participant project such as this is an area that could be improved on for next competition. Managing workflow, material acquisition and build sessions while keeping the schedule of not only the competition but of the students in mind was difficult. A more proactive approach in regards to the early design and testing phase will be enacted and will result in a less hurried build and increase the time available to attempt more test flights. A greater emphasis will be placed on pre-competition test flights as the team believed the flights they had done were one of the main reasons the team enjoyed success on competition day.

6. Summary and Conclusions

Rocket flight assessment. Overall, the rocket performed as expected. Multiple test flights allowed to team to modify both the airframe, and data recording systems in time for the competition flight. The rocket successfully launched three times at competition, with successful parachute deployments ending in three safe flights with the rocket recovered in flyable condition. All systems worked as expected in the rocket, including altimeters, GPS tracker, and the electric generation system. Voltage generation was recorded from the turbine system on the first flight in the pre-apogee portion of flight. Additionally, during the three flights, an apogee height of 3,143 feet was recorded as the closest apogee height to the target.

With the overall success, there are still various improvements that could be made for the following year. One of the complications faced was the failure of the Arduino upon the water landing. For next year, attempting to water-proof the Arduino or having back-up Arduinos with uploaded code is suggested.

Moving forward, next year the Rocketeers will focus on improved documentation throughout the competition, as well as completing as many test flights as possible. Since the apogee height was the part of the competition the team struggled with most, more data points will give the team a better understanding of how the weight of the rocket and possible other factors contribute to the height the rocket reaches.

Team assessment. The CRL competition was a great opportunity for the students involved to use the skills they had been learning in their classes in a practical application that continuously kept everyone engaged. From the early stages of the competition, the team had to think critically when they were brainstorming and deciding how they would proceed with the design of the rocket. Once they had made the decision to use an inner turbine system, they then decided to make the electrical components modular, in order to allow for an iterative design process for this system in concurrence with the build of the rocket airframe. Additionally, while the design process and construction were going on, the team had multiple papers and deadlines to keep track of as well.

Acknowledgement. The team would like to acknowledge and thank the NASA Wisconsin Space Grant Consortium for this opportunity to compete in the CRL competition. The authors

would like to recognize the other team members: Brian Eberwein, Drew Eisenberg, Shawn Schumacher, Maddison Sauer, and Justin Walters. Additionally, the team would like to acknowledge the support they received from the University of Wisconsin-Fox Valley and the University of Wisconsin-Platteville's Collaborative Engineering Program. The team also appreciates the guidance from their faculty adviser, Dr. Warren S. Vaz and would like to thank their industry mentor, Frank Nobile.

7.References

Wisconsin Space Grant Consortium. Collegiate Rocket Competition Handbook. (2017, September 5). PDF.