A "Rockoon" System For Efficient Small Payload Launches: A Proof Of Concept

By Josh Cohen

Ardsley High School

Abstract

Despite recent advances in rocketry and reusability, the cost of launching a payload into space is still prohibitively high, and a large amount of the energy expended to reach orbit is expended in the lower atmosphere, where the air is thick. However, as electronics continue to shrink in size, small satellites called CubeSats have become increasingly popular for a myriad of applications. Small payloads such as CubeSats could be lifted to a high altitude by a balloon, then launched from the balloon into orbit using a much smaller and less expensive rocket - a "rockoon" system. Though small-scale rockoons have been launched before, none have attempted to measure the increase in efficiency of a rocket launched at altitude, nor have they attempted to create a reusable platform design that could be feasibly scaled up for use in commercial applications. Using a model rocket constructed from standard cardboard body tube and 3D printed components, and a custom launch platform modified to hold the guide rail, blast plate, and electronics needed for launch, this project demonstrates that launching at even 6,000 meters of altitude has a significant effect on the efficiency and maximum height of the rocket. The proof of concept can be used to launch from a much higher altitude, such as 25 kilometers and a scaled-up version could effectively launch from 50 kilometers, which could allow it to launch a CubeSat into low earth orbit.

Introduction

Model Rockets

Functionally, rockets and model rockets are identical, but model rockets are differentiated by size and scale. Both have a similar general structure; They both typically have an aerodynamic nose cone at the top, and propellant at the bottom that combusts explosively to propel the rocket upwards. While conceptually similar, model rockets have a few key differences that differentiate them from real rockets (Apogee, 2010):

The entirety of the flight of a model rocket occurs in the atmosphere, so aerodynamics are very important, while real rockets are outside the atmosphere for a significant portion of their flight, so aerodynamics are less important. A model rocket burns propellant and accelerates for a small portion of its flight, and coasts unpowered for most of its time in flight, while real rockets accelerate for a large majority of their flight. Model rockets use solid propellants only, and have a low propellant-to-mass ratio, while real rockets use both solid and liquid propellants, and have a high propellant-to-mass ratio. Model rockets typically have only passive stabilization (fins, wings, etc.) and fly unguided, while real rockets have passive stabilization and active stabilization, such as thrust vectoring, and fly guided. Model rockets fly at comparatively low speeds, so atmospheric heating is not an important factor, while real rockets fly at much higher speeds, and must be designed to deal with atmospheric heating and shear forces. Model rockets are built out of inexpensive materials such as balsa, cardboard, and plastic, while real rockets are built out of expensive, high-strength materials such as aluminum, titanium, and nickel alloys.

Despite these differences, much of the underlying mechanics overlaps between the two. This makes model rockets an integral part of aerospace research; They are low-cost, prolific, reusable, and highly modifiable to fit any niche where they are needed. Prefabricated rocket kits or the parts to construct your own rocket can be purchased from many physical and online vendors, and more recently a 3D printer can build many of the needed parts on demand as well.

High Altitude Balloons

Weather balloons are a type of high-altitude balloon specifically used for transporting scientific payloads into our upper atmosphere. They can carry their payloads as high as 40 km ~ (130,000 ft). High altitude balloons are used all over the world for meteorological research by governmental agencies, science research, education and simply enjoyment. The balloons and hardware used by students are off-the-shelf, commercial hardware with typical maximum altitudes up to 35km. At altitudes that can be reached by these systems, experiments can be conducted in conditions vastly different than on the ground, including extremely cold temperatures, over 90% less air pressure, and even high cosmic radiation. “Although not the ultra-high vacuum of space, the conditions at these altitudes are similar to those encountered on the surface of the planet Mars” (Larson, 2009).

Every day approximately 800 meteorological weather balloons are released at 00:00 and again at 12:00 GMT at locations around the world. This provides a “snapshot” of our earth’s upper atmosphere twice a day. The few launches done by amateurs every day are just a drop in the bucket compared to the 1,600 or so launches done by meteorological organizations around the world.

Balloon flight systems that reach these altitudes must be capable of operating in these extreme conditions, and must survive the journey back down to the surface of Earth for recovery, analysis, and eventual reflight. Engineering robust flight systems within tight constraints on mass and power is only part of a high altitude ballooning program; scientific experiments also play a prominent role, with opportunities ranging from probes of the structure and composition of the atmosphere, to measurements of cosmic radiation, to tests of high-altitude rockoon systems.

Rockoons

Rockets are currently humanity's only method of getting any payload into orbit. However, this method is wildly inefficient, with even the most efficient rockets having only a 5% payload-to-total mass ratio. This is mostly because it takes a very large amount of energy to push through the thick air near the Earth's surface, where the gravity is strongest as well. There is a method to avoid this problem, and raise the payload to a height where the air is 95% less dense, greatly reducing the size of the rocket required to make it to orbit. The original concept dates back to 1949. Pioneered by space scientist James Van Allen who worked with Naval Commanders Lewis and Halvorson and space scientist Singer, developed and launched the first rockoons (a term coined by Van Allen) in the 1950s sponsored by the US Office of Naval Research (Corliss, 1971). Many rockoons were fired during the following decade from vessels in the sea between Greenland and the US, others from the Equator, reaching more than 100 km in altitude and helping Van Allen make important discoveries on high altitude radiation and Earth magnetic fields. Records show that both Australia and Japan made tests with this technology, but with no progress past the testing phase.

The concept was soon discarded as more powerful sounding rockets appeared, and it offered, at that time, no clear advantages compared to other systems, and neither in the next decade in comparison to space launchers and the possibilities offered by satellites. The effort to lift a large rocket to an altitude that it can take advantage of the reduction in air pressure was simply not worth the cost and disadvantages.

The post-cold war era has seen the attempt to recover this technology, in an effort to achieve low cost access to space. Great examples of this are the L5 Society from Alabama, an amateur team who successfully launched a rockoon with a camera to an estimated altitude between 55 and 65 km and the US based company JP Aerospace with a simple design, proven to work at lower altitudes. Notable is also the Romanian-based ARCA project aiming to win the Google XPrize (Nizhnik, 2012) and proposed launching a moon probe from a high altitude balloon. Although not going far in terms of the original plans, a successful in-air ignition of the rocket propulsion system was demonstrated and 40 km of altitude were reached. Most recently the Spanish Zero2Infinity company announced its innovative concept to lift small payloads to Low Earth Orbit using a rockoon launch vehicle architecture. Other air-to-space launch systems involve aircraft. This is the case of the Virgin Galactic proposal and a number of similar smaller launch vehicles that are under development worldwide. However, up-to-date data from the Pegasus launch vehicle program show that such systems may be less cost-effective as it would be desired and significant durations of the pre-launch operations are experienced.

CubeSats

When the Space Age began, satellites were large, heavy, and often fragile pieces of equipment that were loaded onto large rockets and launched into space. However, as computers got smaller and more powerful over the years, a new type of satellite emerged: The lightweight CubeSat. The concept dates back to 1999 when Professors Jordi Puig-Suari and Robert Twiggs invented the idea of extremely small satellites and coined the term “CubeSat” (Chakrabarti, 2019). Since their conception, over 2,300 CubeSats have been launched.

CubeSats are cheap, robust, light, and versatile. The original CubeSat standard specification was created by California Polytechnic State University, San Luis Obispo and Stanford University's Space Systems Development Lab in 1999 and together they formed a CubeSat organization, which now includes over 100 members (CubeSat, 2019). The CubeSat design specification, now in its 14th version defines CubeSats. They are, as the name suggests, in the shape of a cube or rectangular prism, with solar panels simply placed onto some of its sides instead of extending off of the body. Inside the body of the satellite is its processors, antennae, and any other equipment it may have. They are compact and light, and many are not launched on their own rockets but rather on Rideshare programs. The size of CubeSat is defined as a function of the “standard” 1U size that is a 10 CM cube, weighing less than 2 KG (CubeSat, 2020). Today CubeSats routinely come in sizes ranging from 0.25U to 27U (Kulu, 2019). The CubeSat is loaded into the payload bay of a larger rocket carrying a large payload or multiple other payloads, then after the primary payload is deployed the rocket places the CubeSat in the orbit that it is needed in.

Being a secondary passenger means that poor placement of these CubeSats is common, and they are often limited by the orbit of the primary payload. However, if a cost-efficient method of launching CubeSats as the primary payload instead of being forced to Rideshare were to exist, CubeSats would become much more viable for a host of different ventures, scientific and industrial alike.

The launching of CubeSats is the perfect mission for a Rockoon. A number of start-up companies are currently pursuing this idea, including Leo Aerospace, Zero2Infinity and JB Aerospace. “SpaceWorks Enterprises Inc. issued a report last year estimating that as many as

2,600 nanosatellites or microsatellites will be launched over the next five years. To accomplish this, more companies that can send the satellites into space are needed" (Mraz, 2019).

Recent Research

Columbia University, Global Balloon Challenge – Rocket Team, 2019. As part of the Global Balloon Challenge a group of Columbia University students submitted two entries, a typical Ballooning project and a mid-power rocket launch from a balloon. Unfortunately, due to weather conditions on the day of launch the launch with the rocket was scrubbed. Moreover, the ignition plan was predicated on lighting multiple motors in hopes of one working, the team was simply firing the rocket out of a tube with limited directional control, and the rocket was not trackable (Columbia Space Initiative, 2016)

Amentum Aerospace, Edge of Space Rocket Launch Attempt – 105,000 ft, 2013. A group of students attempted to launch a rocket from a high-altitude balloon. The balloon achieved the expected height (70,000 feet), but the igniter did not light due to the environmental conditions. The payload was recovered and the team launched the rocket from the ground demonstrating that the problem was the launch environment at 70,000 feet (Phil G, 2013)

Adrian Ruiz and Sebastian, High Altitude Rocket Transport (HART), 2016. Two aerospace engineering students planned a project to launch a high-power rocket from a high-altitude balloon with the goal of reaching the Karman line (62 miles, 100km above sea level). The project was not launched primarily due to the FAA approvals needed to launch a high-altitude balloon and a rocket of the size needed to achieve their goal (Ruiz, 2018).

Stanford University, Project Nearsite, 2015. A group of students built a rocket and launch tube and succeeded in launching a high-power rocket from a high-altitude balloon at 30,000 feet. They believe that the rocket flew over 10,000 feet. This research project launched from a simple tube without directional control, did not track the flight and was not focused on developing a reusable platform (Becerra, 2015).

JP Aerospace, Rockoon prototype, 2012. JP Aerospace built a rocket and launch platform and launched a mid-power rocket from a high-altitude balloon at 30,000 feet. The rocket launched successfully. JP launched numerous additional rockets. This research project used multiple high altitude balloons to carry a large payload (20+ kg) to 30,000 feet, because it was a proof of concept for a commercial venture that is intended to lift heavy rockets. This is not a tenable solution for small rocket launches as it would require FAA approval and much more expensive components (JP Aerospace, 2010).

In summation, there is a gap in research for a small, inexpensive reusable platform and rocket combination that can be effectively launched from a high altitude balloon, for research purposes and to be a proof of concept for future applications of a rockoon system.

Project Summary (Rockets, High Altitude Balloons, CubeSats)

The goal of this engineering project is to develop and test the components needed to launch a mid-power model rocket from altitude achieved by a high altitude balloon and to conduct launches at two altitudes, 5 kilometers and 10 kilometers. The environmental conditions of launch and the flight statistics of the rockets, including altitude achieved, acceleration, flight path and maximum speed will be tracked. These flights will be compared to a control flight from the ground in order to determine the difference between ground launches and high altitude launches. Conditions at higher altitudes are significantly different than on the ground:

Changes in Temperature, Barometric and Air Pressure by Altitude									
Altitude Above Sea Level			**Temperature**		**Barometer**		**Atmospheric Pressure**		
Feet	**Miles**	**Meters**	**F**	**C**	**In. Hg. Abs.**	**mm Hg. Abs.**	**PSI**	**Kg / sq. cm**	**kPa**
0		0	59	15	29.92	760.0	14.696	1.0333	101.33
1000		305	55	13	28.86	733.0	14.16	0.996	97.63
5000	0.95	1526	41	5	24.90	632.5	12.23	0.86	84.33
10,000	1.9	3050	23	-5	20.58	522.7	10.1	0.71	69.64
20,000	3.8	6102	-12	-24	13.76	349.5	6.76	0.475	46.61
30,000	5.7	9153	-48	-44	8.903	226.1	4.37	0.307	30.13
50,000	9.5	15,255	-70	-57	3.444	87.5	1.69	0.119	11.65
80,000	15.2	24,408	-62	-52	0.8273	21.0	0.406	0.032	2.80
100,000	18.9	30,510	-51	-46	0.329	8.36	0.162	0.013	1.12

This engineering project is proof of concept for the development of a simple, inexpensive capability of launching rockets from high altitude platforms for both research and the future purpose of carrying cubesats into low earth orbit.

Methods

Design Requirements

The following engineering components are required to be developed for this research project:

1. A stable launch platform that can be a payload for a high-altitude balloon
2. A rocket that can effectively launch from the platform at the anticipated altitude
3. A flight control system comprised of:
    a. A launch control system that will ascertain that the platform is presenting conditions that will allow for launch (height, time and angle of launch)
    b. A remote ignition system, which will ignite the chemical propellent at the order of the launch control system
4. A balloon release system that will allow for easier recovery of the launch platform

Design Limitations

Due to the available time and materials, as well as the unique challenges that a rockoon presents, the design is constrained by certain factors, such as:

1. The design of all components must use only parts that can be purchased either online or in-person and parts that are 3D printable.
2. The weight of the platform and rocket must not exceed 2 kg to make FAA approval unnecessary. A payload with a weight over 2 kg requires more extensive FAA approval than simple notification.
3. Both the platform and the rocket must be individually able to survive descent from altitudes exceeding 10 kilometers, and be recoverable and reusable with minimal refurbishment or repairs.
4. Both the platform and the rocket must be separately trackable with enough accuracy and precision to enable reliable recovery.
5. The rocket must be ignited remotely, when launch parameters are verified. The Launch parameter for a safe launch is that the rocket is not at greater than a 30-degree angle. Additional parameters are determined by the test launch plan, such as altitude and time.

6. The rocket must be trackable during flight with enough accuracy and precision to determine the apogee of its flight after launch.
7. The rocket must be able to transmit its flight data either to the platform or to a user on the ground, to enable data collection in the event that the rocket is unrecoverable.
8. Due to weight and certification requirements for larger motors, the rocket must use an E30-7T composite propellant motor, produced by Aerotech.
9. The platform must be stable enough to carry the rocket, microcontroller(s), batteries for the microcontroller(s), and camera(s) to high altitudes in the weather conditions expected at high altitudes without tilting more than ten degrees in any direction for an extended period of time.

Platform Design

The platform must be able to carry the rocket, a microcontroller to ignite the rocket, a microcontroller sever the string connecting the balloon to the platform, a flight data recording systems, batteries to power all onboard electronics that require an external power source, a parachute to slow its descent, and two cameras to record the launch. Moreover the platform must insure safe launch conditions, particularly that the launch angle does not exceed 30 degrees.

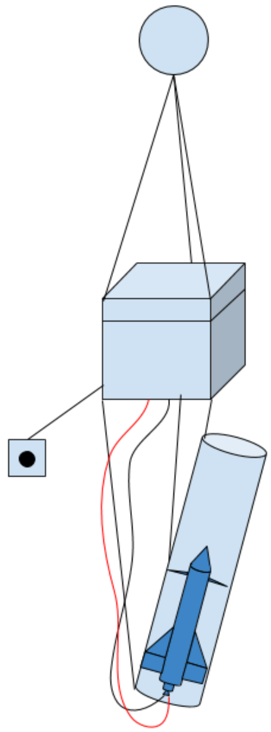

Figure 1. Platform design. Rocket is in a tube suspended below a Styrofoam box that contains the electronics.

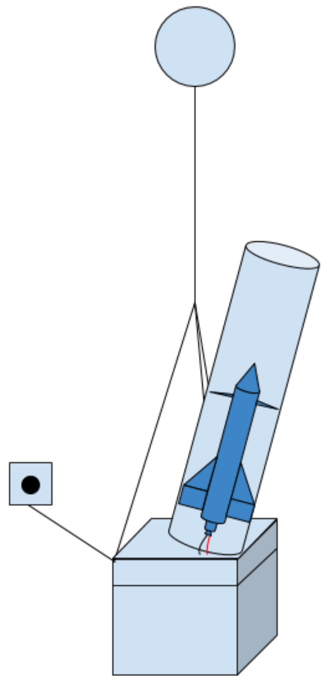

Figure 2. Platform design. Rocket is in a tube placed on top of a Styrofoam box that contains the electronics.

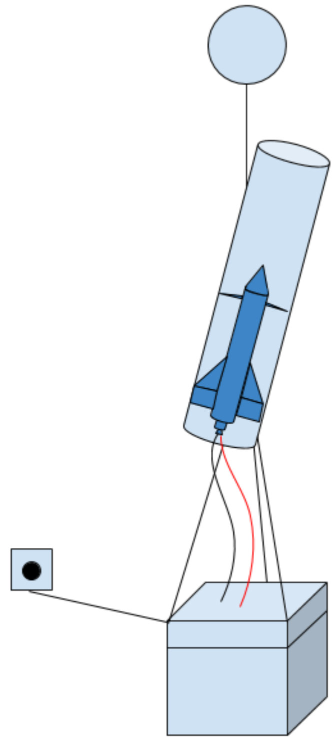

Figure 3. Platform design. Rocket is in a tube suspended on the balloon string, above a Styrofoam box that contains the electronics.

Pictured above in Figures 1, 2, and 3 are three of the initial designs considered. This early design planned to utilize a small Styrofoam box to contain the electronics and protect them from the environment at high altitudes, as well as a guide tube to fit the rocket inside to protect it from the elements and guide its trajectory upon launch. This design had three configurations; One possibility was to hang the tube below the Styrofoam box (Figure 1), another configuration was to mount it to the top of the box (Figure 2), and a third configuration was to affix it to the balloon string above the box (Figure 3). These designs were similar in concept to work done by prior researchers such as the Stanford team and Amentum Aerospace. However, upon initial construction and testing it was determined that there were numerous disadvantages. Primary disadvantages of this design were that the guide tube would raise the mass of the platform above the mass threshold, the long run of the wires would increase the likelihood of launch failure, the tube design would be difficult to scale up to a more guided launch, and the blast effect of using the guide tube could damage the launch platform. Other downsides of this design were the requirement to affix the camera on a long boom, the low width of the platform possibly causing instability during flight, and the difficulty of attaching components, like a balloon string, to a material of low structural integrity like Styrofoam. Thus these designs were abandoned.

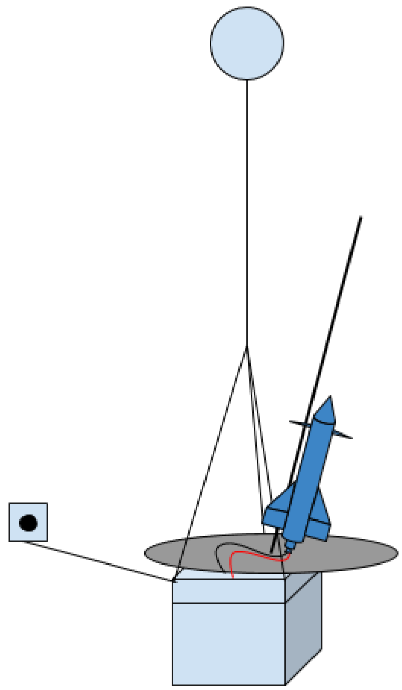

Figure 4. Platform design. Rocket is attached to a guide rail and rests on top of a blast plate, affixed to the top of a Styrofoam box containing the electronics.

Pictured above in Figure 4 is the next iteration of the platform's design. Instead of a guide tube, a guide rail and launch lug would be used to guide the rocket on launch, and a blast plate would protect the rest of the platform from the exhaust. This would leave the rocket exposed to the elements, but would dramatically reduce the mass of the platform. However, this design still posed multiple challenges. It would be difficult to attach the strings needed for the balloon to the styrofoam box if the large blast plate was placed on top, and the camera would still have to be mounted on a boom like in the previous designs. This design was abandoned as well, in favor of significantly modifying a commercially available high altitude balloon platform as the base of the design, which provides more stability and higher structural integrity.

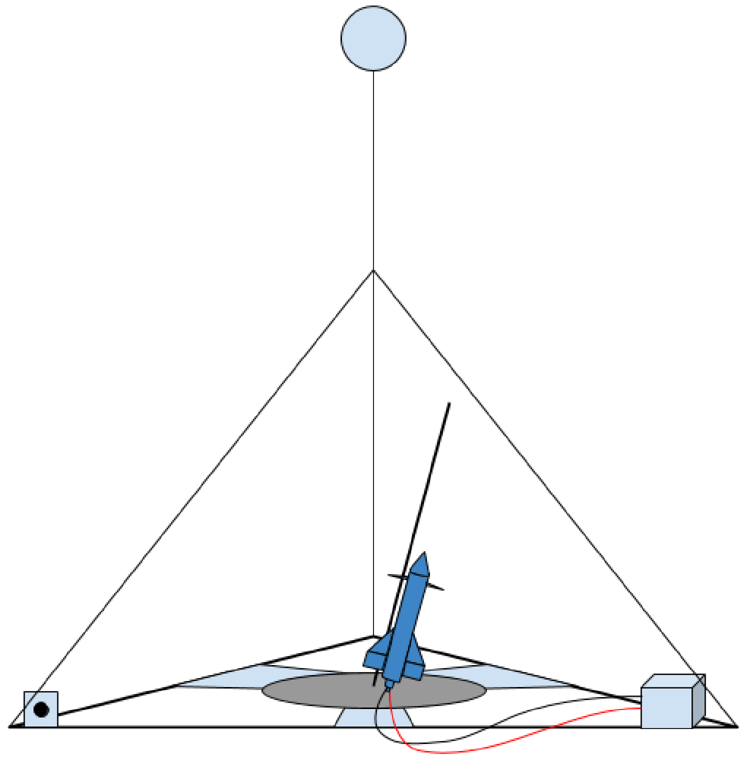

Figure 5. Platform design. **A triangular wooden frame holds the balloon string, electronics, and camera, and a 3D printed structure in the center holds the rocket, guide rail, and blast plate.**

Pictured above in Figure 5 is the final iteration of the platform's design. This design uses the High Altitude Science Eagle Pro Weather Balloon Kit as a base (balsa wood triangle), then extends arms inwards to a central piece that holds the rocket, guide rail, and blast pad. The electronics and camera are all mounted on the flat surfaces on the corners of the Eagle Pro Kit. This design was chosen to be the final configuration of the system due to the stability and strength of both the triangle design of the payload platform and the 3-D printed launch platform. This design will result in more assutrity of launch since it will be very unlikely to swing more than 30 degrees, will effectively absorb the force of the launch of the rocket, will provide directional control due to its stability and be reusable. It is expected that this platform design can be retrieved and re-launched immediately.

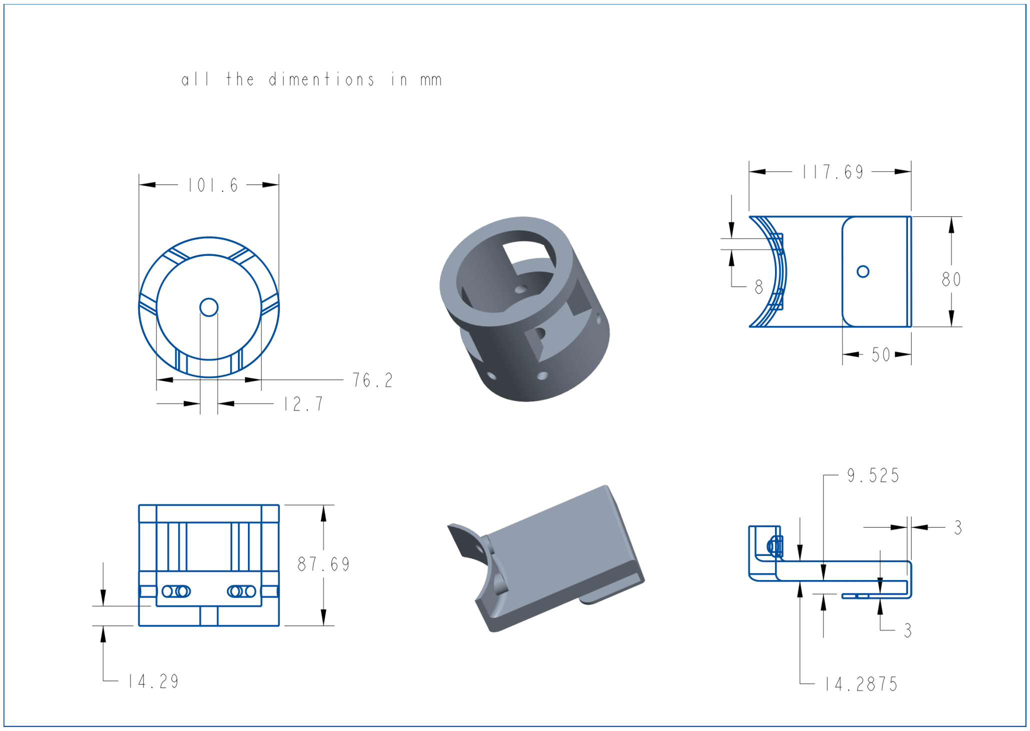

Figure 6. Schematics and printable 3D models of the individual components for the platform components that hold the rocket, blast plate, and guide rail.

Figure 7. Fully constructed platform.

Pictured above in Figures 6 and 7 are the 3D models for the platform, as well as the final state of the platform itself. The 3D printed components of the platform consist of one cylindrical core piece and three identical arms, printed in red PLA plastic using a Dremel Digilab 3D40 Flex 3D Printer. The arms are affixed to the core piece with one metal bolt and one metal nut per arm. The microcontroller is affixed to one of the arms with double-sided mounting tape.

Rocket Design

In order to guide rocket development with simulated launches, a commercially-available rocket simulation program, RockSim version 10 was used to determine expected rocket performance given the environmental conditions, rocket design, motor choice and launch angle. The rocket design chosen must be able to hold a 24mm engine that can be ignited using the microcontroller, and must have an ejectable nose cone assembly connected to the main body by a shock cord, to allow the rocket to deploy a parachute with the ejection charge of the engine. The rocket must also have a payload bay large enough to carry the electronics needed to both track its flight and locate it for recovery.

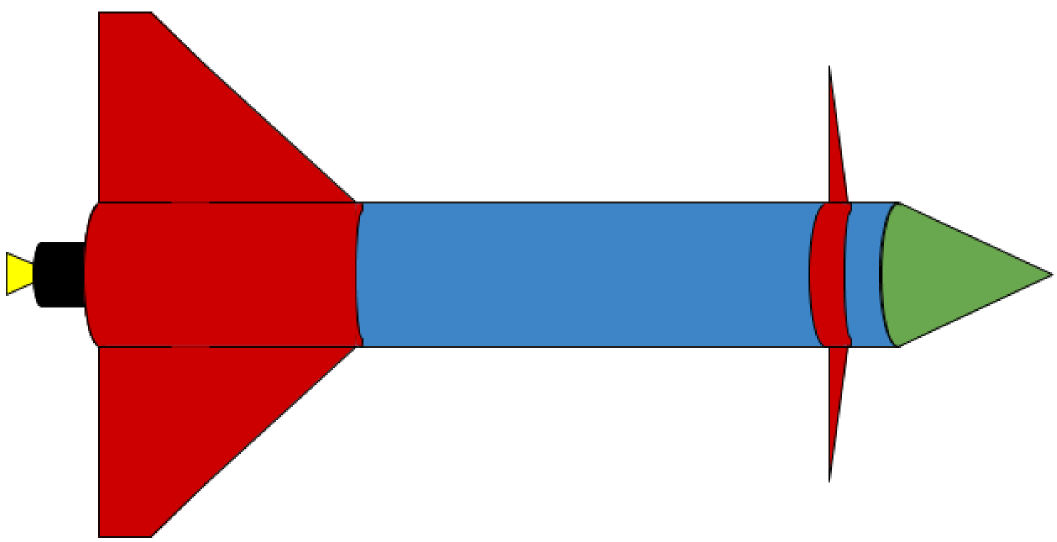

Figure 8. First design of rocket.

Pictured above in Figure 8 is the first iteration of the rocket's design. This design was made alongside the first iterations of the platform's design. It has no defined sizes of any of its components, or of itself as a whole, as it was scrapped before leaving the design phase. It has a set of lower fins for flight stability, intended to be 3D printed, and a second set of cannards near the nose cone for stability while resting in the launch tube that was originally included in the platform design. However, when the design moved away from the launch tube, the concept of the cannards was discarded, along with this initial design.

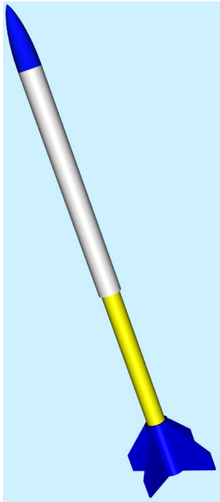

Figure 9. Second design of rocket. Generated in Rocksim 10.

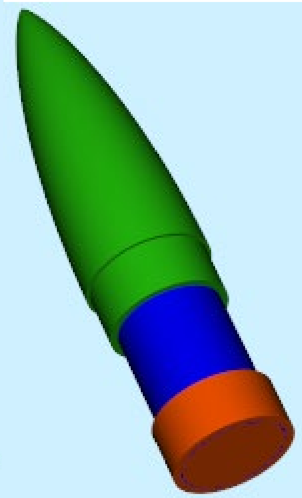

Figure 10. Payload bay for second design of rocket. Generated in Rocksim 10.

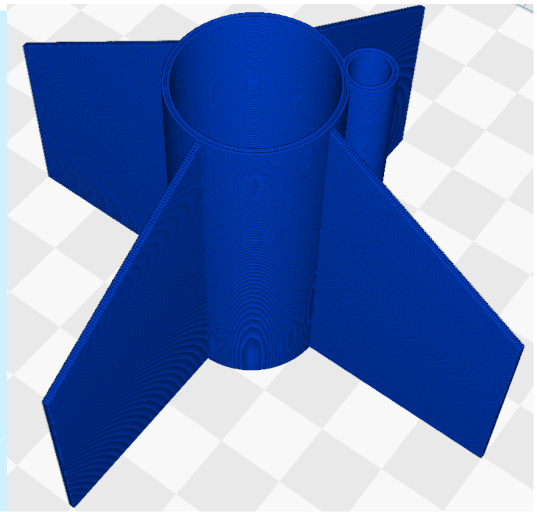

Figure 11. 3D model of the fin assembly, prepared for 3D printing.

Pictured above in Figures 9, 10, and 11 is the second iteration of the rocket's design. This design is a U.S. Rockets Model 07175 "Hammerhead" rocket, modified to include a payload bay as part of the nose cone to enable it to safely carry a Featherweight GPS Altimeter during flight and the addition of custom-designed and 3D printed fins. Typical commercial rocket fins are lightweight and structurally weak, routinely just glued to the rocket. In testing these commercial fins routinely came off. The decision was made to create custom fins, even though it would increase weight. However, this design was unable to carry a satellite tracker, and as a result proved impossible to locate and recover after launch.

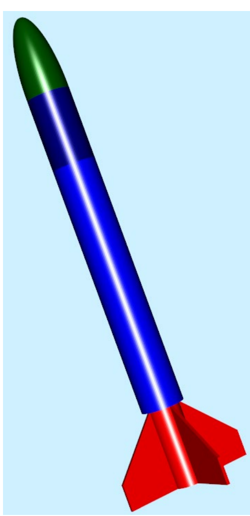

Figure 12. Final design of rocket. Generated in Rocksim 10.

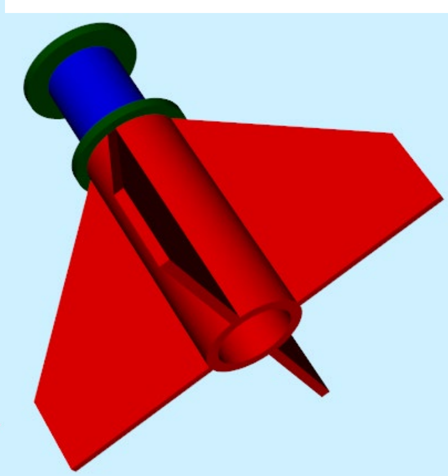

Figure 13. Fin assembly and rocket mount assembly for final design of rocket. Generated in Rocksim 10.

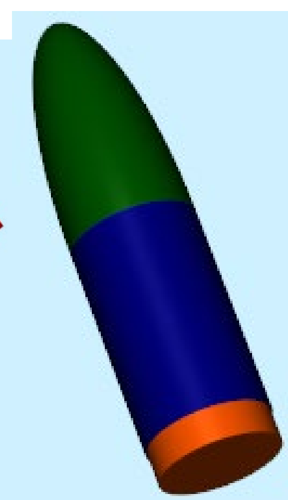

Figure 14. Payload bay for final design of rocket. Generated in Rocksim 10.

Pictured above in Figures 12, 13, and 14 is the 3rd and final iteration of the rocket's design. This design uses a standard Apogee BT-60 body tube cut to 9.5 inches in length as its main body. The motor mount is a 3D printed fin assembly attached to a standard 24mm motor mount tube, which is affixed to the main body tube with two Apogee CR 24-41.6 Cardstock centering rings. The payload bay and nose cone are attached to the main body by a ⅜ in. thick rubber shock cord. The increased diameter of the main body and payload bay allows the rocket to carry a Featherweight GPS Altimeter for accurate flight path recording, and a Tracki GPS Tracker to provide accurate and reliable location data during recovery.

Microcontroller Circuit Design

The microcontroller circuit or circuits must be able to operate environmental sensors to calculate its current altitude and determine if the platform is level, and must be able to ignite the rocket engine at the correct altitude. It must also be able to activate the separation system to release the balloon from the platform. The separation mechanism used was a simple one. The microcontroller ignites a small ½ A rocket motor which is tied into the balloon string. The motor ignition severs the string, so the balloon continues to ascend while the platform drops back to earth using its parachute.

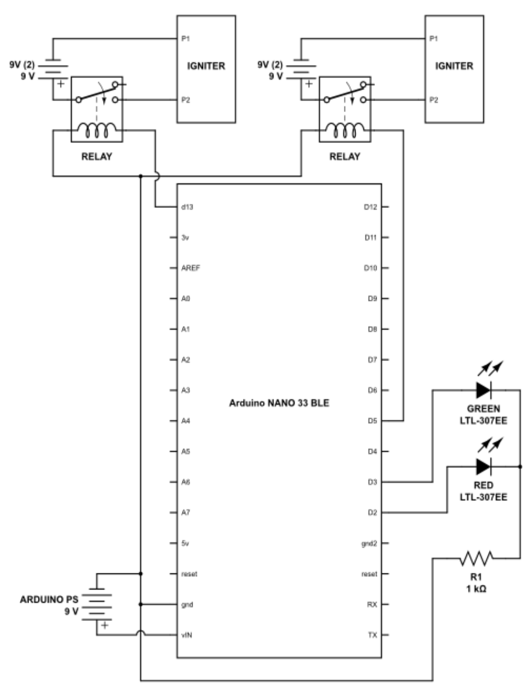

Figure 15. Schematic for first design of microcontroller circuit.

Pictured above in Figure 15 was the first design of the microcontroller system, centered around an Arduino Nano. This circuit was constructed using a solderless breadboard. The two LEDs are used to display whether the microcontroller is level or not. The use of a solderless breadboard made construction easy, but it caused the circuit to be fragile, and connections frequently came out of the pin slots. In addition, the igniter circuits did not have any safety switch, and the microcontroller would often cause the relays to briefly close during bootup, which could prematurely ignite the engines. This circuit was never used to ignite an engine.

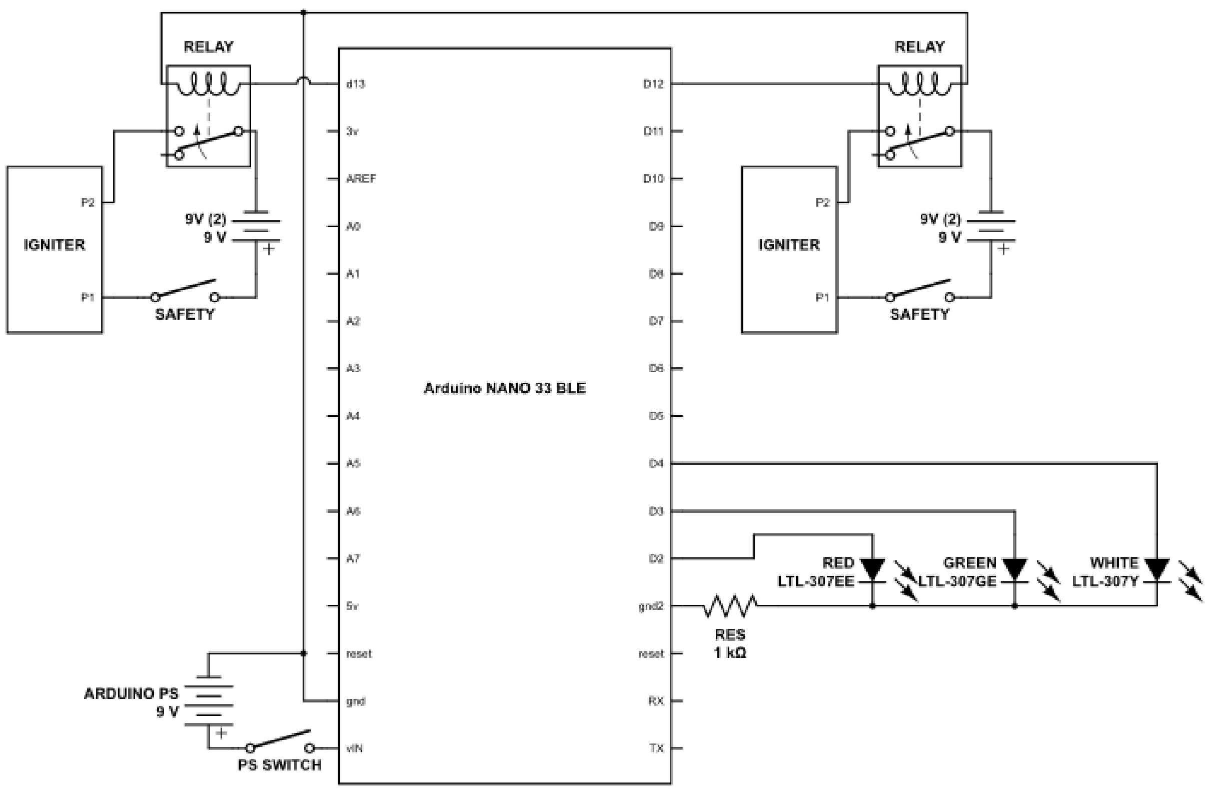

Figure 16. Schematic for second design of microcontroller circuit.

Pictured above in Figure 16 is the second iteration of the microcontroller circuit. It is very similar to the first iteration, but with four notable differences. Firstly, the relay circuits now have safety switches installed, to be opened during bootup and then closed to ensure the engine does not ignite prematurely. Secondly, a switch has been installed on the power supply circuit, so that the microcontroller itself can be powered and unpowered without requiring the removal of the battery. Thirdly, a third LED has been added; This LED turns on every half second and stays on for one half second before turning off, and is used to ensure that the timer loop is running properly. Finally, this circuit is assembled on a solder breadboard. The use of a solder breadboard reduces the physical size of the circuit itself, and prevents any connections from coming loose. However, this design was scrapped as well; Having both igniters connected to a single microcontroller was found to be unreliable. Moreover, having the microcontroller requiring separation attached to the platform requires two 4-meter wires to be connected from the microcontroller to the engine causing separation, because separation needs to occur above the parachute. These wires may interfere with the launch and have a high likelihood of being disconnected during balloon flight and rocket launch. This design specifically failed in Balloon Launch/Rocket Flight 1.

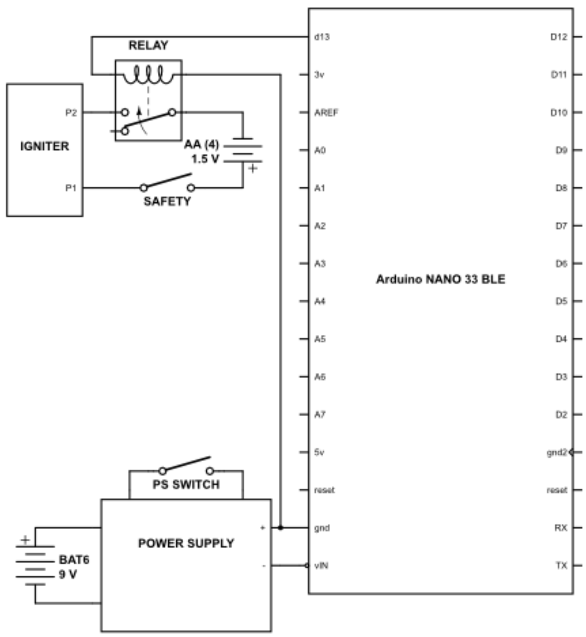

Figure 17. Schematic of the rocket ignition part of the final design of the microcontroller circuit.

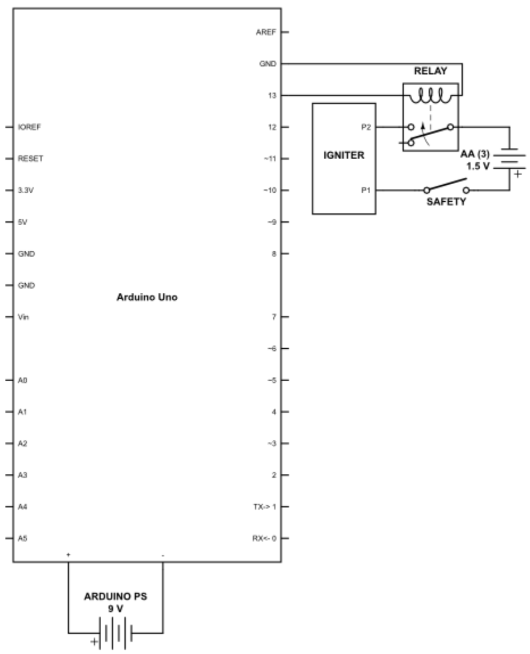

Figure 18. Schematic for the balloon separation part of the final design of the microcontroller circuit.

Pictured above in Figures 17 and 18 is the final iteration of the microcontroller circuits, which was used in both Balloon Launch/Rocket Flight 2 and 3. Instead of connecting both relays to a single microcontroller, the rocket is ignited by a microcontroller centered around an Arduino Nano according to altitude (with time as a backup launch metric), and second microcontroller centered around an Arduino Uno using a simple timer to determine when to separate the balloon and platform. The LEDs have been removed from the circuit, and the igniter circuits use clusters of 3 and 4 AA batteries instead of clusters of 2 9V batteries, for increased reliability. The Arduino Uno is connected to the balloon string instead of the platform, and remains connected to the balloon after separation. It is equipped with an Apogee 18” plastic hexagonal parachute to ensure a safe descent separate from the platform, and is not intended to be recovered.

Microcontroller Code Design

The launch microcontroller code must be able to efficiently instruct the microcontroller to carry out the requirements the circuit was designed for. It must use accurate calculations for all applications where calculation is needed, and must efficiently utilize the limited capacity and processing power of the microcontrollers it is installed on. Specifically, the code reads the altimeter and runs a launch clock. Altitude was chosen as the primary launch metric with time as a backup, due to the inconsistent nature of the Arduino Nano 33 BLE altitude calculations. The code must also determine if safe launch parameters exist, specifically if the platform is not aiming the rocket at an angle greater than 30 degrees.

The first iteration of the code used the onboard 9-axis IMU of the Arduino Nano 33 BLE to determine if the microcontroller was level. It also utilized the onboard barometric sensor to determine the barometric pressure, and used that value to calculate the current altitude. This iteration utilized the delay() function to loop once every 1000 milliseconds. This iteration was abandoned, because the delay() function is a “busy” wait, and occupies 100% of the microcontroller for that length of time. As a result, timing inaccuracies slowly accumulate.

The second iteration of the code uses the millis() function to record how many milliseconds have passed since the microcontroller has been activated, and triggers a loop every time the millis() function returns a multiple of 1000. This iteration also includes the code required to output the current altitude to an LCD screen. However, due to a multitude of software bugs and hardware issues with the LCD screen, this iteration was abandoned.

The third iteration of the code uses the millis() function as well, but does not output to an LCD screen. This reduced the complexity of the code and allowed it to run more efficiently, as well as not requiring the microcontroller to power an LCD screen alongside itself.

Results

Five experimental launches were conducted, two tethered launches where the balloon was attached to 350 feet of high-strength kite string and three full launches. In addition, a ground launch was conducted as a control. Each launch was instructive in iterative design and taken together the three full launches demonstrate that the project achieved success in each sub-part goal and overall goals.

Tethered Test Fight 1:

Figure 19. Balloon is inflated and ready to launch.

Tethered Test Flight 1 was accomplished on September 5, 2020 from the Thorn Preserve in Woodstock, New York. This launch was primarily a test of the microcontroller and microcontroller code. The primary goals of the launch was to confirm the ability to 1) remotely launch the rocket and 2) remotely achieve balloon separation. This launch used the first iteration of the microcontroller and the second iteration of the code. The relay to ignite the rocket was attached to a 13mm rocket with a 1/2A3-2T engine, and the relay to separate the platform was attached to a 1/2A3-2T engine taped to the platform. The second 1/2A3-2T engine tests balloon separation, but since recovery of the balloon and platform by reeling back in the kite string was desired, the engine was not mounted to the string in a way that it would create separation. Instead it was simply mounted to the platform with duct tape. The launch altitude was set to 300 feet, the launch time was set at 10 minutes, the separation mechanism was set to ignite 10 seconds after launch and the platform was attached to a 350 foot long kite string.

Platform launch went as expected. During ascent, the wind caused the platform and balloon to move laterally, and nearly all 350 feet of the kite string was unwound before ignition was visually and audibly confirmed. Ignition was confirmed visually and audibly at the expected time, but not the expected altitude due to the lateral movement. However, it was discovered upon reeling in the platform and balloon that only the mock separation engine ignited. When the Arduino was powered off, the rocket engine ignited from ground much to the surprise of all observers. The platform was recovered, but the balloon was not recoverable. This test revealed that, when powered, the 3V relays switch states. This prompted the addition of safety switches in the next iteration of the circuit. The most significant achievement of this test was confirmation of the ability to remotely fire rocket engines at a specified time.

Tethered Test Flight 2:

Tethered Test Flight 2 was accomplished on September 22, 2020 from the Ardsley High School in Ardsley, New York. This launch was to test the second iteration of the microcontroller and code, as well as a test of the platform's ability to launch a rocket. This launch used the second iteration of both the microcontroller and code. The relay to ignite the rocket was attached to an 18mm rocket with a C6-3 engine, and the relay to separate the platform was attached to a 1/2A3-2T engine taped to the platform. The launch altitude was set to 200 feet, and the platform was attached to a 350 foot long kite string. The primary goals of the launch was to confirm the ability to 1) remotely launch the rocket and 2) remotely achieve balloon separation.

Platform launch went normally. Lower winds made controlling the ascent of the platform easier, and the lower altitude for ignition meant that the kite string did not have to be reeled out to nearly its full length. The rocket was visually confirmed to have launched at the proper altitude and prior to the secondary launch parameter (time), with a straight ascent profile and no spiraling or instabilities. Visual confirmation of the mock separation engine followed ten seconds after the launch of the rocket. The platform was reeled in and recovered, and the balloon was deflated and recovered as well. This test proved that the microcontroller circuit and code was 1) capable of igniting the rocket and 2) separating the balloon from the platform once reaching the proper altitude.

Balloon Launch/Rocket Flight 1:

Balloon Launch/Rocket Flight 1 was accomplished on October 24, 2020 from the Byram Hills High School in Armonk, New York. The first balloon launch was planned to rise to 5,000 meters, launch the rocket, and separate from the balloon. The goals of this launch include all elements of the project, 1) remote launch of rocket at prescribed height (5,000 meters), with time as a backup metric (65 minutes), 2) tracking of rocket for the purpose of determining full flight path, 3) separation of platform at prescribed time (70 minutes) and 4) recovery of platform and rocket. This launch used the second iteration of the rocket and the second iteration of the microcontroller circuit and code. The balloon used was a 350 gram helium balloon purchased from High Altitude Science.

During setup, it was discovered that using a single microcontroller for both the rocket and release posed problems, as the wires could not reach all the way up to the separation motor and be expected to stay attached during flight. So, the wires were disconnected, and recovery plans were changed to anticipate the platform rising to the balloon's maximum altitude of approximately 15,000 meters. Approximately ten minutes after launch, connection to the Featherweight GPS Altimeter on the rocket was lost. The satellite tracker onboard the platform was followed over 300 kilometers to Falls River, Massachusetts where the platform was found and recovered. The rocket was never recovered, and most likely landed in the Long Island Sound. Unfortunately, since the Featherweight connection was lost as well as the rocket, there was no flight data on this launch.

The video recording reveals that, due to a software bug, the rocket launched at 5,922 meters instead of 5,000 meters by using the secondary launch metric of 65 minutes. The temperature at launch was -20 degrees Celsius. Using RockSim and an analysis of the obvious contrails in the video (see Figure 22), it is estimated that the rocket exceeded 1,000 meters in height from the platform. Due to the outcome of this launch, the rocket was redesigned to its final iteration, and the microcontroller and code were also redesigned to their final iterations as well.

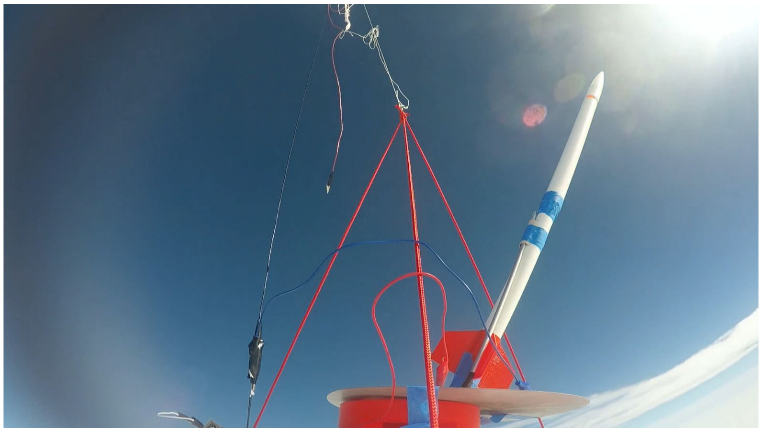
Figure 20. Rocket on the platform at an altitude of 5,920 meters, right before launch.


Figure 21. Rocket just after launch. It leaves the guard rail and flies straight.


Figure 22. 10 seconds after launch. Contrail is visible, showing the rocket's straight path.

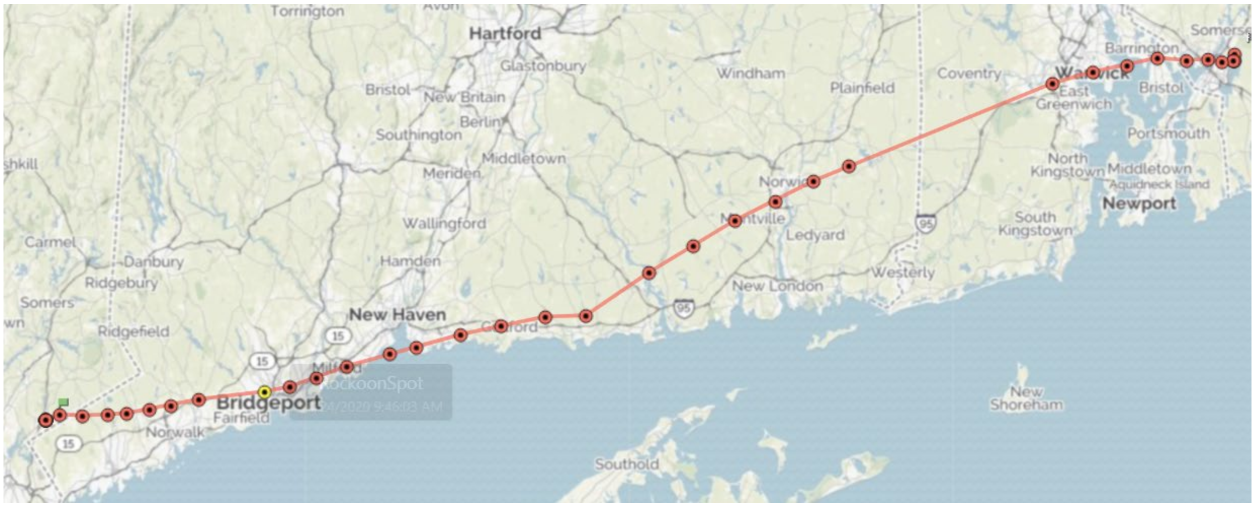

Figure 23. Flight path of the balloon (SPOT Satellite Tracker)

Time	Lat	Long	Altitude (feet)
8:05:25 AM	41.1366	-73.6891	557.1
9:03:33 AM	41.14456	-73.6571	
9:08:33 AM	41.14422	-73.6097	4888.5
9:14:51 AM	41.14541	-73.5527	6817.6
9:19:09 AM	41.14864	-73.513	7949.5
9:24:59 AM	41.15341	-73.4635	
9:29:59 AM	41.16023	-73.4148	
9:34:59 AM	41.17062	-73.3546	12900.3
9:46:03 AM	41.18227	-73.2138	
9:51:03 AM	41.19008	-73.1588	
9:56:03 AM	41.20609	-73.0991	19544
10:01:45 AM	41.2235	-73.0357	
10:06:45 AM	41.24401	-72.9407	
10:11:45 AM	41.25448	-72.882	25951.4
10:17:26 AM	41.27601	-72.7874	28333.3
10:22:24 AM	41.28954	-72.6998	30607
B Launch	8:54:00 AM	14.437	
R Launch	62 min.		

Table 2. Latitude, longitude, and altitude of balloon from SPOT Satellite Tracker during flight.

Ground Launch 1:

Figure 24. GPS coordinates of the Featherweight GPS Altimeter during flight.

TIME	LAT	LON	ALT (feet)	HORZV	VERTV	HEAD
40:04.8	40.57823	-74.68	51	14	6	107
40:05.8	40.57818	-74.6798	63	57	0	92
40:06.8	40.57807	-74.6797	-4	19	-88	175
40:07.8	40.57805	-74.6798	3	24	68	-68
40:08.8	40.57815	-74.6799	159	63	156	-18
40:10.8	40.57841	-74.6802	360	18	-2	-69
40:11.8	40.57864	-74.6802	668	15	10	-58
40:12.8	40.5791	-74.6802	1239	9	-22	-81
40:13.8	40.57933	-74.6805	1435	14	-40	-106
40:14.8	40.57938	-74.6806	1443	11	-47	-131
40:15.8	40.57938	-74.6807	1418	15	-52	-125
40:16.8	40.57935	-74.6808	1380	19	-47	-136
40:17.8	40.57933	-74.6809	1334	15	-55	-149
40:18.8	40.5793	-74.6809	1289	16	-53	-148
40:19.8	40.5793	-74.681	1248	16	-48	-152
40:20.8	40.57928	-74.681	1208	18	-44	-135
40:21.8	40.57923	-74.681	1167	16	-40	-160
40:22.8	40.5792	-74.6811	1130	13	-42	-147
40:23.8	40.57917	-74.6811	1090	13	-45	-161
40:24.8	40.57915	-74.6811	1049	13	-42	-129
40:25.8	40.57912	-74.6812	1008	12	-40	-152
40:26.9	40.5791	-74.6812	967	12	-41	-143
40:27.8	40.5791	-74.6813	925	9	-41	-112
40:28.8	40.57907	-74.6813	882	10	-43	-131
40:29.8	40.57905	-74.6813	840	13	-43	-137

40:30.9	40.57905	-74.6814	798	8	-43	-115
40:31.8	40.57902	-74.6814	758	4	-39	-139
40:32.8	40.57902	-74.6814	716	8	-40	-150
40:33.8	40.579	-74.6814	675	8	-40	-178
40:35.0	40.57897	-74.6814	634	5	-41	142
40:35.8	40.57897	-74.6814	593	2	-41	145
40:36.8	40.57894	-74.6814	551	2	-42	-119
40:37.8	40.57894	-74.6814	510	3	-39	-93
40:38.9	40.57894	-74.6814	470	3	-40	54
40:39.8	40.57894	-74.6814	429	3	-38	27
40:41.0	40.57894	-74.6814	387	3	-44	-108
40:41.9	40.57894	-74.6814	344	4	-40	-60
40:42.9	40.57894	-74.6814	304	0	-40	-68
40:44.2	40.57894	-74.6814	262	0	-41	21
40:44.9	40.57894	-74.6814	217	0	-47	138
40:45.8	40.57892	-74.6814	172	3	-44	135
40:46.9	40.57892	-74.6814	127	1	-45	0
40:48.1	40.57892	-74.6814	80	3	-47	13

Table 1. GPS coordinates, altitude, horizontal velocity, vertical velocity, and heading of Featherweight GPS Altimeter during flight. Yellow highlighted values are inaccurate readings

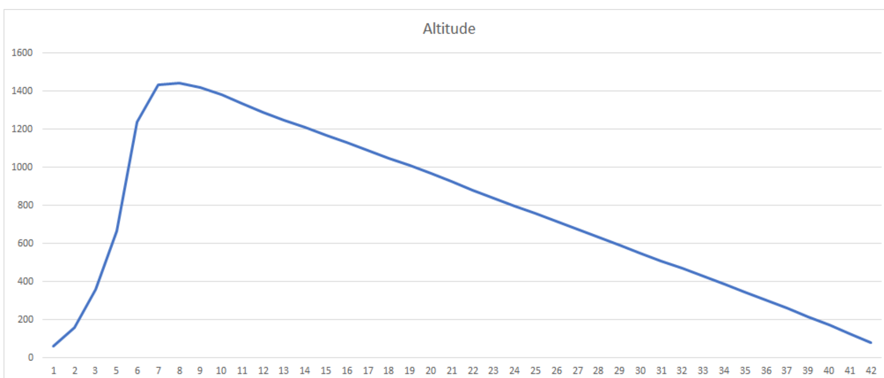

Figure 25. Plot of altitude (ft) of the Featherweight GPS Altimeter versus time (sec) during flight.

Ground Launch 1 used the final (3rd) iteration of the rocket, but was ignited manually instead of with a microcontroller. It was launched with the platform, but from the ground, with no balloon. It was launched at the same 12 degree angle as the balloon launches. This launch was intended to be the 'control' to compare the efficiency a rocket gains when launched at altitude. The engine ignited without problem, and the rocket reached a peak altitude of 437 meters (1,443 feet). The rocket was successfully recovered, but during descent the nose cone came off and all electronics were lost as they landed in the river as demonstrated by the flight path map. Future launches used a piece of duct tape to secure the nose cone during flight.

Balloon Launch 2:

Figure 26. Flight path of the balloon from iTrack Satellite Tracker on rocket

Figure 26. Rocket on platform shortly after launch.

Balloon Launch 2 was accomplished on November 7, 2020 from the Pawling High School in Pawling, New York. The second balloon launch was planned to rise to 10,000 meters, launch the rocket, and separate from the balloon. This launch utilized the final iteration of the rocket, the final iteration of the microcontroller circuits, and the final iteration of the microcontroller code. The balloon used was a 600 gram balloon purchased from High Altitude Science. The goals of this launch were the final demonstration of all aspects of the project, 1) remote launch of rocket at prescribed height (10,000 meters), with time as a backup metric (65 minutes), 2) tracking of rocket for the purpose of determining full flight path, 3) separation of platform at prescribed time (70 minutes) and 4) recovery of platform and rocket.

All connections were verified on the ground, and the balloon was launched without issue. Despite the usage of a Tupavco TP513 Yagi antenna to connect to the Featherweight, connection was lost approximately twenty minutes after launch. The trackers on the platform and the balloon were tracked to Southbury, Connecticut. Both the platform and the rocket were recovered, and it was found that the rocket had not launched. Reviewing the camera footage of the flight, it was found that the contacts for the rocket engine igniter were touching, and caused a short, preventing the engine from igniting. However, the release mechanism worked appropriately, and separated the balloon from the platform at the correct time (70 minutes). The SPOT satellite tracker on the balloon never started due to the fact that it did not sense motion, but the iTrack satellite tracker in the rocket did send signals appropriately.

Balloon Launch 3:

Figure 28. Flight path of balloon from FeatherWeight GPS Tracker on rocket

Figure 29. View of downwards-facing camera at exact time of launch at an altitude of 2,667 meters.

TRACKER	TIME	LAT	LON	ALT (feet)
FthrWt01010	26:33.8	41.14924	-73.6988	7829
Extrapolated	30:40.8	N/A	N/A	8802
Extrapolated	30:41.8	N/A	N/A	8915
Extrapolated	30:42.8	N/A	N/A	9034
Extrapolated	30:43.8	N/A	N/A	9152
Extrapolated	30:44.8	N/A	N/A	9515
Extrapolated	30:45.8	N/A	N/A	10188
Extrapolated	30:46.8	N/A	N/A	10419
Extrapolated	30:47.8	N/A	N/A	10428
Extrapolated	30:48.8	N/A	N/A	10413
Extrapolated	30:49.8	N/A	N/A	10377
Extrapolated	30:50.8	N/A	N/A	10341
Extrapolated	30:51.8	N/A	N/A	10305
Extrapolated	30:52.8	N/A	N/A	10269
Extrapolated	30:53.8	N/A	N/A	10233
Extrapolated	30:54.8	N/A	N/A	10197
Extrapolated	30:55.8	N/A	N/A	10161
Extrapolated	30:56.8	N/A	N/A	10125
Extrapolated	30:57.8	N/A	N/A	10089
Extrapolated	30:58.8	N/A	N/A	10053
Extrapolated	30:59.8	N/A	N/A	10017
Extrapolated	31:00.8	N/A	N/A	9981
Extrapolated	31:01.8	N/A	N/A	9945
Extrapolated	31:02.8	N/A	N/A	9909
FthrWt01010	31:03.9	41.14647	-73.6793	9873
FthrWt01010	31:09.8	41.1465	-73.6787	9644
FthrWt01010	31:10.8	41.14647	-73.6787	9608
FthrWt01010	31:12.8	41.14645	-73.6785	9531
FthrWt01010	31:39.9	41.14604	-73.6763	8509
FthrWt01010	31:58.8	41.14591	-73.6747	7827
FthrWt01010	31:59.9	41.14591	-73.6746	7790
FthrWt01010	32:13.9	41.14557	-73.6735	7290
FthrWt01010	32:17.8	41.1455	-73.6733	7151
FthrWt01010	32:21.8	41.14545	-73.673	7014
FthrWt01010	32:22.8	41.1454	-73.6729	6980
FthrWt01010	32:52.8	41.14447	-73.6711	5930
FthrWt01010	32:59.9	41.14435	-73.6707	5690
FthrWt01010	33:02.8	41.14424	-73.6705	5581
FthrWt01010	33:06.8	41.14412	-73.6703	5444
FthrWt01010	33:25.8	41.14353	-73.6697	4793
FthrWt01010	33:32.8	41.14322	-73.6695	4558

Table 3. Featherweight GPS Altimeter data and extrapolated data from the rocket launch.

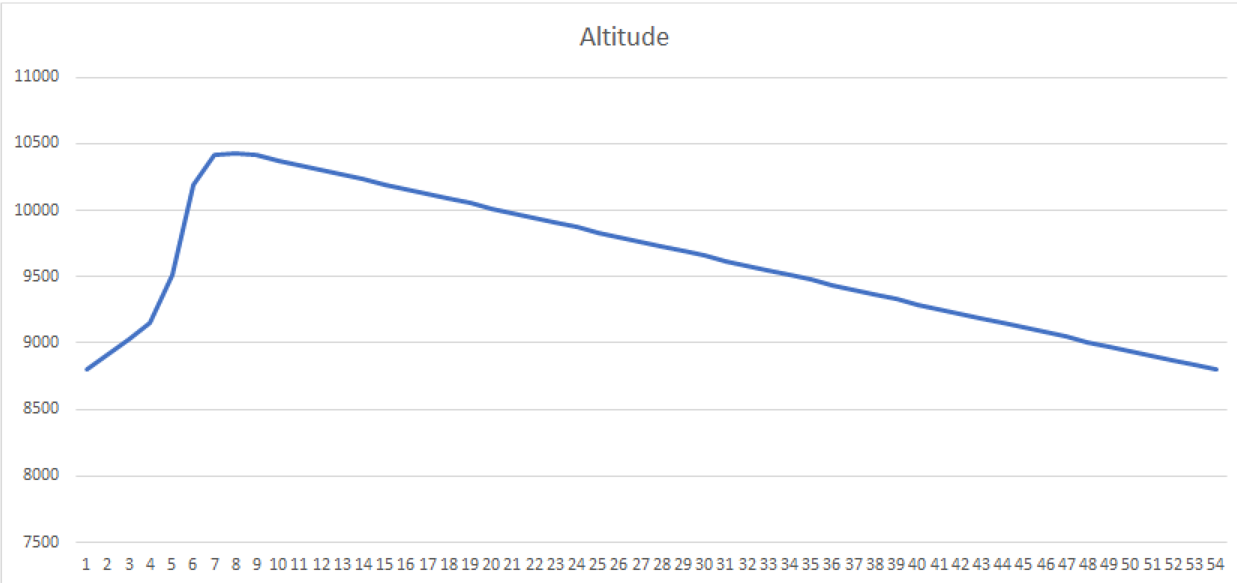

Figure 30. Altitude of rocket plotted against time after ignition.

Balloon Launch/Rocket Flight 3 was accomplished on November 8, 2020 from the Horace Greeley High School in Chappaqua, New York.The third balloon launch was planned to rise to 5,000 meters, launch the rocket, and separate from the balloon. The primary launch criteria was set to 5,000 meters and the secondary launch criteria was set at 30 minutes. The lower height and quicker launch were chosen for this launch because the balloon being used was the 200 gram balloon recovered from the Tethered Balloon Test 2 and would likely burst before reaching 10,000 meters. In addition, the lower height would reduce the distance from the Featherweight tracker, and make data collection easier. This launch utilized the final iteration of the rocket, the final iteration of the microcontroller circuits, and the final iteration of the microcontroller code. A secondary camera was attached to the platform in addition to the primary camera as well. The contacts for the rocket igniter were taped in place with duct tape to ensure that a short could not occur.

All connections were verified on the ground, and the balloon was launched without issue. Due to extremely low winds and clear skies, visual contact with the balloon was maintained for approximately thirty minutes. Connection to the Featherweight was smooth for approximately thirty minutes as well, but connection was then lost until at approximately the forty minute mark, where it was momentarily regained on the rocket's descent. The balloon rose significantly slower than expected because of the use of the 200 gram recovered balloon. Therefore, the remote launch was triggered by the secondary criteria, time, and occurred as expected at 2,667 meters (8,802 feet). The temperature at the time of the launch is unknown because the launch platform has not been recovered. It landed 35 meters up in a tree, in Stamford, Connecticut. Recovery will hopefully occur at a later time. Due to unknown issues with the satellite tracker onboard the rocket, it did not activate tracking, and the rocket was unable to be located. The SPOT satellite tracker on the platform also did not start properly and only began sending signals upon landing. The platform was successfully located to its landing site, but it had landed in a tree approximately 35 meters above the ground and was deemed presently unrecoverable. However, the two cameras were knocked off the platform during landing. The camera recording the rocket did not have any usable footage, but the second camera pointing downwards had recoverable footage. The exact time of launch was identified using the footage, and by using the time of launch and the data points collected while the Featherweight was still connected, the maximum height of the launch was able to be calculated. Using the ascent rate, descent rate and time of launch, as well as the flight path calculated by the rocket simulation software RockSim 10 and the data from the ground launch, the apogee of the launch was calculated to be 493 meters above the altitude it launched from, at a total altitude of 3,160 meters.

Discussion

Considering all three untethered balloon launches, most major goals of the project were achieved, although no rocket was successfully launched from 10,000 meters. Since the Featherweight tracker had intermittent failures, speed was unable to be accurately determined. In Balloon Flights/Rocket Launch 1 and 3 remote launching of a rocket was achieved after confirmation of safe launch conditions. In both cases, launch was achieved when the back up criteria, time, was reached. It is noteworthy that in Tethered Test Flight 2 the primary criteria, altitude, was successfully used to trigger the remote launch. In Balloon Flights/Rocket Launch 2 and 3 successful remote separation was achieved at the proper separation time. In Balloon Flights/Rocket Launch 3 enough flight data was collected to track the flight path of the rocket. In Balloon Flights/Rocket Launch 1 a high altitude rocket launch in excess of 5,000 meters was achieved, while in In Balloon Flights/Rocket Launch 3 a lower launch at 2,667 meters was achieved. Although the launch from Balloon Flights/Rocket Launch 3, where flight data was collected, was performed at an altitude where the difference in pressure is not extreme, the altitude gain was still significant. The apogee of the ground launch was 418 meters above ground level, while the apogee of the launch from 2,667 meters was 493 meters above the launch altitude.

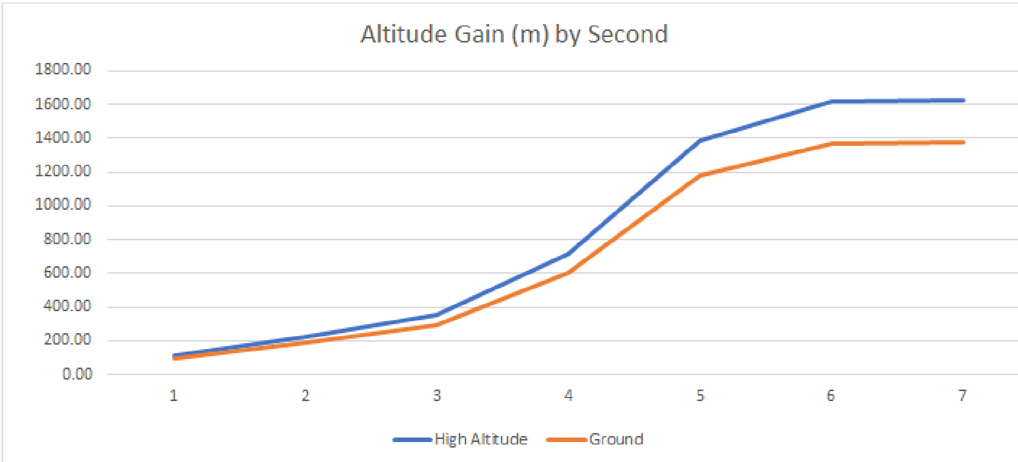

Figure 31. Altitude gain per second for both the launch from the ground and the launch from 8000 feet of elevation.

When launched at an altitude of 2,667 meters, the balloon-launched rocket increased its altitude approximately 18% more than the same rocket launched from the ground. In addition, the rockoon reached a total altitude of 3,160 meters.

It is noteworthy to compare this research project launch within the context of typical rocket launches. Maximum height achieved is one of the most widely used achievement metrics used. The Level-2 rocket from Madcow Rocketry, the model rocket with the closest maximum altitude to the total altitude of the rockoon launch, is a fiberglass model rocket with a 54mm motor mount, and without any motor weighs 8 pounds. It requires a Level 2 High Power Rocketry certification to fly with a K660 Reload rocket motor, which has an average apogee of 3,235 meters when simulated using Rocksim 10. Combined, the Level-2 rocket and the K660 motor cost $585, and can reach a maximum altitude that is only 75 meters higher than the maximum altitude of the rockoon system. The rockoon system is constructed with $15 of cardboard rocket parts, a $50 wooden frame, a $20 200g helium weather balloon, $40 of helium, and $30 of 3D printer filament, and requires no certification to own and launch. So, in order to achieve the same height that the lowest rocket launch of this research project achieved a much more expensive rocket would be required along with a Level 2 certification and a much larger and more expensive rocket motor.

Conclusion

In recent years, as electronic components and scientific devices have become significantly more miniaturized, making small satellites such as CubeSats a viable, inexpensive, and simple endeavor. As a result, the demand for launches of small payloads such as CubeSats has risen dramatically, with over 1,200 launched to date. However, current space infrastructure is centered around the launches of larger payloads. While endeavors to retrofit current rockets to carry CubeSats as part of rideshare programs have so far been successful, they have limited launch windows, limited orbital placement possibilities, and even individual slots onboard rideshare programs are prohibitively expensive. A full-scale rockoon system could launch from nearly any location, at any time, and place a client's CubeSat into whatever orbit they require, at a significantly lower cost than a rideshare slot. Moreover, CubeSats continue to get even smaller, which makes a rockoon system an excellent candidate for their launch. New generation of smaller satellites, PocketQube, SunCubes, Zeposatellites, are as much as 75% smaller than the original CubeSat (Kulu, 2019).

This scaled-down rockoon system proves that high altitudes can be reached at a much lower cost with a rockoon than with conventional rockets, and that when launched at a high altitude, the efficiency of the rocket increases significantly. Follow-up experiments will have to mitigate the issues found in this experiment with tracking both the rocket and the platform. Future experiments will also need to include more comprehensive flight computers and data tracking, higher altitudes, larger and more powerful rockets, and more extensive flight and launch control. These factors will pose their own unique engineering challenges; at higher altitudes, the electronic components will have to be protected from the cold, and the rocket motor may have to be as well. The dramatic decrease in air pressure will reduce the ability of the rocket to passively stabilize itself with fins alone, and thus may require passive stabilization techniques such as spinning during flight, or active stabilization methods such as thrust vectoring. With larger rockets, the amount of fuel will conflict with certain FAA regulations, and platform configuration, launch location, and other factors may have to change; In addition, the platform may have to be expanded to be capable of launching the larger engines without damaging itself or the rocket. Needing new passive and active stabilization techniques will pose unique challenges, and may require complete redesigns of the platform, rocket, or both. When scaled up to full size, rockoon systems will significantly reduce the cost of launching small payloads into orbit, making space vastly more accessible to smaller institutions such as startups, universities, high schools, and even individual researchers.

References

Apogee Components. (2010). *NEW TO MODEL ROCKETRY?*. https://www.apogeerockets.com/New-to-Model-Rocketry.

Larson, S., et. al. (2009). The First Frontier: High Altitude Ballooning as a Platform for Student Research Experiences in Science and Engineering. *American Journal of Physics*. 77, 489. DOI:10.1119/1.3097775. https://www.researchgate.net/publication/229042541_The_first_frontier_High_altitude_ballooning_as_a_platform_for_student_research_experiences_in_science_and_engineering.

Corliss, W. (1971). *NASA SOUNDING ROCKETS, 1958-1968 | A Historical Summary*. Scientific and Technical Information, National Aeronautics and Space Administration (NASA). https://history.nasa.gov/SP-4401.pdf.

Nizhnik, O. (2012). A Low-Cost Launch Assistance System for Orbital Launch Vehicles. *International Journal of Aerospace Engineering*, vol. 2012, Article ID 830536. https://doi.org/10.1155/2012/830536

Chakrabarti, S. (2019, May 6). Beanie Babies, *The invention of CubeSat and student-designed and built satellites*. The Conversation. https://theconversation.com/beanie-babies-the-invention-of-cubesat-and-student-designed-and-built-satellites-115354

CubeSat. (2019). *THE CUBESAT PROGRAM*. https://www.cubesat.org/about.

CubeSat. (2020). *CubeSat Design Specification - Rev 14*. https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/5f24997b6deea10cc52bb016/1596234122437/CDS+REV14+2020-07-31+DRAFT.pdf.

Kulu, E. (2019). *What is a CubeSat & other picosatellites*. Nanosats Database. https://www.nanosats.eu/cubesat.

Mraz, S. (2019, February 19). *Start-up to Launch CubeSats from Hot Air Balloons*. MachineDesign. https://www.machinedesign.com/mechanical-motion-systems/article/21837538/startup-to-launch-cubesats-from-hot-air-balloons

Columbia Space Initiative. (2016, April 5). *High Altitude Balloons*. ColumbiaSpace. https://columbiaspace.org/missions/mission-balloons/.

[Phil G]. (2013, October 27). *Edge of Space Rocket Launch Attempt - 104,000 ft*. YouTube. https://www.youtube.com/watch?v=-t96x5UGOLE

Ruiz, A. (2018, October 2). *High Altitude Rocket Transport*. HART. https://hartvr.wixsite.com/hartvr.

Becerra D. [Stanford]. (2015, January 30). *Stanford students launch high-altitude rocket from a balloon*. YouTube. https://www.youtube.com/watch?v=H-AcSucRBbw.

JP Aerospace. (2010, August 19). *Rockoons*. http://http://www.jpaerospace.com/rockoons.html.