Analysis and Design of an Affordable High Altitude Rocket System

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This paper discusses the design of the Rarefied High-Altitude Zenith Experimental Rocket (RHAZER) which is launched at an altitude of 35 kilometers from a weather balloon. The weather balloon is capable of carrying up to 2 kilograms of payload to this altitude, and the rocket can carry a payload of approximately 150 grams to an altitude of at least 80 kilometers and be recovered safely after landing. It is designed to be aerodynamically stable at its launch point, while using fins to spin-stabilize before it enters the low-pressure upper atmosphere. This system has been designed to be used as an educational tool by K-12 schools, so affordability has been the primary driver.

Nomenclature

A	=	aspect ratio, area
C_D	=	drag coefficient
c	=	root chord length
E	=	modulus of elasticity
F_D	=	drag force
FI	=	flutter index
G	=	Earth's surface gravitational acceleration, 9.81 m/s^2
G_E	=	shear modulus
I	=	area moment of inertia
k	=	column buckling length factor
L	=	unsupported column length
m	=	meters
mm	=	millimeters
P	=	static pressure, force applied to column
P_0	=	sea level static pressure
P_{cr}	=	column buckling force
t	=	fin thickness
V	=	velocity
V_a	=	speed of sound
V_f	=	flutter onset velocity
X	=	geometric flutter parameter
λ	=	ratio of tip chord length to root chord length
ρ	=	atmospheric density

I. Introduction

The region of the upper atmosphere between the operational limits of high altitude balloons and low Earth orbit satellites is still of great importance despite the relatively limited class of vehicles that operate continuously at these altitudes. Any vehicle launching from the Earth or re-entering the Earth's atmosphere must traverse this region, so it is necessary to understand the dynamics of this traversal with great detail. Sounding rockets have served this purpose for many years, but it is difficult to launch a scientific payload that can measure the minute changes in pressure and density at high altitudes while still surviving the high-stress environment at lower altitudes. Therefore, it would be useful to have a system that allowed a scientific payload to move gently through the thick, lower atmosphere, and then ascend above the operational limits of high-altitude balloons to conduct experiments in the region just below orbiting satellites. Additionally, a balloon-launched system has the potential to be considerably more affordable than a ground-launched alternative. This paper will focus on the design of such a system. A weather balloon will climb to an altitude of 35 kilometers, with the option of carrying two different payloads. If the experimenter wishes to investigate only the region of the atmosphere below 35 kilometers, then these experiments will be contained in a payload box hanging from the balloon. If there are experiments that require altitudes above 35 kilometers, a rocket will be hung from the payload box with the necessary equipment inside. Once the balloon reaches 35 kilometers, a signal will be sent from the ground to launch the rocket and activate any on-board experiments. The rocket will then ascend into the more rarefied regions of the atmosphere. Both the rocket and the payload box will be designed to be modular, in that the user can easily plug any equipment into the pre-existing systems with only minimal instructions. The system will be designed primarily with affordability in mind to allow easy access to space.

II. Trajectory Simulation

To begin the analysis off this system, a MATLAB® program was written to integrate the equations of motion of the rocket over time to determine the maximum altitude, velocity, and acceleration of the rocket. It was assumed that the only forces acting on the rocket were the motor's thrust, gravitational acceleration, and atmospheric drag. Therefore, the vertical motion of the rocket as it is ascending can be described by the equations

$$a_y = \frac{T}{m} - g - \frac{\rho V^2 C_D A}{2m} \quad \Delta v_y = a_y \Delta t + v_y \quad \Delta y = v_y \Delta t + y \tag{1}$$

where a_y is acceleration, T is thrust, m is the rocket's mass, g is Earth's gravitational acceleration, ρ is the air density, V is the velocity, C_D is the drag coefficient, A is the rocket's cross-sectional area, v_y is the velocity, and y is the altitude. By summing the differential changes in velocity and altitude due to the changing acceleration, the motion of the rocket can be determined.

The following requirements were used to select the motors:

1. At minimum, the rocket shall reach an altitude of 80 kilometers. NASA designates any person who has flown above this line as an astronaut, so this can be considered NASA's definition of space.
2. The maximum acceleration and duration of large accelerations shall be limited to allow for relatively fragile payloads.
3. The rocket shall be designed to carry enough weight to allow for tracking equipment and a small experiment.
4. The largest motors that can be used shall require no more than a Class 1 rocketry license to purchase. This requirement was imposed to make the entire system easier to purchase and build for anyone who wants to utilize it as an experimental platform

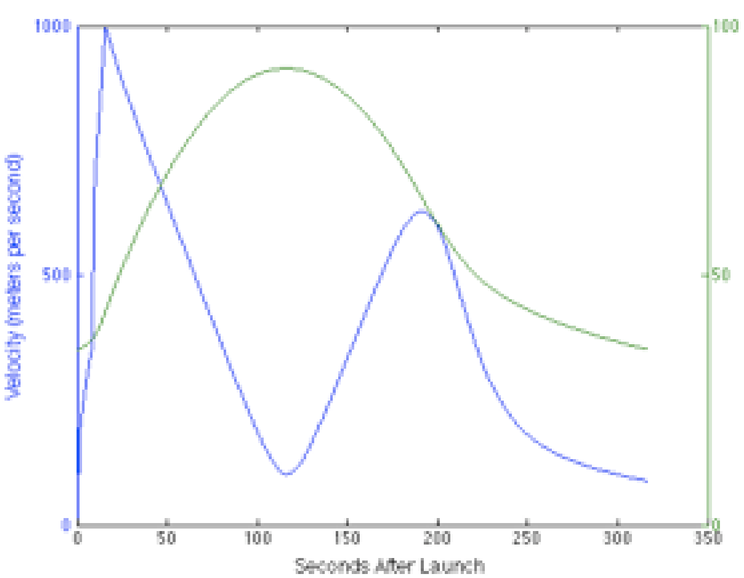

Figure 1. Velocity of the rocket after launch with the resulting altitude attained.

After running the program with many different classes and numbers of motors, it was decided to use the Aerotech I59 motor staged twice. This configuration allows for 0.25 kilograms of fairing, equipment, and experiment mass while achieving an altitude of over 90 kilometers, which allows for a margin above the 80 kilometer requirement. The velocity of the rocket throughout the flight is plotted along with its altitude in Fig. 1. All of the figures in this section are plotted for a rocket launching from 35 kilometers altitude with an initial angle of 5 degrees with respect to vertical. The reason for the 5 degree tilt will be discussed in the component design section. Additionally, the velocity and acceleration plots are absolute values. Regardless of whether the rocket is moving/ accelerating upwards or downwards, the value is plotted as positive. The altitude plot shows that the rocket follows a parabolic arc for nearly 150 seconds, which allows for approximately 2.5 minutes of weightlessness for any experiments inside. The magnitude of

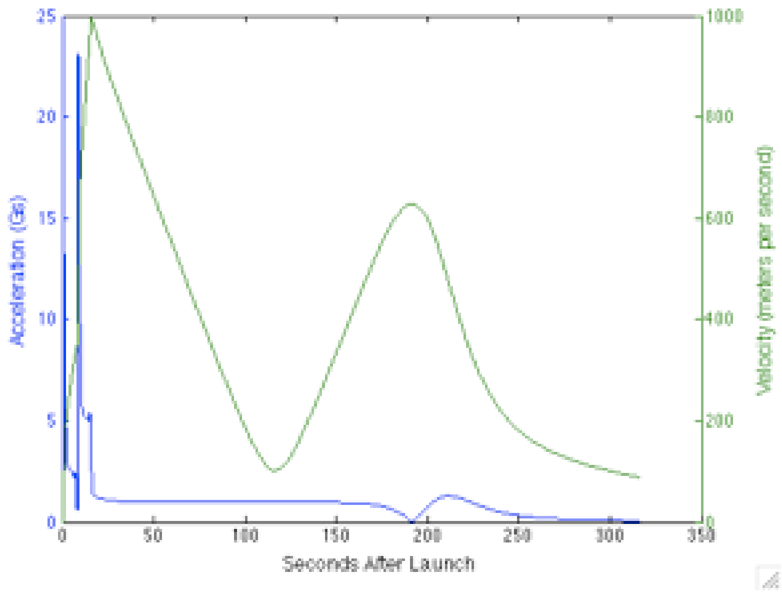

Figure 2. Acceleration (measured in Earth g-forces) of the rocket with the resulting velocity.

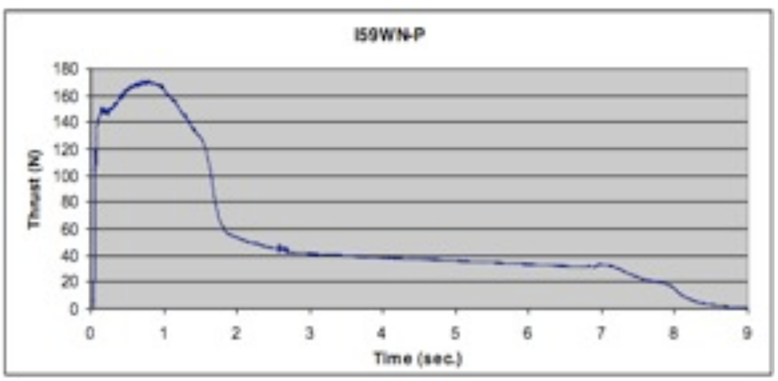

Figure 3. Thrust trace of an I59 motor[1].

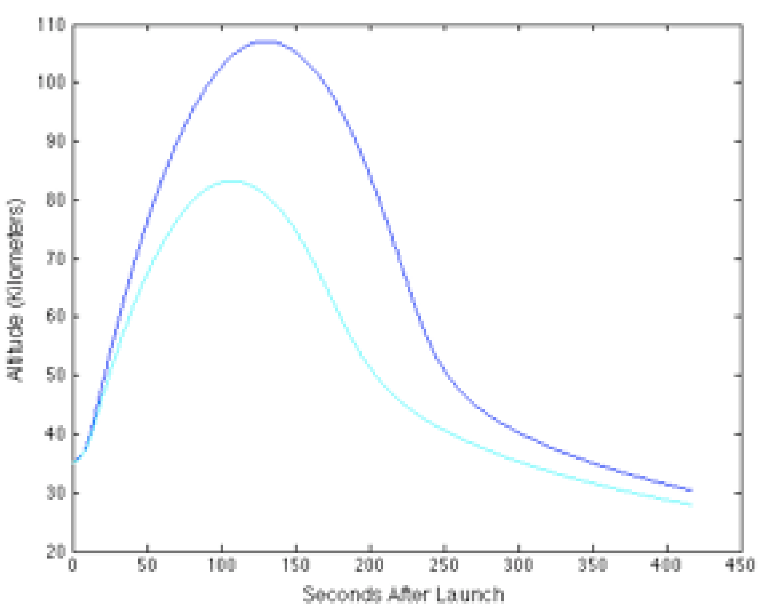

Figure 4. 3-σ deviation of altitude reached by rocket.

the velocity and acceleration of the rocket is plotted in Fig. 2. Although the rocket does achieve a velocity of 1000 meters/second (which is nearly Mach 4), this will not result in destructive aerodynamic loads, mainly because of the low air density at such high altitudes. The largest drag force the rocket experiences is only 2.23 Newtons. The rocket coasts until the parachute is deployed by a small explosive charge 130 seconds after launch, as the rocket is reaching its maximum altitude. The velocity does not drop to zero because of the horizontal component of velocity that the rocket has due to the 5 degree angle upon launch. The horizontal velocity is approximately 100 meters per second until the rocket begins to re-enter the lower atmosphere. This velocity results in a total horizontal distance travelled throughout the flight of 27 kilometers, with no consideration for wind. Setting the deploy location to the apex of the rocket's flight insures that the rocket gradually slows as it re-enters the atmosphere without any high g-loads on the parachute lines. The drag force on the parachute reaches a maximum of 11.9 Newtons, which is still very moderate for high-power rocketry. Each I59 motor burns for 7.99 seconds, so the total acceleration phase lasts about 16 seconds. The maximum altitude attained is very sensitive to the timing of the motors. By moving the firing of the second stage from 8 seconds after launch to 11 seconds after launch, the maximum altitude attained drops by almost 4 kilometers. This will influence the design of the second stage firing electronics. The large spike in acceleration at the beginning of the rocket's flight is due to the second stage I59 motor. Due to the time scale of the flight, it is difficult to see the exact shape of the acceleration, so the thrust curve of the I59 motor is plotted in Fig. 3. It begins with a high thrust and then gradually tapers off, which allows for a large initial acceleration to either escape the launch rod or separate from the first stage. This initial spike in thrust results in a maximum acceleration of 14 G's on the first stage and 24 G's on the second stage. Electronics can survive these g-loadings as long as fragile components (such as crystals) are not used, and the structure of the rocket was designed to deal with the forces involved. After the motors have completed their burn, the rocket experiences a brief deceleration due to aerodynamic forces, then coasts up to 94 kilometers within 2 minutes of launch. The acceleration remains constant at 1 G throughout the cruise phase until the rocket begins to re-enter the dense, lower atmosphere at approximately 175 seconds.

In order to determine the actual height reached by the rocket based on the variance in the motor's selected, the standard deviation of the rocket motor was located. By adding or subtracting three times standard deviation from the thrust of the motor at every point, the change in the trajectory can be found. The altitude reached by the rocket with these thrusts is shown in Fig. 4. A 3-σ deviation accounts for 99.7% of all possible outcomes, so the rocket will most likely follow a trajectory between the two trajectories in this figure. The rocket will achieve a minimum altitude of 83 kilometers and a maximum altitude of 107 kilometers. Therefore the rocket will reach its required height of 80 kilometers within a 3-σ standard deviation of motor performance. The apex of the trajectories occurs at 108 seconds and 128 seconds for the low and high end thrusts respectively. As there are no timed events occurring after this point, the difference in timing between the two trajectories is inconsequential.

This motor configuration was chosen after considering a 9 stage rocket consisting of a mix of G and E motors, a two stage rocket consisting of two larger, more expensive I motors that would have allowed for slightly more payload, and a two stage rocket with an H and I motor. The first was rejected due to structural and staging issues, the second was rejected due to the higher cost with a very small payload benefit, and the third was rejected because it is generally cheaper to buy propellant refills for two identical motors than it is to buy two separate refills.

III. Component Design

Once the trajectory and motors were selected, the rest of the system was designed based on the motors parameters. The casings are 38 mm in diameter and 232 mm long. Fully fueled, each one weighs 487 grams. The rocket's maximum payload is 250 grams, so the full rocket will weigh roughly 1.224 kilograms. The following sections will describe the design process for each component of the system.

A. Rocket

There are many different methods to successfully launch and recover a multi-stage rocket. The most commonly used method in high-power rocketry is to have a chip and timer onboard that send electrical signals at predetermined times after the first motor fires. They would first send a command to fire a charge to separate the first stage, then send a signal to light the second motor, and then send a signal to deploy the parachutes. This requires placing pyrotechnic charges in between the two stages and in the parachute container, which adds additional weight and complexity. The reason all these events must be deployed with pyrotechnics is because of the relatively short timeline of most rocket flights. There is not enough time to trust that the parachute will slowly drag free when the time from launch to potential impact is less than twenty seconds. However, this system will spend a great deal of time in flight with very little outside disturbance, so it was decided to use a slightly simpler system to save weight. Figure 5 depicts the fully assembled rocket ready for launch. The black interstage is attached firmly with structural adhesive to the first stage rocket motor, and the lower section of the second stage motor slides into the interstage with a small amount of friction. Once the first stage has completed its burn, a release charge that has been gradually burning will fire up through the top of the first stage. This blast will safely eject the first stage, and at 8 seconds into the flight, a timer in the nose cone will send a signal to light the second stage. Figure 6 depicts the rocket a moment after the first stage has been ejected. The second stage is connected to the nose cone with a U-shaped wire system. Two flammable wires run from the nose cone, down around the second stage, under the exhaust nozzle, and back up to the nose cone. Four streamers are attached to the second stage motor, and are pinned down flush against the walls of the second stage motor by the wires. These wires hold the first stage in until the exhaust burns them apart. The second stage is also attached to a parachute inside of the nose cone. As the rocket re-enters the dense, lower atmosphere, the streamers

Figure 5. Rocket configuration.

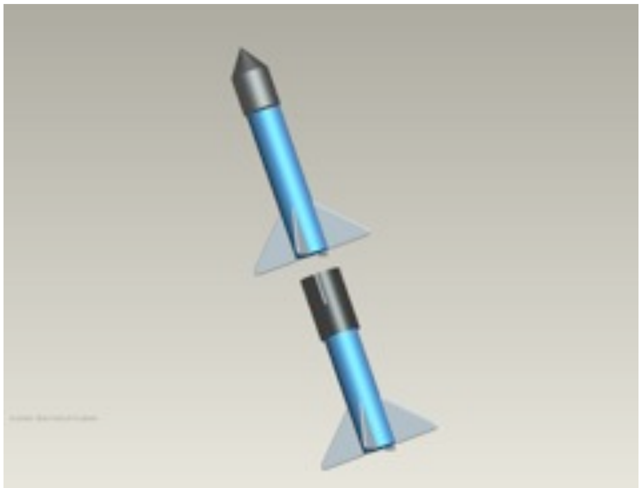

Figure 6. First stage separation.

attached to the second stage will cause it to slowly drag free of the nose cone and deploy the parachute passively.

The rocket must be designed to survive its environment throughout the flight, including large accelerations, low temperatures, and high velocities. The rocket in its two-stage configuration must survive a g-force of up to 14 G's and the upper-stage configuration must survive 24 G's. As can be seen in Fig. 6 and 7, the blue motor casings themselves serve as structural members. They are designed to survive the extreme internal pressure generated by the combustion of their propellent; as such, they are over-designed structurally. However, the interstage, nose, and fins all need to be designed with both affordability and structural integrity in mind. Using this philosophy, low-cost options were investigated. By performing a compressive strength and a stability analysis, it was found that 51 mm diameter aluminum cans had the necessary structural integrity. To determine the stability of a given column, the equation

$$P_{cr} = \frac{\pi^2 EI}{(kL)^2} \tag{1}$$

is used, where P_{cr} is the buckling force of the column, E is the elastic modulus, I is the area moment of inertia, k is the length factor, and L is the length of the column. Aluminum cans are made out of 6061 aluminum alloy, which has a modulus of elasticity of 70×10^9 pascals and an ultimate strength of 55×10^6 pascals. Using the diameter (51 mm) and thickness (0.284 mm), the area moment of inertia was calculated to be 5.693×10^{-9} m^4. Finally, the unsupported length of the interstage will not exceed 50 mm, and although the behavior of this column should more closely resemble a beam with a k value of 0.5, a k value of 2 was assumed for margin. It was then determined that the critical force for the interstage is 3.933×10^5 Newtons. The expected force it will experience due to the g-loading from the upper stage is 109 Newtons, so there is a very large margin for stability. The interstage was then evaluated for compressive strength using the equation

$$\sigma_Y = \frac{P}{A} \tag{2}$$

where σ_y is the yield strength of the aluminum, P is the maximum force the interstage can withstand, and A is the cross-sectional area of the aluminum. By solving this equation for P, it was found that the aluminum will yield at a compressive force of 932 Newtons, which is substantially closer to the actual maximum force experienced, but still allows for a very large margin. Therefore, this size aluminum can was selected due to its adequate strength, low weight (~7 grams), and extremely low cost. The aluminum can will be attached to the first stage motor with epoxy. Rubberized electrical tape will be wrapped around the interior of the top of the aluminum can, allowing the aluminum interstage to grip the second stage motor lightly, but not firmly enough to prevent the separation event.

The fins of the rocket were also designed with affordability and structural integrity in mind. At high speeds, fins have a tendency to “flutter.” This fluttering can result in shredding of the fins if the oscillations become too large. To accurately model fin flutter, the National Advisory Committee for Aeronautics (NACA) developed the empirical relationship

$$V_f = \frac{2V_a G_E}{(P/P_0)(\lambda+1)(X)} \tag{3}$$

where V_f is the velocity at which flutter occurs, V_a is the speed of sound, G_E is the shear modulus of the fin material, P is the ambient pressure, P_0 is sea level pressure, λ is the ratio of the tip chord to root chord, and X is the geometric parameter. X is defined by the equation

$$X = \frac{39.3A^3}{(t/c)^3(A+2)} \quad (4)$$

where A is the aspect ratio of the fin, t is the thickness, and c is the root chord length[2]. After performing this analysis on fins that were sized appropriately for the rocket, it was found that the extremely low pressure at the launch altitude resulted in flutter speeds in excess of 22 kilometers per second. Essentially, fin flutter is inconsequential at these altitudes, because the need for fins with a large surface area to generate the necessary aerodynamic force results in fins that are over-designed structurally. Therefore it was decided to use lightweight G10 fiberglass fins for their adequate structural properties and very low weight. Epoxy will be used to attach the fins to the motor casing.

The largest problem in dealing with the low temperatures experienced by the rocket is insuring that the motors will ignite when the command is given. In order to mitigate this risk, chemical warming pads will be draped over the rocket when it is still attached to the launch platform on the balloon. The pads will remain attached to the launch platform when the rocket is launched. The second stage will only have 8 seconds to lose heat after it leaves the warming pads before it is ignited, which will not result in a significant heat loss. After the second stage has fired, it will remain attached to the nose cone. Since the motor will be very warm from performing its burn, it will provide a source of heat to the electronics in the nose cone throughout the coast and descent phases of the rocket's flight.

Although the rocket is experiencing high velocities, this is a minimal problem due to the low density of the atmosphere at its operational altitudes. However, the nose cone does need to support the avionics package structurally while protecting any sensitive instruments from harmful atmospheric conditions. Off the shelf nose cones are available, but they are all designed with aerodynamics in mind in the lower atmosphere. As a consequence, most nose cones weigh above 90 grams[3], which would account for almost half of the rocket's available payload weight. Therefore, it was decided to create a custom nose cone with low weight and affordability given priority over aerodynamics. The leading edge of the nose cone is made of light paper rolled asymmetrically, with a thin internal layer of epoxy for structural integrity. This design allows for easy customization in height and base diameter. Therefore, the base diameter can be modified depending on the size and shape of the payload the rocket is carrying. The cylindrical section running from the base of the cone to the top of the parachute compartment will be constructed out of an aluminum can. The two most commonly manufactured sizes of aluminum can have a 51 mm diameter and 65 mm diameter. The trajectory analysis above was performed for a maximum rocket diameter of 51 mm with a drag coefficient of 0.9. Increasing the diameter to 65 mm while maintaining the same payload weight results in the maximum altitude attained decreasing to 88.7 kilometers. However, even with a 3-σ deviation in the thrust curve, the rocket still reaches its target altitude of 80 kilometers. This means the nose assembly can be customized to hold payloads of varying shapes and sizes with relative ease.

A parachute compartment is attached to the bottom of the aluminum can. This compartment consists of a 51 mm aluminum can which slides over the top of the second stage motor and is held in place by the flammable wires running under the exhaust nozzles. The parachute sits inside the 51 mm diameter can and is pinned between the nose cylinder and the motor. As the streamers attached to the second stage pull the motor free of the parachute compartment, the parachute is pulled out by a line that runs from the second stage, to the parachute, then two the nose cone. As a disclaimer, this system is untested as of this writing. A viable alternative that will be explored in the future is discarding the parachute and relying only on the streamers to slow the rocket. The streamers would be attached to the top of the rocket to destabilize its flight and prevent it from becoming a lawn dart that could possibly injure someone. Crushable materials would surround the electronics in the nose cone to prevent any damage during landing. The nose cone itself would be re-built before every launch. If this system is found to work, it will replace the parachute system due to the reduced number of deployment events that occur.

B. Launch Platform

Three architectures have been identified for launching a rocket off of a balloon platform. The are as follows: 1) The rocket can fire directly through the balloon, popping it in the process, 2) it can be mounted in-between multiple balloons and fired through the gap, or 3) the rocket can be hung from a very long wire and fired at a slight angle to miss the balloon entirely. The first option would require either complicated computer modeling, or an expensive test to properly simulate and insure that the rocket would not divert from its flight path. Additionally, it would end the balloon's mission as soon as the rocket launched, which might be an inconvenience. The second method was attempted by Cal Poly Space Systems (CPSS), and it turned out to be difficult to keep the balloons properly separated and even[4]. Although their system was successful in ground based tests, shown in Fig. 7, it would be very difficult to insure that the balloons remain oriented correctly throughout the entire ascent to 35 kilometers.

Figure 7. CPSS rocket launch platform.

Additionally, weather balloons swell to roughly 6 times their original diameter as they approach their maximum altitude, so it would be a challenge to keep them separate throughout the entire flight. Therefore, it was decided to hang the payload box 30 meters below the balloon and attach the rocket an additional 10 meters below that. To insure that the rocket misses the balloon by 0.5 meters as it passes, it must be hung at an angle of 5.262^0. This angle results in a small decrease in maximum altitude (~600 meters), but this is an acceptable loss. The standard method in the past for hanging a rocket at an angle has been to construct a cage to hold the rocket, this cage usually ends up contributing a large percentage of the mass that the balloon must carry. To avoid more stringent FAA regulations, the entire weight that the balloon carries must be limited to 4 pounds, which led to the need for an lighter launch platform design. In this lighter method, the rocket slides onto a single aluminum rod with a paper straw that is attached to the interstage. It is prevented from sliding forward by the angle of the rod and by the ignition charge inserted into the first stage nozzle. This screen capture of a test of the assembly is depicted in Fig. 8. It is 1 meter long, which gives the rocket some guidance as it is initially accelerating. Two support wires run from the cage up to the payload box to hold the launch rod at the proper angle. When the rocket is launched, the upper wire is sheared off by a razor blade attached to the rocket, as shown in Fig. 9. A small electrical circuit will run down the lower wire to send a signal to launch the rocket. The timer in the rocket will be activated when it experiences a sustained g-load of 2 G's, and will fire the second stage rocket 8 seconds later.

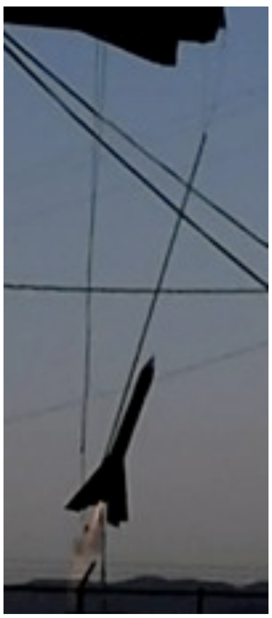

Figure 8. Test rocket on launch rod.

Figure 9. Straw and razor blade on test rocket.

C. Payload Box

The payload box must be designed to contain the necessary circuitry and antennas that run the system, as well as keeping them warm and protecting them from ground impact. The completed product is shown in Fig. 10. The design of the box selected is based closely on plans published by Parallax[5], with a few modifications. A foam pad has been inserted under the bottom of the styrofoam box, which provides cushioning upon landing and allows for a faster descent speed. A fast descent is desired to reduce the amount of horizontal drift the payload box experiences during its entire mission. Holes have only been cut in places necessary to reduce the heat flow out of the box. The box is an 8.5 inch cube externally with a 7 inch cubical internal space. The only external components on the box are two antennas for communicating with ground controllers, and one GPS receiving antenna on top of the box. The antenna shown on the right of the box in Fig 10 is a proven system, but is relatively heavy and expensive. The antenna projecting downwards in this picture is much lighter and cheaper and will be tested on the first flight to investigate if it is a viable alternative. Two straps support the box and attach to a ring which runs up to the parachute. The parachute has an outer diameter of 2.9 feet with a 6 inch diameter vent hole for stability. It has 8 shroud lines running up to support 8 gores. The sea level descent speed for the payload box was determined to be 23 feet per second, calculated using the equation

$$F_D = \rho V^2 C_D A / 2 \tag{5}$$

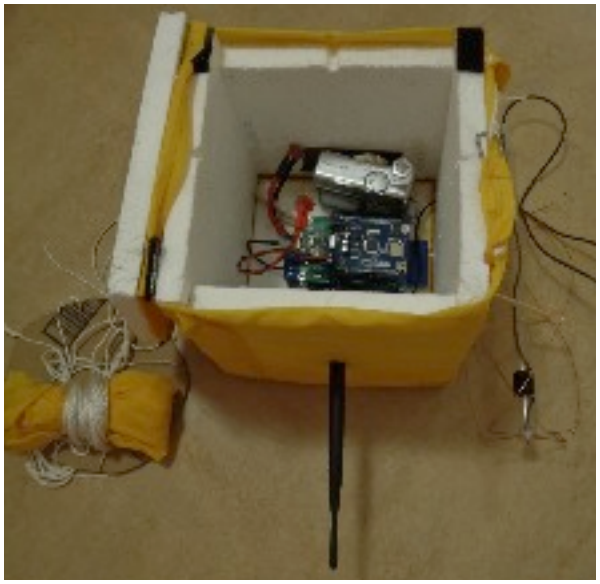

Figure 10. Payload box with interior components, antennas, and parachute.

where F_D is the force due to drag and A is the parachute's area. By setting F_D equal to the maximum weight of the payload box (4 pounds) and using appropriate values for the other variables, the descent speed can be found. The balloon is connected by a metal ring to the top of the parachute. This configuration prevents the parachute from getting tangled in any other lines during the ascent phase by constantly keeping it in tension. Additionally, a hoop is seated at the bottom of the riser lines to keep every line separate and further limit any possible tangling. The rocket launch platform hanging below the payload box will serve to increase the descent speed of the assembly, but the actual landing speed will remain constant because the launch rod contacts the ground before the payload box itself lands.

D. Electronics

The payload box has a modular chip with multiple ports to plug experiments into. The chip is able to record various types of data by importing pre-written codes into it before the flight. The chip also contains a GPS module that allows it to be tracked throughout the flight, and a radio to receive commands from the ground. If the rocket is being utilized in a given flight, the ground controller will wait until the balloon has reached 35 kilometers, or stops ascending, and then will command the rocket to launch. On the first test flight, the payload box will be fitted with multiple cameras to record the mission. The rocket will also include a camera on the first mission to represent its payload. The permanent rocket electronics package includes a slightly scaled down version of the payload box chip. This chip will has a timer to fire the second stage, a GPS module, and a radio transmitter to send its coordinates to either the ground or the payload box, because it has not been determined if the rocket will have a powerful enough transmitter and antenna to send a clear signal all the way to the ground. Additionally, the chip includes the data processing ability to save the pictures that the camera takes. This electronics system is being designed primarily by Justin Kenny of the Electrical Engineering Department[6].

IV. Construction Methods

In order to make this system easily accessible to any users, instructions on how to make the different components are included in this section.

A. Rocket

The rocket instructions are written assuming that the user plans on launching a payload that can fit into a 51 mm aluminum can.

Materials needed:
51 mm aluminum can (3)
Electrical tape (2 yards)
Duct tape (2 yards)
Epoxy
G10 medium swept fiberglass fins from Aerospace Specialty Products (8)
38 mm motor casing from Aerotech (2)
I59 WN-P motor refill from Aerotech (2)
Light card stock paper (1 sheet)
1/2 inch eyebolt (2)

1) Attach 4 fins each to the rocket motors. They should be placed with the bottom of the fins flush with the bottom of the motor itself. The second stage motor should have the fins aligned along the center axis of the motor, but the bottom fins should be canted at 1 degree from the vertical to impart a slow spin to the rocket for stability. To match the fins to a vertical line, use an L-bracket laid flush along the rocket, then use a marker to draw vertical

lines every 90° around the motor. Use hot glue on the very top of each fin to hold it in place, then place epoxy along the entire surface between the motor and fin.

2) Construct the interstage. Cut the top and bottom off of a 51 mm aluminum can using metal cutting shears (51 mm cans are used by Red Bull and V8 and can be found at most grocery stores). Apply layers of duct tape to the outer surface of the top of the first stage motor to size the motors diameter up to 51 mm, then apply a coat of epoxy to the outside of the duct tape. Slide the interstage over the epoxy and allow it to dry.
3) Apply layers of electrical tape to the inside surface of the top of the interstage until the diameter is scaled down to 38 mm. Mark where the slots in the top of the interstage should be by putting the second stage on top. The total height of the interstage should be 4 inches, with the slots for the second stage fins extending downwards 3 inches. The second stage should be supported by the four points of contact where the fins touch the interstage, and the interstage should grip the second stage firmly enough to prevent it from sliding out when the rocket is inverted.
4) Construct the nose cone. Draw a 4 inch diameter circle on a piece of card stock, then divide the circle into thirds radially. Cut out two thirds of the circle and roll the paper around the "center" of the old circle. This should create a cone with some paper sticking out of the bottom. Size the cone's bottom diameter to the diameter of the aluminum can by wrapping it over the can, then cutting off any over-hanging flaps. Tape the outer end of the paper to lock the paper into the cone shape. Coat the inner surface of the cone with a thin layer (~1 mm) of epoxy, and rotate the cone to prevent the epoxy from settling in any one direction until the epoxy has partially solidified.
5) Cut off the top only of the second aluminum can, leaving 4 inches of the can. Cut a 1.5 inch diameter hole in the middle of the side of the can to allow for access to the interior of the payload bay. Attach the top side to the base of the nose cone with epoxy. Use a sharp object to puncture a small hole for the second stage ignition line in the outer rim of the bottom of the can.
6) Construct the parachute compartment. Attach one of the eyebolts to the bottom of the nose cone assembly, and attach the other eyebolt to the top of the second stage motor. These eyebolts will provide a connection point for the parachute. Cut off the top and bottom of the third aluminum can, again leaving 4 inches of length. Attach this aluminum can to the bottom of the nose cone assembly with epoxy. Add layers of electrical tap around the exterior of the top of the second stage motor to increase the diameter to 51 mm, then slide the parachute compartment over the top of the second stage.
7) Insert the parachute, payload, and fuel rods. The construction of the parachute will be discussed in the next section.

B. Parachute

These instructions are specifically for constructing the larger payload box parachute. In order to construct the rocket parachute, scale the outside diameter down to one foot, remove the vent hole, and only use four shroud lines.

Materials needed:
Rip-stop nylon (1 square yard)
1/8 inch mason line (30 yards)
Sewing thread
1 inch key ring (2)
Embroidery hoop (1)

1) Cut a 2.9 foot diameter circle out of the rip-stop nylon using a soldering iron cutting tip to prevent the edges of the nylon from fraying. Then cut out a 6 inch diameter circle from the center of the nylon to create a vent hole.
2) Cut four mason lines to a length of 15 feet each. Mark the center point of each of these lines, then center them on the parachute vent hole.
3) Use a sewing machine to sew the lines onto the top of the nylon. Have the machine stitch around the mason line itself without going into the line. This should allow the line to slide back and forth to correct any centering errors. After all the lines have been centered and sewn in, sew a few stitches through the mason line on the edge of the parachute to lock them into place
4) Tie the end of each line to its opposing end to create four equal length loops. Wrap duct tape around each knot to prevent them from untying. Attach a key ring to the intersection of all the lines in the vent hole of the parachute. This ring will be used to attach the balloon to the top of the parachute. Slide another key ring around the intersection of the lines at the very bottom of the shroud line loops. Tie another mason line onto this ring, then use this line to attach the payload box to the parachute.
5) Cut 8 grooves into the outside of the embroidery hoop and seat the 8 riser lines in these grooves. Allow the hoop to slide down to its natural position when the lines are supporting the payload box, then epoxy each line into

place. The hoop will serve to force the lines apart and prevent them from tangling throughout the ascent phase of the mission.

C. Payload Box/Launch Platform

The instructions to construct the payload box are fully detailed fully in reference 5. The mason line from the parachute will be 30 meters long and attach to the key ring above the box. The lines for the launch platform attach to the bottom of the straps which support the payload box. The bottom line is a thick, load-bearing mason line, while the upper line is three twisted pieces of sewing thread. This allows the razor on the rocket to easily shear the upper line upon launch.

V. Testing

Figure 11. Launch platform tests.

A. Launch Platform

The launch platform used in this design is a relatively untested idea. The concept is that the razor will shear the upper wire and the rocket will be able to free itself from the launch rod before it begins to tip over significantly. In order to determine the validity of the this design, a smaller rocket with a similar thrust-to-weight ratio to the full size rocket was constructed. The launch platform was hung from a roof to simulate its dynamics when it is hanging from the balloon. The results from the two test were filmed and screen captures of each test are shown in Fig. 11. Both rockets freed themselves of the launch rod well before the it tipped over any measurable amount. The rocket then continued at the same angle that it followed along the rod. The second picture in Fig. 11 provides an excellent view of the launch assembly a moment after launch. The upper line provides adequate support to the rocket before launch, but is sheared with very little resistance. Therefore, this launch platform will function properly while reducing the total mass supported by the balloon by approximately one kilogram from the cage launch method.

B. Payload Box Parachute

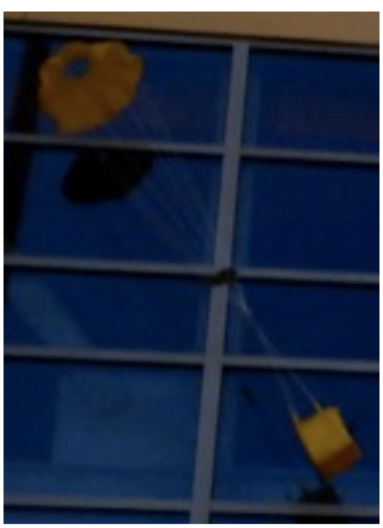

Figure 12. Parachute drop test.

In order to insure that the parachute will open and to determine the range of landing velocities and impact forces that the payload box will experience, a drop test of the parachute was conducted. The parachute was lifted to a height of 50 feet in its folded position while being supported by the key ring in the vent hole. This support location mimics the configuration that the parachute and payload box will be in immediately before the balloon bursts. The assembly was then released and the results were filmed from the ground. A screen capture of the test is shown in Fig. 12. The payload box briefly accelerated but the velocity became relatively constant within 1.5 seconds of being dropped. By using the frame rate of the camera and the height of the divisions between the windows located behind the payload box in the video, the vertical velocity was calculated to be approximately 16 feet per second. This is lower than the expected velocity of 23 feet per second for several reasons: the calculation did not take into account the drag of the payload box or line separation hoop, the actual weight of the box was less than the 4 pounds used in the calculation, and the wind served to create a small lifting force on the parachute as it moved sideways through the air. For the calculation, a payload box weight of 4 pounds was used because this is the maximum weight that the balloon can be before it must comply with FAA regulations. However, the box used on the first test flight will weigh only 2.2 pounds because only video and communication equipment is being launched, without any additional experiments. Therefore, the payload box was tested at a weight of 3 pounds to more accurately reflect its true descent speed while still allowing some margin.

VI. Conclusion

All the detailed design of the RHAZER balloon-launched system has been completed. Some testing has been conducted, but three key experiments remain to verify the full operation of the system. The first experiment will be conducted in the coming weeks to test the balloon system. The balloon will be launched with a mass model of the rocket on the launch platform. The electronics will be tested and verified, and a camera will film the movement of the launch platform throughout the flight to investigate if the rocket will remain attached during the balloon's ascent through the lower atmosphere. The next experiment will be a firing of the rocket from sea level with the streamer and crushable material descent system. If this method serves to protect the payload adequately, the parachute system will be removed from the final design. The final experiment will consist of a full test of the entire system. The payload box will be fitted with cameras to view the rocket's initial launch behavior to see if the fins are sized properly for the low pressure at 35 kilometers altitude. Additionally, the rocket will be fitted with a camera to record its behavior throughout the launch and coast phases. Once this test has been successfully conducted, the entire system will be sold as a kit to schools to allow them to conduct experiments in the upper atmosphere.

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