Innovative Sounding Rocket for Collecting Atmospheric Samples at Various Altitudes

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Abstract

A sounding rocket is a rocket that is designed to conduct a scientific experiment during sub-orbital flight. The Intercollegiate Rocket Engineering Competition (IREC) is an international rocket competition hosted by the Experimental Sounding Rocket Association (ESRA). Participating teams are required to design and manufacture a sounding rocket that will carry an experimental payload to either 10,000 feet or 30,000 feet. The team from Colorado State University has accepted the challenge to design an advanced rocket, the Aries IV rocket, that will travel to 10,000 feet through performance-enhancing innovations in the payload, airframe, propulsion, and controls subsystems. While the competition will not take place until the end of June in New Mexico, ground testing and flight testing have been and will continue to be conducted in order to understand the progress and success of the design.

1. Introduction

1.1 Project Overview

For the payload, an atmospheric sampling device is being developed that will suck air into evacuated chambers every 1500 feet as the rocket descends. These samples will later be analyzed for concentrations of methane and carbon dioxide back on the ground. The size and amount of airborne particulate will also be monitored approximately 10 times a second from launch until the rocket lands. The goal of the experiment is to validate whether or not greenhouse gases are actually well mixed throughout the atmosphere.

The airframe must be as light as possible, but be able to withstand forces encountered through the duration of the flight and must not be damaged upon landing. Due to these constraints, a fiberglass-aeromat composite was used to manufacture the fuselage and nose cone.

The experimental flight is powered by a student-designed second generation liquid rocket motor composed of ethanol as the fuel and nitrous oxide as the oxidizer. This motor is designed to carry the 100-pound sounding rocket to altitudes in excess of 10,000 feet.

To increase the innovation score, a control system is being implemented into the rocket. An included flight control module uses an advanced apogee prediction algorithm and engages air braking flaps to slow the rocket precisely to the final target altitude of 10,000 feet.

A large portion of the final score is the recoverability of the rocket. At apogee, the recovery system engages, firing pistons which split shear pins on the airframe, releasing the dual-deployment parachutes. These parachutes bring the entire airframe, motor, and atmospheric samples back down to the ground safely and gently.

1.2 Project Goals

The primary goal of this project is to win the Intercollegiate Rocket Engineering Competition next June, which is hosted by the Experimental Sounding
Rocket Association. To do this, the team must design and manufacture a rocket that will carry an experimental payload to 10,000 feet. The scoring will be based on how close the maximum altitude of the rocket is to 10,000 feet, as well as the scientific merit of the payload, the recoverability of the rocket, and overall innovation.

2. Design and Analysis

2.1 Airframe

The airframe team is responsible for creating a lightweight, strong airframe to protect the subcomponents of the rocket, integration of all subsystems, as well as Computational Fluid Dynamics for the entire team. Through design and testing, the airframe team has determined that a fully composite airframe is the best suitable material for the given loads. Carbon fiber has an extremely high strength to weight ratio, although with budget constraints, fiberglass is a close second option. The team has decided to use a 6 oz. fiberglass 2x2 twill weave laminate with an Aero-Mat core. Aero-Mat is a flexible honeycomb foam mat used to add structure and thickness to composite laminates. The hexagonal pattern of the Aero-Mat (Figure 1) allows for epoxy resin to be infused through the dry fiber [1].

![Aero-Mat hexagonal construction](image)

The decision to use this laminate sequence was primarily done with testing. Three small scale parts were manufactured with different fiber stacking sequences and subjected to compressive loading. The chosen stacking sequence withstood over 4500 lbs of force as seen in Figure 2. After testing, the team was confident in the composite, because the loading experienced in flight will be of a magnitude lower.

![Compressive loading of fiberglass composite](image)

Many high powered rockets created by smaller companies utilize hand-layups to wet-out the dry fiber with epoxy resin. This process, although easier than resin infusion, has many drawbacks. First of all, due to human error, not all parts of the fiber receive equal amounts of resin. Due to this, the volume fiber fraction is lower than wanted. Volume fiber fraction ($V_f$) is defined as $V_f = \frac{m_f \times (\rho_c + \rho_f)}{\rho_c}$ where $m_f$ is the mass of dry fiber, $\rho_c$ is the density of the composite and $\rho_f$ is the density of the fiber [2]. Volume fiber fraction is important because it is directly used in stiffness calculations, and gives an overall idea of how well the fiber was laid-up. The team realized that not only do hand layups require more time and are more messy, a lower fiber volume fraction was achieved. Due to this, the team researched, tested and implemented Vacuum Assisted Resin Transfer Molding (VARTM) for the fuselage of the rocket, also known as Resin Infusion. VARTM consists of pulling vacuum through the outlet of the mold allowing resin to be drawn through the inlet and into the mold as shown in Figure 3.
High fiber volume fraction can be obtained, as high as 60% with very low void content, as well as faster and lower labor required. A picture of a section of airframe during the VARTM process is shown in Figure 4.

Lastly, a major component that the airframe team designs and manufactures is the bulkheads. Bulkheads separate sub-components of the rocket and transfer force from the engine to the airframe. In previous years, high quality plywood with threaded inserts were used. This years team quickly found that using threaded inserts would split the plywood even before being attached to the airframe. To battle this, the team came up with a two-part design that has proven superior to the previous (Figure 5).

Using ¼ inch high quality birch plywood, the bulkheads were machined with a CNC Vertical Milling Machine to achieve outstanding accuracy. In addition, the new design takes a six operation procedure down to a single operation, which saves time and money.

### 2.2 Propulsion

The propulsion team is responsible for developing a reliable liquid propulsion engine that can carry the Aries IV to 10,000 feet. To accomplish this the team has developed a trajectory analysis code to accurately predict apogee of this and other propulsion systems, as well as designed and tested a small scale engine that has generated great performance. The thrust data from this small scale engine has been imported into the developed and scaled by the trajectory analysis code to design the full scale engine.

The trajectory analysis code takes into account atmospheric conditions at the launch site, the mass, dimensions, and aerodynamic performance of the rocket, and the thrust and mass flow characteristics of the rocket engine. The code allowed the team to also use for loops to “test fire” thousands of different configurations to determine what configuration can take the team to 10,000 feet with the smallest mass.

Engine development was loosely based on last years design, but major differences exist. The team last year used nitrous oxide and ethanol, stored and pressure connected by concentric tanks separated by a piston. The team last year had the engines injector at the base of this propellant tank, followed by a wood combustion chamber liner with
a graphite nozzle at the end. This configuration became very long and not only difficult to machine and handle, but easily capable of reaching a harmonic resonance caused by the vibrations in the combustion chamber. The close proximity of the injector to the propellants was also an undesirable feature. It is not fully understood why the engine failed last year, though it’s believed these features were somewhat responsible.

For these reasons the team determined it would be best to separate the propellant tanks and combustion chambers, which required a new form of actuation, a new injector, and a lot more plumbing. This new configuration allowed for a safer and more robust system that could also create better mixing in the combustion chamber, and thus better performance. Slide check valves, actuated by the explosion of a nylon bolt that was fastening a support mechanism, were developed to allow propellant flow. A hexagonal piece of brass stock is centered inside the nitrous flow hole, where 6 holes perpendicular to the direction of nitrous flow jets ethanol into the nitrous, allowing ethanol to mix with the nitrous oxide at the entrance. However, designing, machining, testing, and implementing all of the hardware necessary for this system to work was quite a daunting task.

Figure 6: Small scale

The system was tested more than a dozen times before a satisfactory burn was achieved. In the process the team learned a lot, and all subsystems became much more robust than initially designed. The team has since had a half dozen consecutive successful test fires with consistent thrust and pressure data.

Figure 7: The small scale engine at ignition

Figure 8: The small scale operating under steady state conditions

This thrust and pressure data predicts that the system has a specific impulse of 220 s ± 20s. This performance is about 30% better than the engine developed last year.
This thrust data was imported into the trajectory analysis code where it was scaled by a thrust factor which corresponds to increased mass flow in the subsystem, and a time factor which multiplied the duration of the thrust, the product of these factors determines the volume of the tanks. The code then added the mass of propellant necessary to accomplish this, as well as the aluminum necessary to contain it to the predicted mass and height of the Aries IV, which was then launched and the predicted apogee reported. The most mass efficient configuration from these thousands of configurations that was capable of fitting in the Aries IV framework was then selected.

The full scale design is currently being machined by the team is expected to be tested by May and should be integrated into the Aries IV well before the first day of the IREC competition.

2.3 Flight Control Systems

Considering the primary objective of the competition is “to fly as close to the target apogee of 10,000 feet as possible” and that the atmospheric sampling payload would work ideally by starting at a predictable and consistent altitude, any opportunity to widen the acceptable design margins of the liquid motor can significantly increase the overall performance of the rocket at the competition. To this end, the Flight Control Systems (FCS) Team was founded to develop a solution for affecting the flight-path of the rocket. With the current system, the FCS team has increased the acceptable maximum theoretical final apogee by 20%, another 2,000 feet, with the intent of using that added height to provide the liquid motor more leeway in its design while allowing the final rocket to have as good a chance as possible to precisely meet the 10,000 ft goal of the competition. This system utilizes a suite of sensors and an air-braking mechanism to carefully slow the rocket the required amount.

Initially, the FCS Team was inclined to follow in the footsteps of the previous years team. The objective was to develop a roll-control system using four grid fins each attached to an independently-actuated and custom designed servo gearbox. This system would be expandable to full pitch/yaw/roll control and also be capable of air-braking, with the advanced mechanical hardware serving as the first major milestone. After review, the 2017 team’s work was deemed underwhelming in terms of mechanical strength and robustness, and completely inadequate in terms of angular precision. Review of the previous work on electrical hardware determined that a total redesign was required in order to make the system realistically flight-ready or even feature-complete.

The decision was made to continue on the stated objective but to completely scrap the existing work. In its place, a new electrical hardware scheme was developed and a completely new servo gearbox was designed, taking advantage of 3D printed photopolymer technology to be 10% lighter, 35% more compact, and approximately 200% more rigid. These new gearboxes, shown in figure 9, were rigorously ground tested and ultimately provided an angular output accuracy of +/- 1 degree, a six-fold improvement from the previous design.

Figure 9: Photopolymer servo gearbox

After approximately two months of work on the system, it was flown in a static, unactuated test flight at the beginning of December. While the static grid fin accuracy proved adequate for a stable flight, the rocket gyrated enough on launch to generate concern for whether or not the gearboxes were sufficiently accurate enough to predictably alter the flight-path. When the recovery system failed and the rocket was destroyed and over $600 in FCS hardware was lost the opportunity was taken to re-assess the objectives and progress of the FCS Team. At this point, the consideration was made that even in an
ideal situation, full pitch/yaw/roll control would only provide a maximum increase the final apogee of the rocket about 5%, or feet. Further consideration determined that the FCS Team did not possess the personnel, resources, or time to adequately improve the system and approach this desired 5% improvement.

This led to a complete paradigm shift for the FCS Team towards a robust, single-actuator air braking system. Working closely with the propulsion team to significantly overdesign the liquid motor, the FCS Team was able to increase the design margin of the theoretical apogee from \([9,500-10,500]\) feet up to \([10,000-12,000]\) feet.

The prototype of this system was developed in under a month and utilizes a much more robust sensor suite designed into a rigid shield attached to the main flight computer. This electrical system is driving a four-flap mechanism driven by a single motor. By turning a lead screw, this motor moves a plate up and down, actuating a simple linkage mechanism to accurately adjust the angle of each flap in tandem with accuracy up to 0.1 degrees. This prototype system, which was successfully flown and actuated during a test launch to 3,500 feet, is shown in figure 10.

This test flight successfully validated the mechanism and performed, in every way, according to the expectations of the FCS Team. The data acquired on this launch will allow us to work backwards to an experimental drag coefficient for the air braking flaps and help determine a final sizing of those flaps. It also completely validated the main avionics cluster by acquiring accurate data throughout the flight at the expected sampling rate. With this incredibly successful test, the FCS Team is able to confidently move forward with the 8” design for the system, which contains the same avionics module alongside an advanced, custom design printed circuit board handling power conditioning, I/O, and a robust failsafe system capable of collapsing the fin mechanism in as little as a second in the event of a failure. This 8” system is shifting to a two-flap design to accommodate the needs of the recovery team as well as to avoid washing the stability fins in too much wake. This system is well underway and slated for completion in mid April. CAD of this 8” air braking module is shown below in figure 11.
2.4 Payload

This year the Aires IV payload is an atmospheric sampling device. The design consists of 4 airtight square steel tubes each with a solenoid to control airflow. Figure 12 below shows the general layout.

![Figure 12: Layout of payload](image)

Every 2500 feet as the rocket descends by parachute the device will suck air into evacuated chambers by releasing the vacuum within. These samples will later be analyzed for concentrations of methane and carbon dioxide back on the ground. The size and amount of airborne particulate will also be monitored from launch until the rocket lands using a second device supplied by Colorado State University’s Atmospheric Science Department. The goal of the experiment is to try and determine whether greenhouse gases are actually well mixed throughout the atmosphere. The Space Dynamics Laboratory (SDL) has joined with Spaceport America Cup and IREC and developed a separate payload portion of the competition. They encourage participants to create payloads that accomplish a relevant function and provide useful learning opportunities. Payloads are judged on the following four criteria: Scientific or Technical Objective(s), Payload Construction and Overall Professionalism, Readiness / Turnkey Operation, and Execution of Objective(s). The payload is required to weigh at least 8.8lbs and can be as large as needed for the experiment as long as it is made up of CubeSat Units ((Units x 10cm) ×10cm×10cm).

2.5 Recovery

Recovery of the rocket is accomplished by a dual-deployment system utilizing 2 parachutes to return the rocket to the ground undamaged. The system consists of a 5 foot diameter round parachute that will deploy at apogee of the flight. This allows the rocket to fall rapidly while still in a controlled manner to minimize the influence of any wind.

![Figure 13: Diagram showing advantage of dual-deployment](image)

At 1000 feet the main parachute deploys in order to slow the rocket further to its desired landing speed of under 25ft/s. The main parachute shown in figure 14 is a 10 foot by 10 foot square parachute based off of the military’s new T-11 design. Both parachutes will be constructed from ripstop nylon and 275 paracord. Critical seams are reinforced by sewing in a half inch nylon strap.

![Figure 14: Square parachute](image)

Last year’s team developed a very reliable parachute ejection system that we are reusing. The system features redundant electronics utilizing two different barometric dual-deploy altimeter systems, the Missile Works’ Rocket Recovery Controllers RRC3 and RRC2+. These will be connected to both ejection systems and will release a large amount of current through electric matches when it is time to deploy
the parachutes at their predetermined event altitudes. A piston assembly will be used due to its increased reliability, reusability and need for significantly less black powder. Figure 15 is a diagram of the piston ejection system.

![Diagram of Piston Ejection System](image)

**Figure 15: Piston ejection system**

### 3. Conclusion

The Colorado State University rocket team should be competitive at the IREC competition in June 2018. The composite airframe minimizes weight while reducing drag. The liquid motor is technically challenging and will propel the rocket to 10,000 feet. The flight control system will earn the team innovation points as it predicts apogee in-flight and air-brakes to correct the trajectory. The atmospheric-sampling payload will score high in its category for scientific merit and performance. Lastly, the recovery system with the square parachute will return the rocket safely to the ground in a state that is ready to relaunch. With more ground testing of the sub-systems and full-scale integrated flight tests, the team will be more than prepared for the IREC competition.

### 4. References


