Lightweight Composite Sounding Rocket with Deployable CanSat

Bret C. Keller,[1] James Cox,[2] Alex Kroll[3], Andrew Boggeri[4], Keith Graham[5]
University of California Los Angeles

and

Sara M. Wales[6] and William Hourigan[7]
University of California Los Angeles

With the advent of advanced materials comes the ability to design aerospace structures that are both lightweight and strong, thus allowing for the construction of small rockets with comparatively large payloads. The UCLA AIAA Rocket Project has designed such a rocket. It consists of a carbon fiber body, with carbon-fiber reinforced fins, and a custom fiberglass nosecone as to allow for radio signals to penetrate. The fins attach to a custom slotted 98mm fiberglass motor mount. Electronics in the nosecone allow for real-time altitude and GPS tracking, as well as provide calculated dual deployment for the rocket. The payload consists of a CanSat that deploys at apogee, which has the following capabilities: panoramic photography during entire decent, real-time GPS location, as well as air temperature, humidity, pressure, and density profiling. The recovery system for the CanSat will be a helicopter style rotor during entire descent. This allows for a constant rate of descent which is essential in profiling. A 5000N·s motor allows for a maximum altitude of 13,000ft with the CanSat in the payload bay. This is due to the overall weight of the rocket being approximately 30lbs. This rocket shows that with new materials and rocket construction techniques we can do much more with much less.

Nomenclature

D = diameter
W = weight of rocket
C = constant used in black powder calculation based on psi desired
L = length of pressurized section with black powder ejection charge
m_{BP} = mass of black powder
$\dot{m}_g$ = mass flow rate of the propellant
ρ_g = propellant density
A_b = burn area
r = regression rate of the propellant
a = constant, determined empirically
n = constant, determined empirically
A_0 = engine chamber pressure

I. Introduction

THE purpose of this paper is to communicate the design of our rocket to the aerospace community. In doing so we hope that we can get welcomed feedback both on the report itself and the design of the rocket. This is

---

[1] Project Manager, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[2] Project Director, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[3] Payload Lead, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[4] Electronics Lead, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[5] Aerodynamics and Structures Lead, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[6] Recovery Lead, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member
[7] Propulsion Lead, UCLA AIAA Rocket Project, Engineering IV 38-138A, Student Member

everyone on the teams first time both designing a sounding rocket and writing an AIAA paper. We hope to use this experience for future years to really make unique designs and well-written reports both in academia and jobs.

We designed our rocket on one simple principle, the lighter one component of a rocket is, the rest of the components become lighter as well. However, this is harder than it sounds. Composite and advanced materials must be used in order to accomplish this.

Another goal of ours was to design and build as much of the rocket as possible since we will be competing in a student competition. We will be competing in the 3rd Annual Experimental Sounding Rocket Competition put on by the Experimental Sounding Rocket Association in June. This was a hard task for us as none of us really had any experience in manufacturing or rocket design. However, with the help of our advisors and a couple of friends from the rocketry community we were able to come up with a design and the methods to build it.

The goal of the competition, and thus our main goal, is to design and build a rocket that would go to exactly 10,000ft with a payload that weighs 10lbs. After looking at other rockets that have tried to accomplish this, we determined as a team that they were too big and heavy, and that the best rocket would be one that was designed to be as light as possible. We accomplished this by using the lightest, strongest materials we could find and molding them into a rocket.

II. Design

Aerodynamics and Structure

Airframe

The airframe has been designed to be light and incredibly strong, employing a composite structure of bi-axial carbon-fiber and epoxy resin. The inner diameter of the airframe was selected at 4.5" in order to comfortably fit a 98mm rocket motor mount. Using classical lamination theory, the ratio of airframe wall thickness to compressive strength was determined. The maximum expected load on the airframe was then used to determine the minimum wall thickness of the airframe, with a safety factor of 2. However, this calculated wall thickness was too thin to work with the rest of the rocket structure, so the thickness was increased to 0.0625". This results in an airframe with a safety factor larger than 10. The airframe will be constructed in two 4' sections, and later joined with a fiberglass coupler tube to form the complete 8' airframe section. It will have 3 slots cut at 120 degree intervals for the fins.

Motor Mount

The motor mount is designed to transmit the thrust force exerted by the motor safely to the air-frame. The motor fits inside a fiberglass tube, and transmits all its thrust to the aft end of the fiberglass motor tube. 3 Centering rings, with a total thickness of 1 inch each, rings are glued with epoxy from the outside of the motor tube to the inside of the airframe. The centering rings are composed of ½ inch birch plywood, sandwiched between ¼ inch G-10 fiber-glass. This configuration of materials provides excellent strength and impact resistance, while remaining very light. Large fillets of epoxy and filler material are added to the fin-tube junction, providing a large radius of curvature in order to add strength and reduce stress concentrations on the fin-tube junction. Epoxy and carbon-fiber cloth are used on the exterior fin/tube junction to add stiffness to the fin assembly and create a smooth contour to reduce interference drag. This entire structure effectively spreads the forces of the motor to the airframe through the fins and centering rings. A very large safety factor is obtained with this design.

Fins

Fin shape and has been optimized on the basis of strength, aerodynamic effects, and stability. The fins will be cut into a trapezoidal shape, which minimizes aerodynamic drag and provides a suitable stability margin as determined by center of pressure calculations. The leading edge of the fins will be rounded to minimize flow separation, while the trailing edges will be made into sharp points to further reduce the drag. The width of the fin has been chosen to maximize stability, and minimize an effect caused by vibrations known as "fin flutter."

We will use three fins spaced evenly around the body of the rocket near the base. The base of each fin will be epoxied to slots built into the motor mount. The airframe tube will have three corresponding slits cut into it from the bottom. The fins will be cut from a pre-manufactured 12”x12"x.125” sheet of G-10 phenolic fiberglass.

Nosecone

The nosecone will be the more difficult endeavor as it will require us to mold our own design using fiberglass. The shape of the nosecone will be a von Karman Ogive with a total length of 18” and a base diameter of 4.5”. To create the nosecone, a mold must be made, using a 1.5 ounce fiberglass mat and a polyester resin. Carnauba wax, typically used for cars, will be used as the release agent. We will also be using PVA (polyvinyl alcohol) and non-drying modeling clay to create the mold. Once the mold is created the fiberglass part can then be created. The nosecone will be made sufficiently thick to support all of the loads and stresses we expect to see during our flight.

Electronics

1. *Rocket Control and Telemetry (C&T) System Overview*

The control and telemetry system of the rocket is designed to monitor a number of onboard sensors and report data to the base station in real time using a serial data radio. The C&T system is also responsible for carrying out the autonomous functions aboard the rocket, parachute deployment and payload separation. The system is being built around an Arduino microcontroller module with processing power provided by an Atmel Mega168 8-bit RISC microcontroller. The Arduino monitors an atmospheric pressure sensor, accelerometer, altimeter, and GPS module to determine the rocket's location, heading, velocity and altitude. Telemetry data is sent over the serial radio link to the ground station for recording and post-mission analysis. GPS telemetry is used primarily for recovery operations, as the rocket's launch velocity causes its data rate to lag significantly compared to the rocket's position.

2. *C&T System Components*

The C&T system is composed of an Arduino microcontroller module, Digi serial data radio, GPS module, multi-axis accelerometer, atmospheric pressure sensor, commercial hobby altimeter, and a high-power driving system for parachute deployment.

3. *Flight Computer*

We are writing a custom, low-level flight computer to be run on board the Arduino. The driving reasons for choosing Arduino were cost and ease of use. The Arduino project is released under the Creative Commons license, which means that anyone may use their designs and code and reproduce them for any purpose. Arduino modules are available from a number of retailers, and are very inexpensive in total cost to develop on. Most microcontrollers require additional software and hardware to develop on, leading to increased cost and complexity, the Arduino project has designed a boot loader for the Mega168, which ships with every Arduino board. This boot loader allows code to be loaded over a serial or USB link directly to the Arduino, which immediately begins executing the code. This significantly shortens development time and cost, as programming hardware is not needed, and the software to compile code to the Mega168 is freely available from the Arduino project website.

The flight computer is not very complex as its main function is to gather sensor data and relay it over the serial radio link to the base station for recording. The other task that the flight computer will carry out will be payload and parachute deployment. Based on the data gathered from each sensor, the microcontroller will deploy the CanSat payload and recovery parachutes at predetermined altitudes; should a failure occur the ground station will have the ability to override the microcontroller and deploy the parachutes/payload remotely.

4. *Sensors*

We have decided on the types of sensors to use, and their data communication interface. Most of our sensors will be purchased as breakout boards from Sparkfun Electronics. The GPS unit uses a SiRF Star III sensor unit and an integral patch antenna. The accelerometer will be an inexpensive unit from Analog Devices or Honeywell. The altimeter will be an ALT-05-50K provided by Adept Rocketry and the pressure sensor will likely be custom fabricated.

Radio Communications

Serial communications will be achieved using a Digi serial data radio, either in the 2.4GHz or 900MHz frequencies. Because our required bandwidth is modest, the over the air data rate we are using will be 115K baud. This lowers power requirements and allows for longer range communications.

Parachute Driver

The parachute deployment driver will consist of a simple transistor setup capable of driving up to 1 amp on a yet to be decided number of channels. This module will be activated from the Arduino upon reaching a set altitude. In case of a code failure, there will be a manual failsafe that can be activated over the radio link.

Recovery System

The rocket employs a dual deployment system. At apogee a black powder charge will deploy the drogue chute and our CanSat payload. At 1,000' above ground, the main chute will deploy.

1. Parachutes

The drogue chute slows the rocket's decent to ensure safe deployment of the main parachute, while maintaining a fast terminal velocity to minimize drift. To find the rough size of the drogue chute, we used the following equation.[1]

$$D = 24 * \sqrt{0.14 * W} \tag{1}$$

This equation assumes terminal velocity of 50ft/s. Rounding up, the diameter of the drogue chute is 28"[1] We plan to sew our own drogue chute in a round design made from nylon cloth and reinforced at all attachment points of the cords.

We choose to use a hemispherical design to minimize the necessary diameter of the main parachute. For main chute sizing we used the following equation.[1]

$$D = \sqrt{W * 0.454} * 39.6 \tag{2}$$

This equation assumes a terminal velocity of 15ft/s. The main chute requires a diameter of 54" in order to meet the requirements. We plan to sew this parachute as well using an eight panel design cut out from blue and yellow colored nylon fabric.

To decrease tangling the parachute cords will use swivels to secure the parachute cords to the rocket frame. Squares of Kevlar fabric will also be used to protect the chutes from the black powder blasts.

2. Black Powder Ejection Charges Sizing

As this is the first year of our team we chose to use a black powder recovery system over CO_2 canisters. This saves us weight and increases the reliability of the system. To size the amount of black powder needed we used the following equation.[1]

$$C * D * D * L = m_{BP} \tag{3}$$

Where C is a constant based off of cabin pressure, psi, desired (C = 0.002 for 5 psi, C = 0.004 for 10 psi, C = 0.006 for 15 psi, C = 0.0072 for 18 psi, C = 0.008 for 20 psi). Using this calculation, the main chute requires 3 grams of FFFFg black powder and the drogue chute with the payload requires in 3.5 grams of FFFFg black powder. All of the calculations were rounded up since it is better to generate slightly more force than anywhere under the amount of force needed.

Based on the amount of FFFFg black powder needed, we chose to make our own ejection charge canisters from polyethylene tubing (1/2" O.D., 3/8" I.D.), and four low current Daveyfire SA2000 N28BR electric matches, bound using a hot glue gun. For redundancy we will use two matches per ejection charge canister.

Propulsion

For the purposes of providing propulsion for our engine there are several options. As this is the first year that this team has constructed a rocket, we pursue the simpler options; either a hybrid motor or a solid motor, single stage. Due to its relative lack of complexity and reliability of use, we opt to use a solid rocket motor for rocket. Though a solid rocket motor cannot be throttled and burns completely once ignited, it does not require moving parts and may still give us a relatively accurate altitude achievement through proper calculation.

In our determination of our propulsion system, we considered the two alternatives of purchasing a commercial engine and constructing our own engine. In this process, we had to determine the risks and benefits of either choice.

1. Commercial Engine

In buying a commercial engine, we would be given the benefit of knowing the empirically determined data on thrust, Isp, and flight time of the engine we were using. Perhaps more critically, this would save us the need for all the equipment and administrative obstacles to building our own engine. The phrase "this isn't rocket science" did not arise out of thin air; it requires precise calculations and has potentially hazardous consequences of errors. As such, to do all that is necessary to build our own engine was to incur substantial risk.

The use of a commercial engine limits the range of possibilities with regards to performance, but offers significant benefits concerning ease of installation and accessibility to pertinent information. The purchase of a motor is limited by the permits one has buy it; for our motor, we would be limited to a 98mm L motor due to the certification required in acquiring more powerful motors.. Given that we are launching a 10lb payload to an altitude of 10,000', this is the lower limit of what engine size will allow us to complete our mission. Also, as the motor is fabricated with a predetermined thrust, specific impulse, and burn time, the rest of our rocket, such as mass and airframe, must be tailored such that our maximum altitude is as close as possible to our goal of 10,000ft.

2. Student-built Engine

The alternative to buying a commercial engine is to build our own engine. In doing so, we would be able to tailor our engine to meet our rocket's specifications, rather than the opposite. However, there are logistical obstacles to doing so. One reason is that it is difficult to procure the necessary licenses for purchasing the chemicals needed to construct a rocket engine and for their storage. In constructing our own engine, we have determined that ammonium perchlorate is the most suitable fuel for the construction of our motor. From the design of our airframe, we know that our motor diameter must not be more than 98mm. Given our payload weight, along with that of the airframe, structures, electronics, and recovery system, we must have enough thrust for liftoff and vertical acceleration; this is dependent on the mass flow rate of the propellant. This is in turn dependent on the surface burn area of the solid propellant[2]:

$$\dot{m}_g = \rho_g A_b r \qquad (4)$$

$$r = a P_0^n \qquad (5)$$

Because the constants *a* and *n* are empirically determined, we selected an ammonium perchlorate propellant as there is more historical data available with regards to these calculations.

The burn area of the propellant is dependent on the length of the engine bore and the cross-sectional cast shape. By casting the propellant in differing cross-sectional areas, the overall burn rate of the propellant can be regressive, constant, or progressive. To cast the propellant, it must first be prepared. Doing this by hand would require a heavy duty mixer for the mixing of fuel, oxidizer, and binder. Also, the casting of the propellant requires a hot water bath to provide the heat to set it in its mold. This should be done using an electric heat source; in the interest of safety, the propellant must not be prepared near an open flame, nor heated over one.

Proper design encompasses the possibility that a design alternative will not be feasible. Our purpose is to build our own engine from scratch, to determine each specification from calculations and empirical and historical data. If the logistical hurdles to that are insurmountable within our timeframe, however, we must be able to still power our rocket. As such, our rocket specifications are optimized for a 98mm L engine, and our own engine is being designed to fit our rocket specifications. For future years, knowledge gained from the design process will allow us to optimize the relation between motor and engine with regards to our own design.

CanSat

1. CanSat Mission

This CanSat payload was designed with the goal of providing simple reconnaissance tasks to inaccessible areas. The CanSat provides local atmospheric conditions as well as panoramic photography of an area for possible use in military applications without risking the lives of personnel. The CanSat is also designed to be inexpensive and expendable, though repeated use is possible. The capabilities of the CanSat include: real time telemetry, GPS, live video feed, panoramic photography at varying altitudes, and air temperature, pressure, humidity, and density measurements.

2. CanSat Structure

The CanSat structure is designed to be very simple: internal frame to mount components, with a thin protective skin. Due to the size of the rocket, the dimensions of the CanSat are designed to be larger than a typical CanSat. The length of the CanSat will be 10" and have an O.D. of 3.5". This sizing will allow for proper fitment of the CanSat into the payload compartment of the rocket. The internal frame will be made from aluminum for strength and lightweight properties. The skin of the CanSat will likely be a thin carbon fiber sleeve. This structure will provide essential strength to support the internal components and protect them from shock while also maintaining minimal cost and weight.

3. CanSat Recovery

The CanSat utilizes two free-rotating helicopter blades for recovery. The blades, by freely-rotating, should slow the CanSat enough to ensure a safe landing. The blades are estimated to be about 18" long and 2" in chord. The blades will be hinged and folded along the outside of the CanSat to allow fitment inside the rocket. Upon ejection of the CanSat, the blades will be deployed via a spring loading mechanism. Helicopter blade recovery was selected over basic parachute recovery to minimize complexity of the CanSat and minimize drift in high wind conditions.

4. Camera System

There are several considerations that need to be made in the selection and implementation of the camera system. These considerations include shock resistance, battery power, weight, and the question of real time transmission versus on-board recording. We narrowed our selection to two contenders – a commercial solid state camera from Oregon Scientific Inc. and a wireless transmission camera from Black Widow AV.

The first consideration was that the camera survives the g-forces not only at the launch, but also at the decoupling of the CanSat from the rocket. The Oregon ATC2K already has significant shock resistance while the Black Widow AV KX-131 camera would need to be mounted with custom shock absorbers. Power consumption was also a paramount criterion. The ATC2K runs with onboard AA batteries for over one hour while the KX-131 requires a 5V, 120mA external power source. This power requirement was within the reach of the CanSat's capabilities but would come at the expense of either added weight or added cost. Finally, while the ATC2K had 32MB on-board recording which could be expanded to 2GB through an SD card, the KX-131 had no on-board recording and instead relied on the use of a 2.4GHz, 50mW uncased transmitter/receiver set. While this may seem a more cumbersome option, there are several advantages to having a transmitted recording. The most obvious advantage is that should a component of our CanSat fail, we would still obtain video up to the point of failure. In addition, the KX-131 also has the option of several wide angle lenses from seventy to 116 degrees along with the added benefit of a weight of 0.8 ounces compared to the ATC2K's weight of 19.2 ounces.

All of these considerations had to be evaluated against each other before a final decision could be made. With the limitations in mind, we chose to use the KX-131 due to its higher degree of customization, larger lens width, lower weight, and transmission capabilities. The deciding factor was the panoramic capability we would achieve with a wide angle lens; a capability which lies at the base of the camera's purpose.

5. Air Sensors

The CanSat will employ air pressure, temperature, humidity, and density sensors to provide ground operators with real time atmospheric condition profiling. These sensors will be fed to an onboard micro-controller, and then relayed back to a ground station, along with other telemetry information. This information is not expected to greatly increase the bandwidth requirements of the transmitter. Air data sensor manufacturers have not yet been explored, however it is expected that these sensors make up a minimal fraction of the CanSat’s weight and cost.

6. *Telemetry and GPS*

The CanSat will integrate the GPS and telemetry systems. A high refresh GPS unit has been selected to provide the most up to date location information as possible. The unit is the MN3310, manufactured by Micro Modular Technologies. The unit requires a 3.3V, 150mW power supply, which will also be used by the telemetry and microcontroller. The accuracy of the unit is less than 3m. The small size of the chip of the receiver chip ensures that the chip can be properly integrated into the CanSat.

All this information will be transmitted from the CanSat via a MaxStream 9Xtend wireless modem. This unit utilizes a 1W, 900 MHz transmitter with a maximum range of 40mi. This unit is a low cost, low weight transmitter that will more than suit the needs of the CanSat. This transmitter will also be used by the rocket telemetry system until apogee.

III. Results

A. Simulated Launch

To test our rocket we designed a rough sketch of it using RockSim[3]. The position of the 10lb payload has been chosen to keep the center of gravity well forward of the center of pressure, providing stability during the flight. It was found that the center of gravity is located at 61.1” from the tip of the nosecone, while the center of pressure is located at 73” from the tip of the nose cone. This gives a margin of 2.49 calibers, so the rocket is stable. Using this model we simulated a launch using an Aerotech L952W motor. Our results were great. The results (Appendix A) show that our rocket was able to reach an altitude of 10,524ft, which is only slightly above our goal of 10,000ft as set forth by the competition. This is also one of the lowest total impulse motors we could find for 98mm L motors.

B. Weights

The wet weight of the rocket was determined to be about 30lbs as seen from Table 1. Weights were determined by looking at each component of the rocket and then totaling those weights. It is interesting to note that our rocket without payload or motor is about 10lbs, our motor is about 10lbs, and our payload is 10lbs.

Table 1. Component Weights

Component	**Approximate Weight (lbs)**
Payload	10
Airframe	3
Fins	1.5
Nosecone	1.5
Electronics	.5
Recovery System	1.5
Nozzle	3
Dry Weight	20
Motor	10
Wet Weight	30

IV. Conclusion

In conclusion, we were able to design a rocket that would meet the specifications of the completion. We can easily meet the altitude requirement of 10,000ft. This is due to the fact we are designing the rocket to be able to use almost any rocket motor, whether we design and build the motor or buy a commercially available one. Although the CanSat does not weigh 10lbs, we can include passive payload attached inside the rocket to make up the difference while still obtaining the optimal altitude. Designing the CanSat gives us the opportunity to be able to compete in the CanSat intercollegiate competition in Texas if the design works well in our own rocket. With all this capability our rocket still only has a wet mass of 30lbs, which is less than half the weight of a rocket with similar capabilities. This is very important as it shows that by using composite materials and carefully thought out designs we can build a rocket that does much more with much less.

Appendix

A. Full RockSim Data

AIAA - Simulation results
Engine selection
[L1300R-None]
Simulation control parameters
Flight resolution: 800.000000 samples/second
Descent resolution: 1.000000 samples/second
Method: Explicit Euler
End the simulation when the first recovery device is deployed.
Launch conditions
Altitude: 5000.00002 Ft.
Relative humidity: 50.000 %
Temperature: 85.000 Deg. F
Pressure: 29.9139 In.
Wind speed model: Calm (0-2 MPH)
Low wind speed: 0.0000 MPH
High wind speed: 2.0000 MPH
Wind turbulence: Fairly constant speed (0.01)
Frequency: 0.010000 rad/second
Wind starts at altitude: 0.00000 Ft.
Launch guide angle: 0.000 Degrees from vertical
Latitude: 38.800 Degrees
Launch guide data:

Launch guide length: 36.0000 In.
Velocity at launch guide departure: 26.7863 ft/s
The launch guide was cleared at : 0.285 Seconds
User specified minimum velocity for stable flight: 43.9993 ft/s
Minimum velocity for stable flight reached at: 95.4318 In.
Max data values:
Maximum acceleration:Vertical (y): 181.061 Ft./s/sHorizontal (x): 0.205 Ft./s/sMagnitude: 181.073 Ft./s/s
Maximum velocity:Vertical (y): 791.5032 ft/s, Horizontal (x): 0.0000 ft/s, Magnitude: 791.5422 ft/s
Maximum range from launch site: 309.18616 Ft.
Maximum altitude: 10524.09562 Ft.
Recovery system data
Time data
Time to burnout: 6.701 Sec.
Time to apogee: 27.261 Sec.
Optimal ejection delay: 20.560 Sec.
Landing data
Crash landing!
Time to impact: 54.576 Sec.
Range at impact: -309.18616
Velocity at impact: Vertical: -692.4440 ft/s , Horizontal: -4.1208 ft/s , Magnitude: 692.4563 ft/s
Competition settings
Competition conditions are not in use for this simulation.

Acknowledgments

The AIAA UCLA Rocket team would like to thank George Cassar and Raytheon for their generous donation to our program that allowed for the design and construction of our rocket. We would also like to thank UCLA and the Department of Mechanical and Aerospace Engineering for providing space for our meetings and rocket assembly.

Special thanks to our faculty advisor, Dr. Richard Wirz from the Jet Propulsion Laboratory for offering to help us start this great UCLA tradition.

We are also grateful for the Experimental Sounding Rocket Association providing a great intercollegiate sounding rocket competition.

Finally, we would like to thank Arizona State's Daedalus team for helping us get this team started. They provided much needed advice when we had nowhere else to turn to.

References

[1] INFOcentral. 2000. Rocketry Online. March 25, 2008 <http://www.info-central.org/index.cgi?recovery>.

[2] Philip Hill, Carl Peterson. *Mechanics and Thermodynamics of Propulsion* (Addison-Wesley Publishing Company, 1992) pp. 598.

[3] RockSim, Ver. 8.0, Apogee Components, Colorado Springs, CO, 2008.