Final Report for
Earth-Based Gravity Machine

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Executive Summary

Microgravity environments are valuable tools that physicists and researchers use for many experiments. Unfortunately, achieving such an environment is expensive, and few options are currently available. Current options include drop towers, parabolic flight paths, sounding rockets, and flights to the International Space Station. Providing a low-cost, easily accessible alternative to the aforementioned options would allow researchers to carry out these experiments more often and in many more locations. This could lead to many scientific breakthroughs in the area and would raise the quality of experiments that actually make it into the ISS for long term testing and may even allow high schoolers access to microgravity experiments.

The proposed design will focus on creating a microgravity environment for 2U CubeSats, which are small scale satellites used to conduct various experiments in space. This device will be carried by a drone to an altitude of 400ft, and then released into free fall. To achieve a microgravity environment, downward propulsion will be used to counteract the effects of air resistance. The expected resistance will be modeled at different speeds that the vehicle is expected to encounter during the drop, and this data will be used to calibrate the amount of thrust provided by 4 electric motors. The goal of this study is to achieve a microgravity environment with an acceleration of less than 10^{-2}G's for a period of at least 3 seconds. This also necessitates the design of an outer shell with minimal air resistance which remains stable for the duration of the free fall.

The second challenge in the design of this device is landing safely. After a maximum of 4 seconds of free fall from 400ft, this device will be going 87 mph and will have 144ft to slow down before impacting the ground. To achieve this level of deceleration, having a parachute will not be adequate on its own. Multiple options are considered when developing the design to assist the device in slowing down and reduce the force transferred to the body and the payload upon impact with the ground. These systems are crucial in achieving the cost efficiency goal of the study as they allow the device to be reusable. All of the currently available options have a fixed cost per time experienced in microgravity, but the proposed device would lower this cost with every drop. A robust design that does not need repair after multiple drops would be extremely cost effective with the only additional cost incurred with each experiment being the electricity needed to power the device and the drone.

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Revision History

Version	Date	Reason for Changes
1.0	11/20/2019	Initial document
1.5	12/06/2019	Competition data added
2.0	12/12/2019	Final document

Glossary

- FSI – Florida Space Institute
- PWM – Pulse width modulation
- FEA – Finite Element Analysis
- CFD – Computational Fluid Dynamics
- FMEA – Failure Modes and Elements Analysis
- RPM – Revolutions per minute
- DC – Direct Current

1. Introduction

Microgravity conditions are universally limited in resource and availability. Currently, the only methods available for microgravity testing are conducted through drop towers, parabolic flights, suborbital flights, and the International Space Station (ISS). Drop towers are the most common approach for testing but only limited institutes are available worldwide in U.S., China, Japan, and Germany. Most of these locations provide over 3 seconds of microgravity but availability is rare. Parabolic flights, such as those offered by the Zero-G's Vomit Comet in the US and the Air Zero-G Experience in France, allow 15-20 seconds of microgravity conditions with 15 parabolic maneuvers but at an average cost of $5000. Suborbital and ISS flights are even more costly and may require years of waiting before testing can be done, thus not ideal for microgravity research. Earth based microgravity can also provide a valuable "proof of concept" for experiments to be later carried out in space.

The intent of this report is to introduce a solution to alleviate the issues of limited access and high costs of microgravity testing. Building an easily reproducible drop vehicle capable of housing the CubeSat 2U class payload while sustaining multiple flights can provide low-cost access to microgravity conditions. The primary obstacles that need to be addressed for a successful drop vehicle are the thrusts' ability to precisely match the exponentially increasing air resistance and the reliability of deceleration mechanisms to support the vehicle's ability to sustain multiple drops without compromising the payload. The proposed device will utilize electric motors to provide a thrust of at least 15 N to counteract the air resistance. A series of deceleration systems comprised of a parachute, a rebar landing spike, and low cost, easily replaced 3D printed components, will help the vehicle brave multiple flights of microgravity testing. This earth-based microgravity vehicle will provide the opportunity to perform countless experiments at a fraction of the costs than any single test using the aforementioned methods, opening up the possibilities of additional graduate, undergraduate, and even high school level research projects.

This document will review the necessary characteristics and properties of the vehicles as per the needs of Florida Space Institute, examine the technology relevant to create the concept design of the drop vehicle, explore the systems requirements and the various concept designs, and conduct the preliminary engineering analysis. Afterwards, the system concept evaluation plans and future works will be discussed.

2. Project Objectives & Scope

This project is the first phase of a multi-phase project, which is intended to be used as a general proof-of-concept for what eventually may or may not become a final product. The uses of the potential end product could in theory range very widely and may be used both in professional settings by engineers and scientists, as well as educational settings such as high schools and universities. Currently, this project is solely intended to be an educational and research venture for Florida Space Institute. As such, the main goal is to meet the set requirements for microgravity performance, but the optimization of the user experience will not be heavily considered as a driving factor of the design.

The main goal for our project is to provide a high quality of microgravity within the proposed budget. If this project is successful, then other goals may be implemented in further stages of development relating to the usability, mass production/manufacture, or ease of assembly by the end user. These factors are certainly important in almost any final product, but it is imperative that these minor factors do not become a distraction from reaching the primary goal.

Lessons learned from this project may be applied to Class 1; Mark 2 and 3 drop vehicles. Longer duration, higher quality microgravity can be achieved in future iterations with the modifications outlined by Mike Conroy and FSI. These improvements include Closed Loop Flight Control, Fly Back, Gyro Stabilizers, and Cold Gas systems. These additions are outside the scope and budget of our yearlong project but are necessary in increasing the quality and duration of atmospheric microgravity.

3. Assessment of Relevant Existing Technologies and Standards

3.1 Propulsion System

Many options were considered to counteract the drag force encountered in free fall, including cold gas, rocket propulsion, and a variety of electric motor types with different configurations. It was determined that the optimal thrust method in this case is the use of counter-rotating, brushless DC motors, which will prevent unintended rotation of the aircraft due to motor torque [1]. These motors will be attached to 5-inch diameter, 3-bladed propellers. This layout is inspired by its application in remote controlled racing drones and following this example should simplify the design process. The brushless DC motors turn the traditional electric motor “inside out” with the permanent magnet mounted outside the rotor and the electromagnets mounted to the stator. They are controlled directly by transistors connected to a processor rather than brushes. The only significant disadvantage of using these motors is the financial cost, but there are many benefits, including more efficient operation, minimal wear over the life of the motor, high speed operation, and good cooling properties. The main benefit in the case of this project is the amount of precision allowed by the computer control by which these motors operate. This is mainly due to the fact that motor speed is directly used in the calculation for motor adjustments [2]. Figure 1 outlines the design of a typical brushless motor [3] .

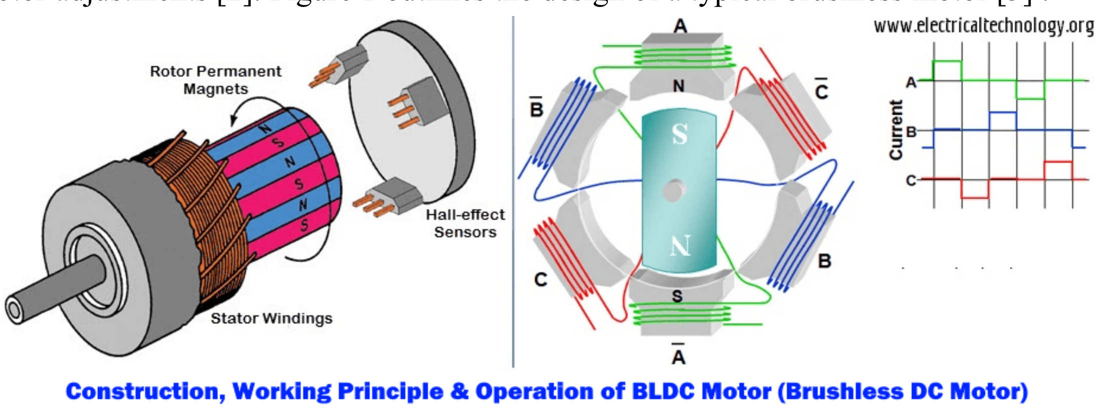

Figure 1: Brushless motor design [3]

For future iterations of the design, surrounding aircraft propellers with ducts will increase the efficiency and the thrust of the system. With an open propeller blade, energy is lost from vortex generation at the tip of the propeller. Through the use of a duct, airflow can be contained to the desired direction of thrust, eliminating vortex generation and associated energy losses. A duct of the same disc area as an open propeller provides about 26% more thrust under a fixed amount of power. According to Gelhausen, a ducted fan can also reduce noise and vibration associated with other propeller driven systems. Ducts also provide impact protection for the propellers and this could be useful in the case of an unsuccessful landing in the vehicle’s system [4].

3.2 Parachutes

A critical technology that is pertinent to the success of this project is the automatically activated parachute deployment system. This system ensures that the payload can be consistently collected after each drop without breaking. There exists such a technology that is commonly used by skydivers called an Automatic Activation Device (AAD). These devices already have accelerometers in them and allow the user to preselect an altitude at which the device would need to deploy the chute [5]. One of the most popular devices, the CYPRES cutter cuts the reserve loop using a microprocessor which activates a piston that pushes into the cord and cuts it, as shown below in figure 2 [6].

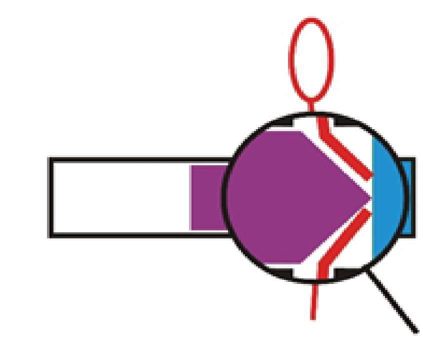

Figure 2: CYPRESS piston cutter system

Some AAD's also deploy a pyrotechnic charge to sever the loop and allow the spring-loaded chute to deploy which may introduce more room for error. These devices, although very convenient, are extremely expensive and used mainly for skydiving and not payload drops, so it is more beneficial for the team to use another microcontroller and altitude sensor to create a parachute release mechanism. However, through further discussion, the team made the decision to use an open loop control system to pre-simulate the entire flight path of the vehicle so that the parachute release will simply rely on a timer which starts as soon as the vehicle is released. There are multiple 3D-printable models of parachute launchers, such as shown in figure 3, which use Arduino and Xbee, as well as a servo on Thingiverse and a github code for release [7, 8]. All else that is necessary is to find a way for the altitude sensor to send a signal to the launcher once it reaches a specified altitude using Xbee [9].

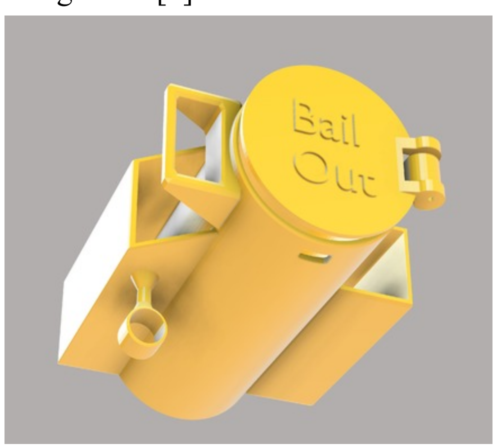

Figure 3: Sample parachute release mechanism model

4. Professional and Societal Considerations

This work primarily focuses on the economic considerations of an existing technology. Microgravity experiments are typically high cost, low availability ventures limited to high level research institutions. This work aims to provide a low-cost alternative to the existing methods, expanding the availability to undergraduate and even high school research projects. The design is simply manufactured using commonly available, low cost materials, and it can be reused for multiple drops. The design is modular, and easily modified to accommodate various payloads. Our initial testing proved its capability to achieve short-duration microgravity without a drone, as long as there is a tall structure available with a safe landing zone. The device is also suited for non-destructive testing so that multiple trials of an experiment can take place without damaging expensive equipment. The experiments can be performed virtually anywhere that there is a large, open space that allows for safe landings, eliminating travel costs and related emissions. Overall, this design has the potential to open up access to microgravity to a wider audience in a low cost, sustainable manner.

5. System Requirements and Design Constraints

5.1 Operation

The main function of this drop vehicle is to achieve a microgravity condition. The main parameters used to characterize this condition are the peak and average acceleration magnitudes, as well as the duration of the microgravity event. In order to meet the critical function parameter, it is imperative that the right amount of thrust is generated to overcome drag forces at any given instant and that the vehicle remains static along the axis perpendicular to the fall path. This requires some subsystems to have the explicit purpose of introducing momentum to the vehicle along the vertical axis, while other subsystems ensure no momentum is obtained along the other two axes. Achieving both sub-functions and precisely balancing the momentum of the vehicle is critical to obtaining a high-quality microgravity environment. The two systems which will likely have the greatest impact on the quality of microgravity are the aero surfaces and the thrusters.

The aero surface is critical as atmospheric drag will serve both to counteract the thrusting systems, as well as induce unwanted vibrations and perturbations into the two-axis perpendicular to the optimal fall path. A well designed aero-surface must reduce the total drag as much as possible in order to reduce the thrust required, which will consequently also be beneficial to the budget and weight requirements, as well as achieve high levels of aero stability by automatically generating a restoring force which keeps the vehicle on path in the case of an unwanted perturbation. The other system which will most directly impact the critical function is the thrusters.

The thrusting system is directly linked to the quality of microgravity for two reasons. Firstly, the thrust vector must be precisely balanced such that it points only along the flight path at all times, else it will induce unwanted lateral momentum into the vehicle which will degrade the quality of microgravity generated. What essentially amounts to pointing the thrusters in the right direction may sound trivial, but it surely is not. Secondly, the thrust will most likely be generated by means of propeller blades spun by an electric motor, which have the potential to generate undesired rotational momentum as well as the intended linear momentum. Balancing and counteracting this rotational force will be incredibly important and will likely be achieved by a combined effort from multiple sub-systems.

One simple mathematical model which is used to define the thrust control system is the free body diagram seen in figure 4. During the microgravity event, the gravitational force remains constant, but the drag force increases exponentially with velocity, thus time. To maintain an inertial reference frame inside the vehicle, this drag must be balanced with the thrusting force. This force has been determined as a function of both PWM input from the microcontroller and a loss coefficient that accounts for increased windspeeds. If these conditions are maintained, the vehicle experiences microgravity as if it was in orbit as shown by the figure to the right. In an orbital situation, objects experience constant acceleration towards the center of the earth, but this acceleration only leads to a constant rotational velocity.

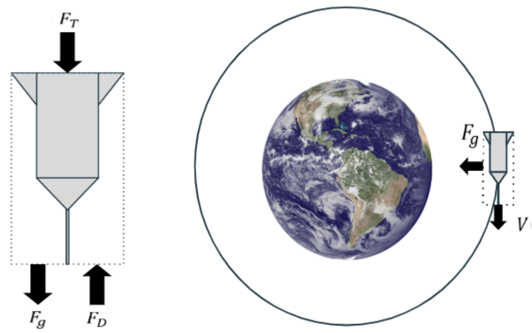

Figure 4: Free body diagram of our vehicle

5.2 Key Requirements

The customer has specified to have quality microgravity simulation with an acceleration of less than 10^{-2}G's that achieves at least 3 seconds of microgravity. The drop vehicle must be able to house a 2U CubeSat with a weight of less than 20lbs (including a 4lb mass simulator payload), have an easily removable instrumentation package, and sustain multiple drops.

5.3 Critical Parameters

The drop vehicle is to create at least 3 seconds of quality microgravity. This must be done within the span of a 400-foot drop, which takes about 5 seconds to descend without deceleration methods. The drop vehicle needs to be able to reduce the speed of its descent through means of a parachute and a spike in the remaining 2 seconds while not exceeding 3G's. In order for the mass simulator to experience microgravity, the acceleration of the drop vehicle must be less than 0.01 g's and be stabilized across all axes of motion.

5.4 Specifications

The thrust system should weigh less than 1lb, have a life span of more than 5 drops, and be able to generate is 13.34N. The control system will regulate the amount of thrust and timing of deceleration devices; it should weigh less than 0.5lb and cost $50 at most. The deceleration system will be used to slow the device while still in the air and should be able to deploy under 1 second and have a maximum deceleration of 3Gs. Similar to thrust, deceleration should have a life span of more than 5 drops and should be able to reset between drops. The aero-surface of the device should be optimized to reduce drag and lower the required amount of thrust needed, thus the coefficient of drag (C_d) should be between 0.05 and 0.5. The drop mechanism will inform the control system that the device has been released. The power source must be capable of powering the thruster, the control system, the data collection and deceleration device.

To achieve quality microgravity the acceleration must be approximately 0.01G, lasting a minimum of 3 seconds. The drop vehicle must also have ease of use, where parameters such as adjustable deployment time, easily transportable and manufacturable parts for assembly, and accessible CubeSat housing. The drop vehicle must be reusable after one drop, while maintaining the safety of the payload. This could be done by having a durable structure and easily replaceable or replicable parts.

6. System Concept Development

6.1 Control System

When generating ideas for the Earth-Based Microgravity project, creating a functional and component decomposition proved to be a critical first step in narrowing down what is necessary in creating a durable drop vehicle that simulated continuous, quality microgravity. Deceleration and thrust are the prioritized systems since it is crucial to the success of the project that the vehicle is able to create a microgravity effect and does not explode upon impact so it can proceed for another drop.

The most important focus in order to achieve quality microgravity would be to overcome drag so that the drop vehicle continuously attains quality microgravity. When discussing how to overcome drag, the three systems considered are electric motors, rockets, or cold gas. After conducting a weighted evaluation for these three systems, electric motors offered precise thrust control, a high-power density, and nearly instant response to inputs necessary to reach the project goal. Our design features four brushless DC motors, two sets operating in opposite directions. They are used to provide 4.5 N of Thrust for each motor and are equipped with 5-inch, three-bladed propellers.

In order to control the vehicle's deceleration, an Arduino Uno microcontroller with a programmed flight path is paired with the motors and the servos for the parachute release. The configuration for the control system can be seen in Figure 5. It is coded to start the motors for a specified duration of time as soon as separation from the drone is detected. Using a slope-intercept equation to increase the RPM of the motors, the thrust continuously balance the air resistance to achieve microgravity. Immediately after the motors stop running, the program activates the servos to release a spill hole parachute. The parachute is intended to control the deceleration of the vehicle in order to preserve it for additional drops. It is spring loaded inside a 3D printed tube similar to Figure 3. It is situated halfway into the mounting system to ensure that the parachute deploys well above the propellers as shown in the figure below.

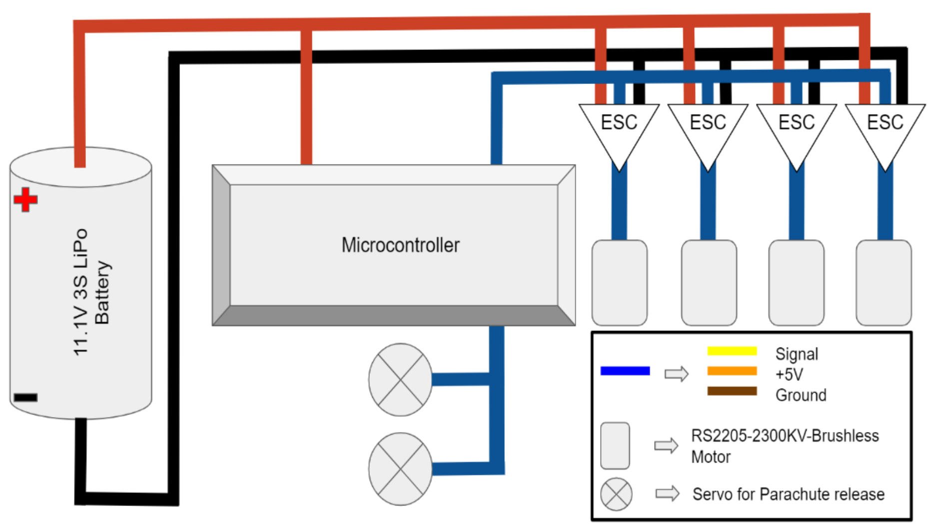

Figure 5: Control system configuration

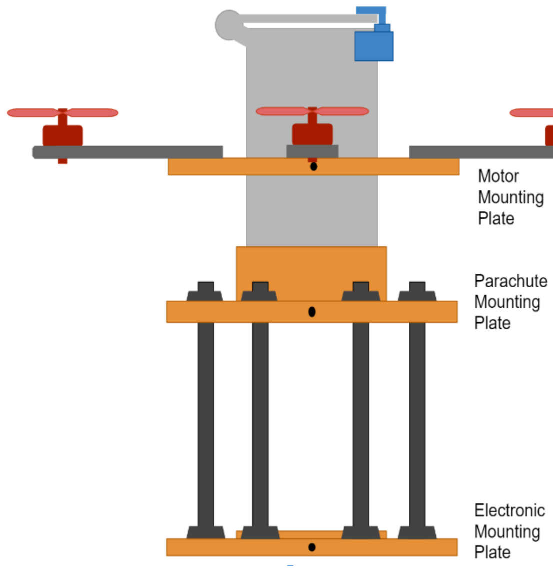

Figure 6: Mounting system

6.2 Landing Gear

In addition to the parachute, a landing rebar is used to prevent the fuselage from coming into direct contact with the surface, thus preventing it from being damaged. Additionally, the rebar pulls down the center of gravity, increasing the deceleration and stabilizing the vehicle. For the vehicle, a steel rebar of four feet is used in which one end is chamfered with a flat tip (Figure 8). It is inserted through a 3D printed nose cone and a set of internal rebar supports that keeps it centered and aligned until it hits the backstop plate that prevents it from piercing through the payload and the control system. In the event that the vehicle falls at an angle, as long as landing rebar is pointed towards the ground, it is still able to penetrate the surface without the fuselage taking much of the impact. The only failures that have occurred with the rebar in which the fuselage was potentially damaged is when it hits a metal or concrete surface, otherwise the most damage that the vehicle has seen is the destruction of the nose cone and rebar supports. Since these parts are 3D printed, it is not a critical loss and replacements can be easily made.

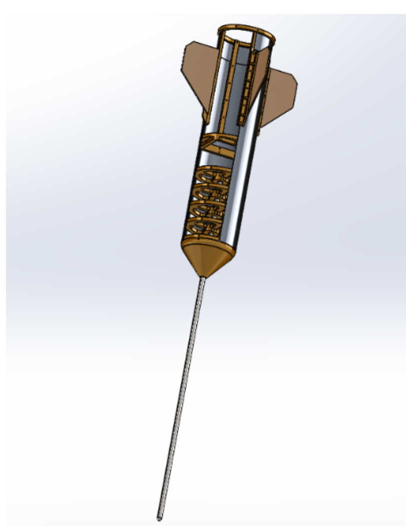

Figure 7: Cross-sectional view of internal rebar supports

Figure 8: Chamfered tip of landing rebar

<u>6.3 Fuselage</u>

For the fuselage, a variety of materials were evaluated as seen in Appendix B. Using a variety of materials instead of just one was also considered, but ultimately an aluminum tube was chosen for its light weight, inexpensiveness, and malleability. The fuselage can be reviewed into thirds in which the bottom third is used for the rebar supports while the middle third is saved for 2U CubeSat payload. The top third is used for the mounting plates for the control system. A rail system was implemented inside the vehicle to make it easier and faster to remove and insert the mounting system. On the outer surface, fin mounts were installed for replaceable fins.

Though the intent of the project was to create a durable drop vehicle that could withstand multiple drops, the design we proposed takes into account that some features could still potentially be damaged. Consequently, we opted for cost-effective materials to make replacements easy. Furthermore, because the fuselage and its components are light weight, the overall weight of the vehicle remained less than 10 lbs.

7. Design Analysis

A number of various ANSYS Finite Element Analyses were used to determine failure conditions of the vehicle when hitting the ground, specifically looking at the stresses formed by the force of the rebar spike coming into contact with the ground at different angles. It was found that failure would most definitely occur if the vehicle were to fall onto a hard surface, such as clay (which was a potential possibility if testing on a softball field). In the worst case scenario, where our vehicle's deceleration systems did not work at all and the vehicle landed on a hard surface at an estimated 16.67 m/s fall rate without the thrust of the motors, the rebar spike would experience stresses close to 1 GPa, which greatly exceeds the 420 MPa yield strength of grade 60 rebar steel, as shown below.

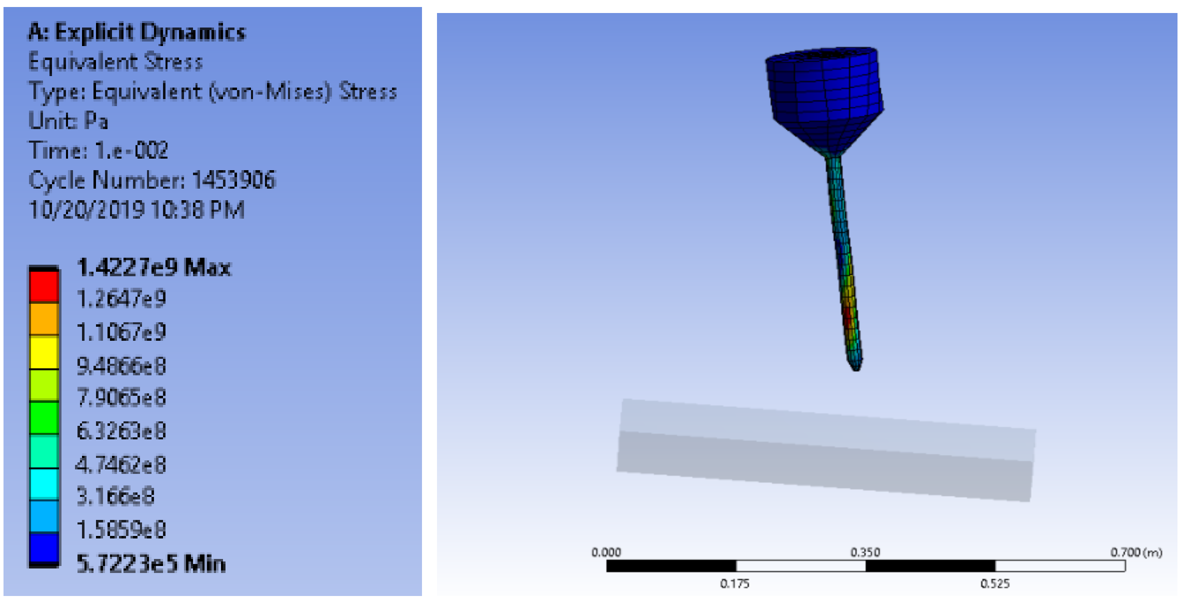

Figure 9: FEA visualization of worst-case failure

Other Finite Element Analyses were conducted to visualize the stresses that the rebar, fuselage and inner support system would experience as a result of the vehicle coming into contact with the ground at an angle. The inner 3D printed support system was too complex to model in ANSYS for FEA, and was constantly changing, so the analyses were performed using simple geometry representing the concept of the vehicle, and decisions about the concept were made based on extrapolations from the results and visualizations.

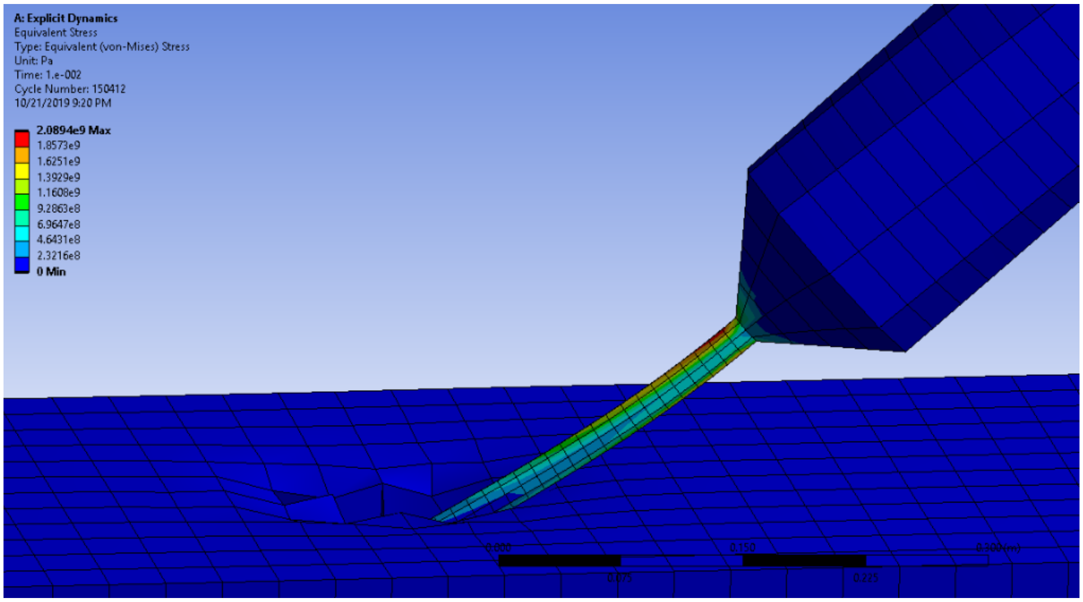

Figure 10: FEA on angular contact with ground plane

Wind tunnel testing was also used to determine the exact effectiveness of the motor-propeller system so the thrusting system could be fine-tuned to meet the requirements of the project. The UCF measurements lab wind tunnel was used for the experiments on the motors. A 3D printed mount was designed and printed in order to accommodate our motor setup with the wind tunnel setup. The setup and resulting data are shown in the figures 11 and 12, respectively.

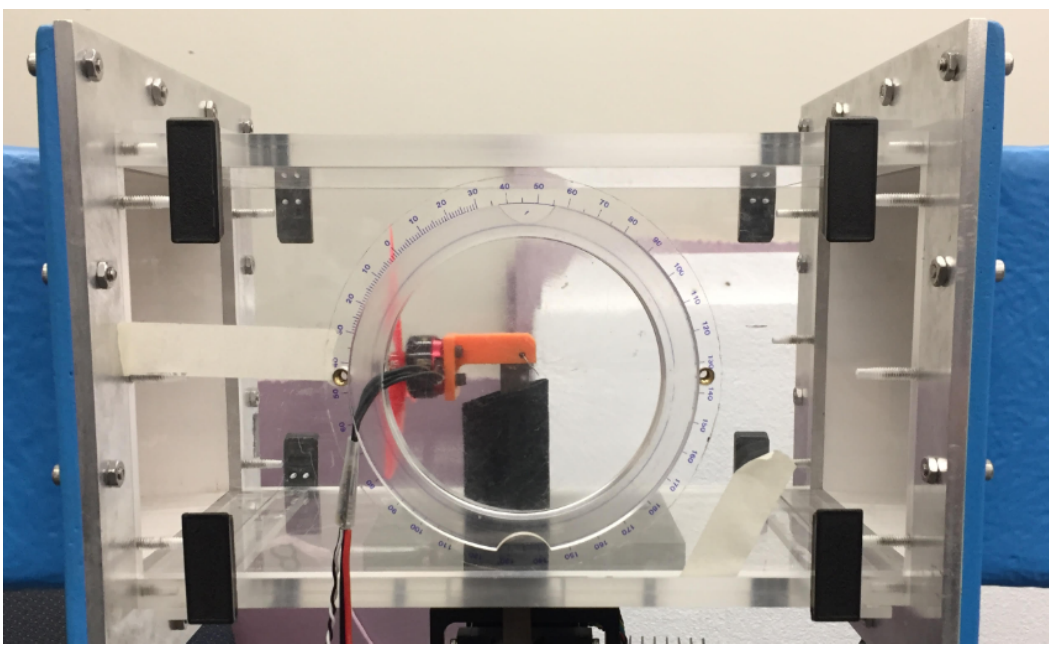

Figure 11: Wind tunnel testing

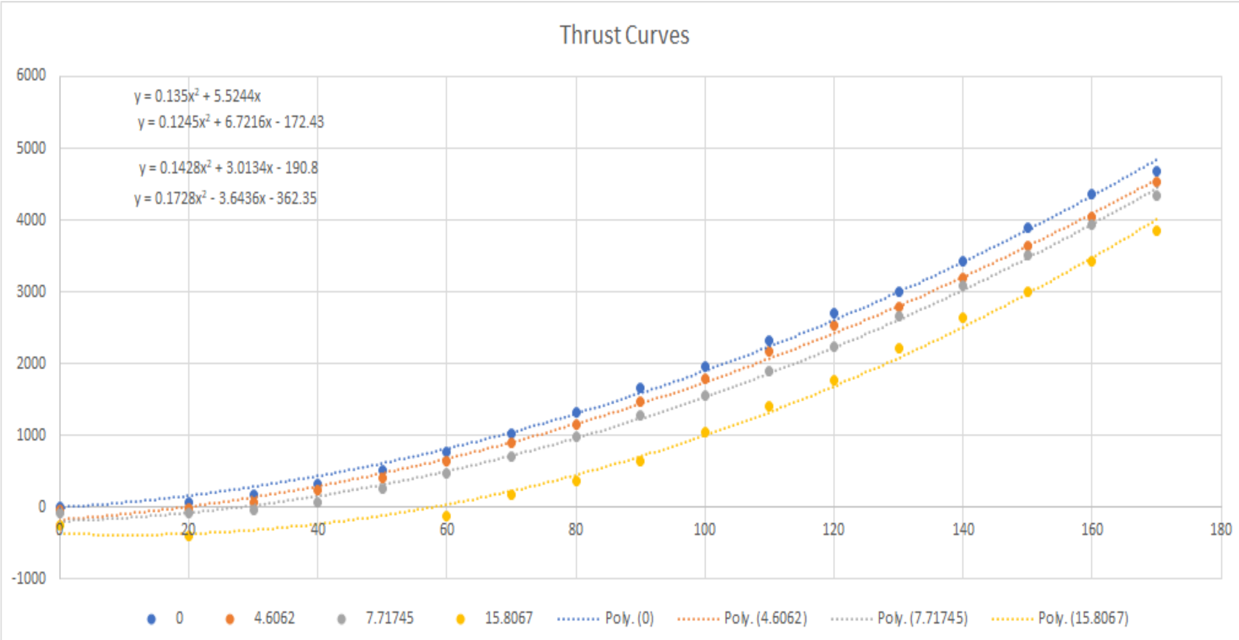

Figure 12: Actual thrust curves derived from wind tunnel data

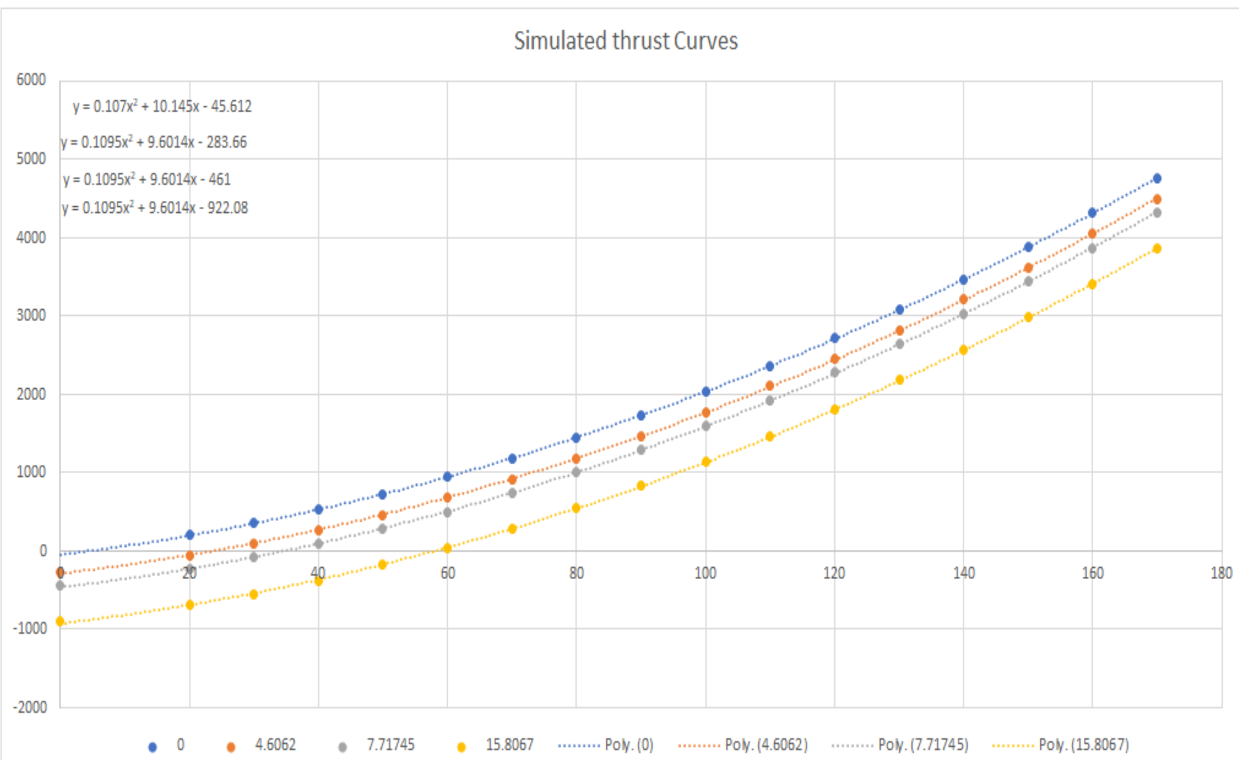

Figure 13: Simulated Thrust Curves

Figure 14: Thrust Error v. Arduino Input

First, the beam which detects forces in any direction was calibrated by hanging a series of weights from it and recording the corresponding output voltage values. From this data, a curve was created which enabled a correlation to be derived between the voltage output and force, which was our thrust value. From initial calculations, approximately 7N of thrust is needed to overcome air resistance during freefall and allow for the vehicle to experience microgravity, therefore, it was concluded that if each motor could product approximately 2N or ~200g of thrust under our 60mph wind conditions, our overall thrust value would be 8N, more than enough to overcome air resistance. It was unknown if the code values which controlled the microcontroller and thus powered the motors correlated to a specific RPM. It was only known that these values corresponded to equal pulse width modulations (PWM) up to 2000 or 180 on the code. Static thrust values were calculated using 20 as a starting code value, up to 170. The measurements were repeated under 4.6 m/s wind conditions, 7.7 m/s, and 15.8 m/s. Under the 15.8 m/s wind conditions, the motor was able to produce approximately double the amount of thrust needed for one motor, so it was concluded that under 60mph conditions it was plausible that the motor could reach the target values.

Thrust data was then modeled as a function of both PWM input and windspeed. Figure 13 shows the data from the modeled equation at the tested windspeeds, and Figure 14 shows the error values of these curves as compared to the tested data. The initial values are not as important in our case, as the initial drag forces are close to zero. For the most important higher thrust values, the error measurements are typically within .05 N of the desired thrust value. Theoretically this thrust profile maintains gravitational acceleration well within a 1% error value, when compared to the overall gravitational force. This equation was not directly implemented in the final design, and it does not account for a wide variety of environmental factors, but it provided valuable insight into the thrust profile that was ultimately used. Additional drop testing would allow for systematic improvement of this equation, thus the quality of microgravity.

In terms of CFD, during the first semester of planning and concept development, a CFD analysis was performed on an early prototype CAD model which resulted in a drag value of roughly 6 N, as shown below.

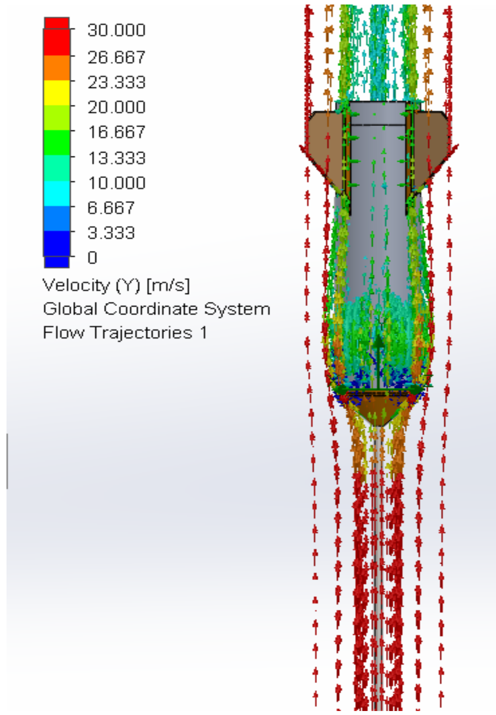

Figure 15: Early CFD analysis on a concept CAD model

From then on, our final design underwent countless small iterations in terms of body shape, fin shape, nose cone geometry, etc., however the final design was not drastically different than the depiction above. Near the end of the second semester, another SolidWorks CFD analysis was performed, and a similar drag value was obtained. This analysis gave us solid information which was used in the wind tunnel testing to accurately recreate the actual drop conditions for our motors. Additional CFD analyses were attempted in the more technical ANSYS software, however the team had little experience in the ANSYS Fluent software so these more in-depth analyses were not completed.

Perhaps the most effective method of analysis for this project was the use of rapid prototyping using 3D printing. Since most of our vehicle was going to be made of 3D printed parts (the inner support system, parachute deployment system, nose cone, fin mounts, etc). it was very accessible to design, build and test under a rapid timescale. Working in conjunction with the UCF police department for safety, weekly test days were scheduled for our vehicle to be dropped from the Libra garage onto a grass patch to get real world feedback on our design. Each week our design iterations improved, adding more functionality to the design each time drop tests were tested, starting with the barebones fuselage and rebar spike. One test which included the use of our parachute attached to the vehicle ended up breaking the vehicle. The parachute shifted the vehicle mid-drop, and the rebar spike landed on top of a metal plate which destroyed sections of the 3D printed nose cone and inner support system, along with bending the rebar.

Figure 16: Aftermath of drop test failure

The final drop test at libra garage included the propulsion system and indicated the potential to create a successful microgravity environment for the 1.5 second maximum drop time available at that height. It is clear to see in figure 17 that the motors had a large effect on the microgravity condition, and there is a large jump in deceleration force after the motor shutoff. This data is overlaid with a line of best fit for both the motorized drop, and another drop in which the motors and control surfaces were removed for optimal aerodynamics. The deviation towards the end of this graph indicates the necessity of the propulsion system for maintaining microgravity conditions for more than one second of drop time.

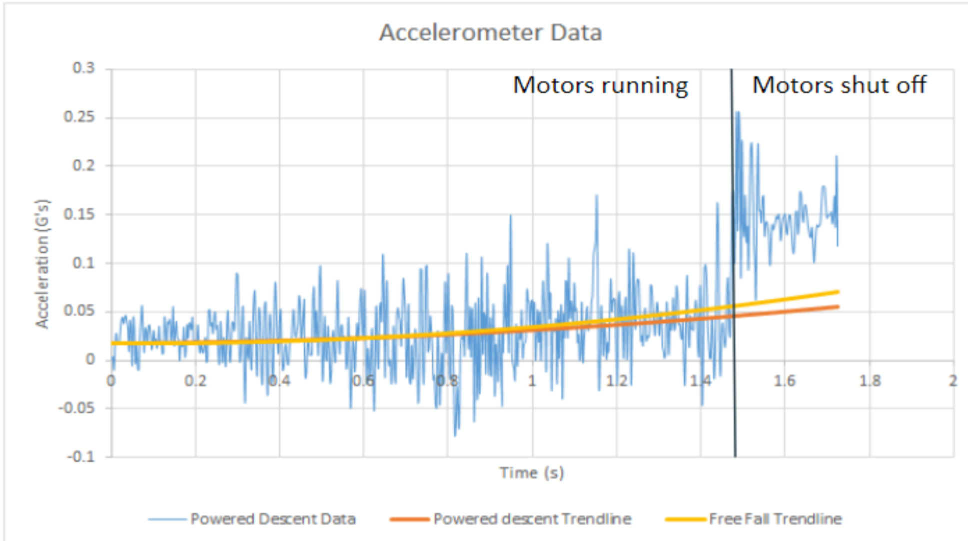

Figure 17: Initial powered drop test

8. Final Design and Engineering Specifications

Figure 18: The final vehicle design, taken after first ever drop

The final design consists of a dart-shape drop vehicle with a landing rebar to prevent the fuselage from being damaged and a control system that is designed to trigger the motors and parachute at specific times to ensure quality and continuous microgravity.

The fuselage itself is 6-inch diameter aluminum duct three feet in length with a tapered end. The un-tapered end contains an 3D printed nose cone attached to it and a set of support plates inside that help align and straighten the rebar. The rebar is a steel, threaded rod that is half-inch thick and 4ft long that is able to protect the fuselage from making direct contact with the surface provided it is not concrete or metal. At the tapered edge, the outer surface contains four fin mounts equally distanced for replaceable fins while the inner surface had four rails in line with the fin mounts to provide easier access to the control systems.

The control system consists of an Arduino Uno style microcontroller, four electronic speed controls connected to four electric motors, two MG90S servos and an 11.1V battery. The microcontroller gives commands that operate both the electric motors and the servos. The microcontroller is programmed to operate each system based on a preset timetable. The process is initiated when the vehicle is released from the drone and a circuit connection is broken. The microcontroller senses this and sends the command to the motors to begin spinning at the desired speed. As the fall time increases, the motors are spun at a predetermined increasing speed in order to overcome the increasing air resistance. The motor rpm is increased linearly. After a set fall time of 1-3 seconds, the motors shut down and the servos are opened, releasing the spring-loaded parachute. Then, after another short pause, the microcontroller stops sending signals to the motors and servos to save battery while the vehicle is recovered by the team.

The programming for the microcontroller, found in Appendix C1 consists of a series of while loops that begin and end based on the time since the vehicle was dropped from the drone. The programming begins a timer when the vehicle's connection to the drone is broken. The timer measures the difference between the current time and the time since the connection was broken.

This is referred to as “gap” in the code. The code then progresses to the next loop that controls the motors’ speed. The program uses gap as the x-value in a linear equation, which outputs the command that the microcontroller sends to the motors. The microcontroller continues sending commands to the motor until the predetermined fall time. This fall time is decided before the drop by the team. At this time, the program progresses to the next while loop, where the servos are fully opened. Once the timer progresses more, the motors and servos are detached, meaning the microcontroller ceases sending signals in order to save battery.

The parachute is 3 feet in diameter with spill hole in the center. The spill hole is intended to decrease rotation and swinging, creating a straighter descent. It is folded in a specific manner that reduces the risk of entanglement but also helps it catch and expand more efficiently. It is then inserted into a spring-loaded sabot inside a 3D printed tube for a smooth and quick release from the drop vehicle.

9. System Evaluation

9.1 Meeting end user requirements

The drop vehicle has five processes that it needs to meet the user's requirements: The Accelerometer, The Drop Release mechanism, the Landing Rebar Deceleration, The Parachute Deployment, and Motors. The Plan for the System Evaluation is detailed in Appendix B.
These processes were tested at an available maximum height of 60 ft. The Landing Rebar Deceleration is used to take the resulting energy from the impact with the ground, acting as a failsafe to the parachute. The Landing rebar underwent 3 types of testing: with Motors, without Motors, and without Motors Skewed. In the test without motors the Drop vehicle was equipped with only the Landing Rebar, the nose cone, and a Steel rod inserted through the side of the fuselage to act as a backstop to keep the rebar in place. It was to be dropped by hand (while holding it at the sides) from the third, fifth, and sixth floors (approx. 30, 50, and 60 ft).

In terms of the performance requirements of the project, we matched the requirements of overcoming the air resistance of our vehicle by confirming that our motors could produce thrust values almost double our drag values at ~30mph through wind tunnel testing, which meant we would be matching the drag values (which was the goal) at our predicted 60mph when dropped from 400 ft. The "cheap and reusable" requirements were most definitely met because our design could be produced using ~$300 - $400, the lowest of the three teams, and our vehicle was also the only vehicle to be able to be dropped twice on the competition day. If given more time, we predict we could have dropped our vehicle many more times for more testing data, which included increasing the amount of time before the parachute is deployed which would get us closer to the 3-4 seconds of microgravity that was desired for this project.

9.2 Failure Modes and Effects Analysis

In analyzing the potential risks and issues associated with our design goals, as well as safety and security which may impact the implementation of our concept, a FMEA was conducted which can be seen in Table 10. The main areas of focus which may impact the concept the most and introduce the most amount of risk are the parachute deployment mechanism, spike, motors, accelerometer, and drop-release mechanism. The most important aspects of our design which, if fail, may render the project a failure are the motors and landing rebar. If the motors fail, achieving and maintaining microgravity will not be possible. The motors which power the thrusters may fail due to electrical failures, microcontroller issues, or some outside force affecting the motors physically which will prevent the vehicle from reaching the microgravity goal. A backup power supply system or microcontroller may be used in this case. The landing rebar is also an extremely important risk factor in the project concept because if the spike does not enter the ground or breaks, the vehicle will sustain severe damage or be completely, utterly destroyed upon impact with the ground, even if the parachute continues to deploy. If the parachute does not deploy at the correct time at the correct speed or if it does not deploy at all, our vehicle will be minimally damaged as long as the rebar is in good condition. The most damage the parachute could incur would be a broken nose cone and broken rebar support.

The accelerometer and drop release mechanism also have risk factors that are worth analyzing, however their effects of failure on the project are much less severe. The accelerometer may also stop working due to an electrical issue which can also be prevented if a backup power supply is used. Should they fail, determining whether microgravity is achieved will be impossible without any data to analyze. The accelerometers are standardized for all teams participating in this project, so there is very little action to take if they fail to function. The risk of the drop release mechanism failing is more severe than the accelerometer in that the vehicle may not drop at all or data may not begin to be collected as soon as the vehicle is dropped. One of the few ways the drop release mechanism may fail is through miscommunication with the microcontroller which can also be prevented by proficient testing.

So far, the design process has considered many variables in order to achieve the ultimate goal of high-quality microgravity. The key parameters in this study will be the amount of drag force encountered, and the amount of thrust generated to counteract this drag. CFD analysis of the design has provided insight into these parameters, and in theory, matching the thrust to the expected drag at various times during the drop will cancel out any vertical acceleration and provide a microgravity environment.

In ideal environmental conditions, once the drone is released the drop vehicle, the motors will instantly bet set off for a specified duration of time, in which it will stop and trigger the release of a parachute, decelerating the fall enough for the rebar to penetrate the surface firmly. Upon landing, the rebar will ensure that the vehicle retain its vertical trajectory. The spike will also assist in deceleration as it creates an increasing amount of friction as it enters the ground.

10. Significant Accomplishments and Open Issues

The drop vehicle was officially tested Tuesday, December 3, 2019 at Fort Christmas Historical Park in Christmas, FL. The vehicle was lifted by drone to 400ft over a clearing of grass and released. The vehicle was dropped twice in the allotted time to collect accelerometer data that will be analyzed.

During the first drop, the electric motors could be heard operating and accelerating immediately after detaching from the drone. The acceleration of the motors was determined by the increasing pitch the motors emitted. Approximately halfway through the drop, the parachute ejected and filled during which, the drop vehicle began to rotate around the parachute. This continued until the spike on the vehicle penetrated the ground. The drone landed to provide a safe environment for the team to recover the vehicle.

The spike was found to be approximately 28 in deep while the rest of the vehicle was intact with no damage. Unfortunately, the accelerometer did not record the data, though it appears that the accelerometer measured up to a few seconds after the drone had been lifted off the ground. The possible cause of this is a low battery. The battery of the accelerometer was replaced before resetting the vehicle for another drop.

For the second drop, the code was adjusted to provide three seconds of accelerated descent. Once the vehicle was dropped, the electric motors could again be heard turning on and accelerating. However, when the parachute was ejected, it disconnected unexpectedly from the vehicle. The vehicle continued to fall, and the spike impacted the ground. Once recovered and inspected, it was noted that the nose cone was severely damaged, and the spike became severely bent penetrating the ground. The accelerometer measured the acceleration of the vehicle during the drop.

A number of observations can be made from the accelerometer data. The first observation is that the electric motors took roughly 0.2 seconds to initiate. This can be seen in the initial rise in acceleration immediately after the drop, followed by a sharp decrease. This is most likely due to the slack in the ripcord. As the fall began, it took this long for the ripcord to become taut and for the circuit to be broken. Another observation is that the acceleration starts to rise rapidly 2.1 seconds after the drop. This is due to the electric motors reaching the maximum output the microcontroller's output to the ESC's and motors 1.9 seconds after the ripcord had been pulled. At this point, the motors could no longer accelerate to maintain the required thrust to match air resistance. 4.0 seconds into the flight, there is a spike that peaks at 6 G's. This corresponds to the deployment of the parachute. The acceleration quickly drops because the parachute disconnected and there is no longer any active deceleration. At 5.4 seconds after the data shows the peak deceleration during impact, which peaks at 16 G's.

The critical values from the accelerometer come from 0.2 to 2.2 seconds after the drop. During this time, the acceleration stayed within 0.05 G's of 0 G.

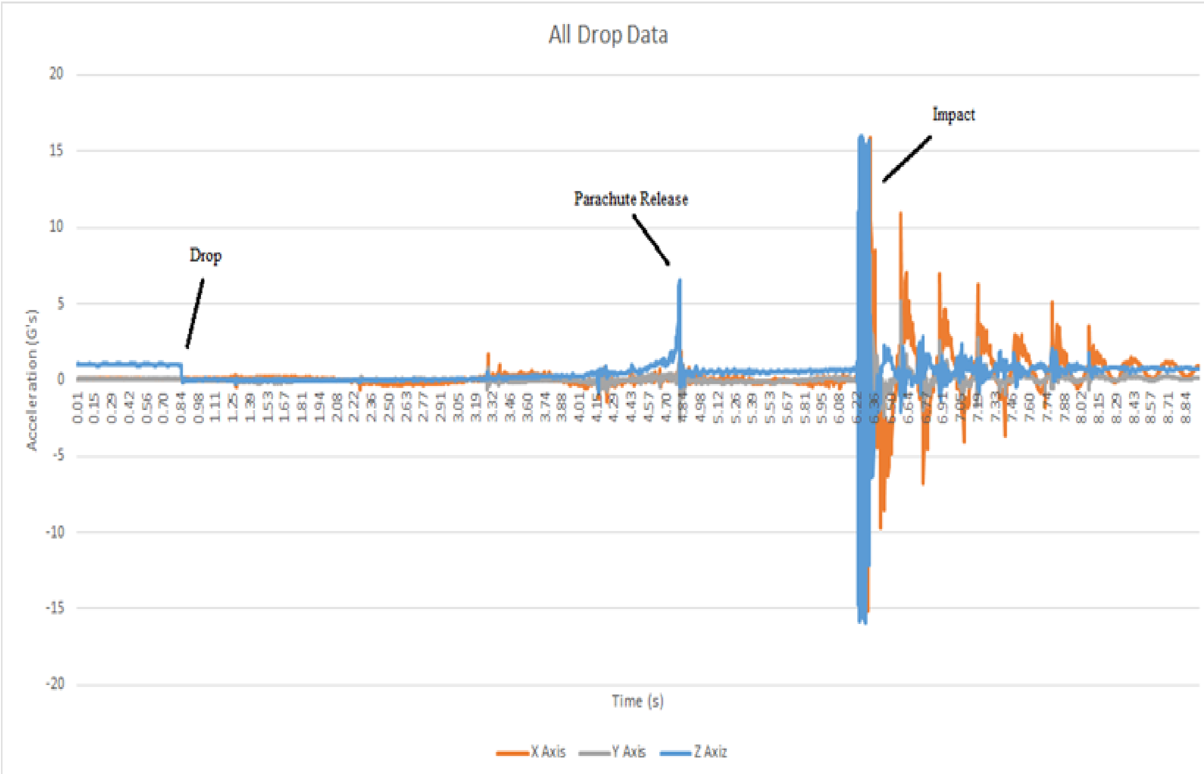

Figure 19: Second Drop Accelerometer Data

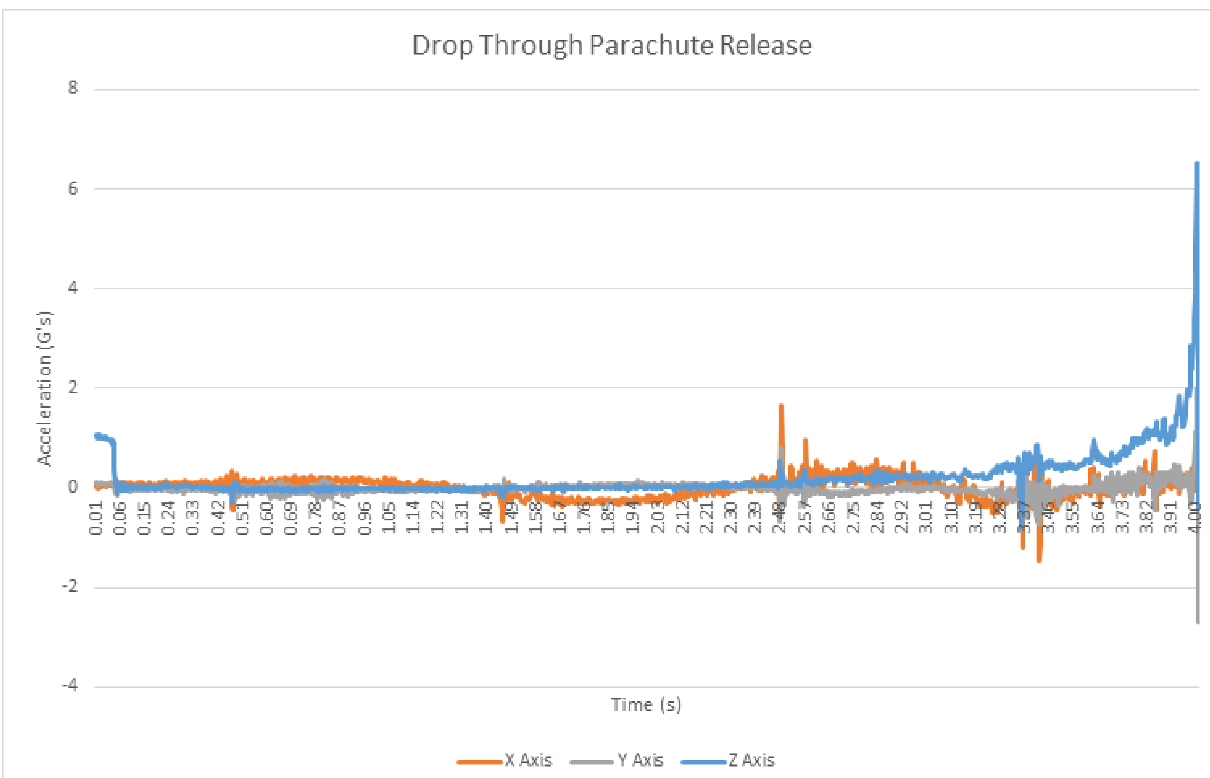

Figure 20: Acceleration Between Drop and Parachute Deceleration

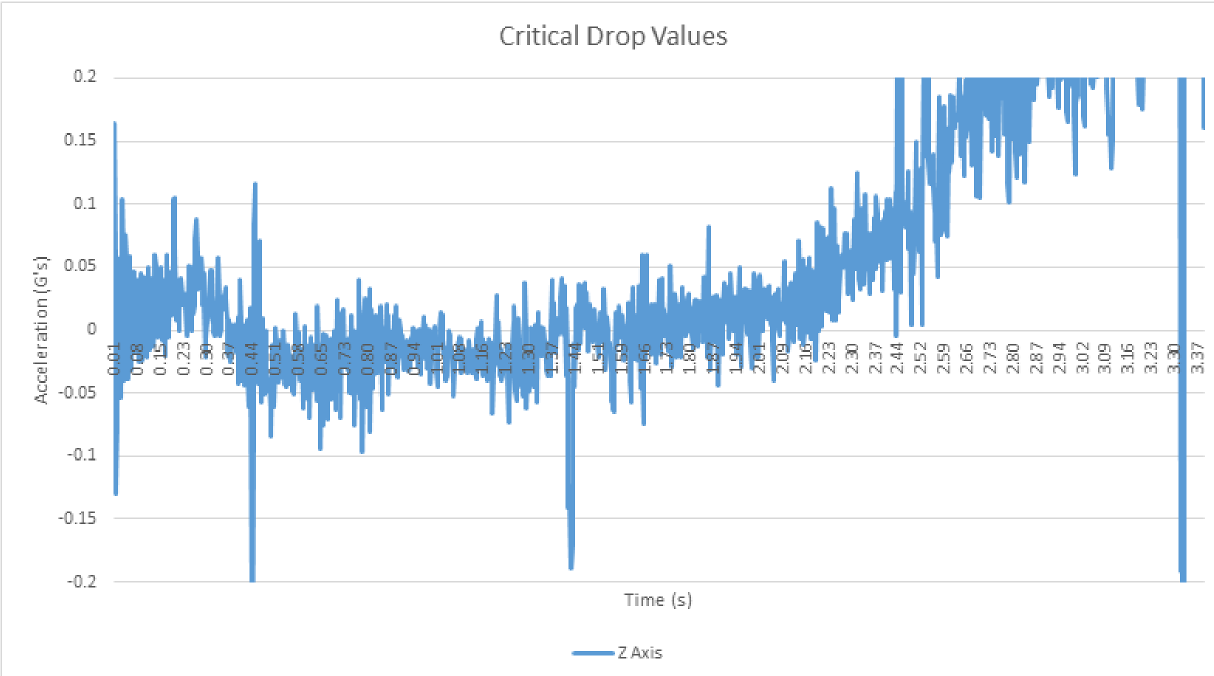

Figure 21: Data from Quality Low Gravity Period

There were a few limitations of this design. The first is that the motors were underpowered. After 2.2 seconds, the motors reached the maximum rpm and could no longer continue to accelerate. Early CFD simulations showed a lower drag force than what testing conditions produced. The only part that failed during testing was the parachute's connection to the parachute ejector tube. During the second drop, the connection failed, and the parachute disconnected from the vehicle. A more secure connection should be designed for future vehicles. Another limitation is the time required to access the internal structure. The current design required up to five minutes to install the accelerometer and the internal structure. While the rail system helped to align all the screw holes, all of the internal components should be rigidly attached to each other to decrease the time required inserting the structure the proper depth into the body. Access holes for connecting the battery and operating the accelerometer would significantly decrease the time required for the final preparations.

11. Conclusions and Recommendations

In conclusion, the team met the project goals as stated in the multi-phase plan initially developed by Florida Space Institute. Seeing as the first phase aims to provide a proof-of-concept prototype, it is expected that the design generated through this academic venture may still lack key functionality and features that a final design should include. That said, the prototype achieved the main goals of microgravity simulation within the given budget and below the weight requirement. The vehicle successfully collected data that can be used to further iterate and polish this current design or can be used as conceptual research for further phases. Phase 1 aimed to explore the relevant physics and technologies associated with the development of a microgravity simulation vehicle for a significantly reduced cost compared to traditional methods. With this in mind as the goal of the project, it is clear that the project was ultimately a success.

Overall, the design proposed proved highly effective in achieving the goal of developing a low-cost, reusable drop vehicle for microgravity simulation. Compared to the competition, this design was the only one to effectively implement a powered descent and survive multiple drops. Ignoring spare parts, this design is also below the allotted budget. Extensive testing of every subsystem and analysis of every failure mode contributed greatly to its success. The general dart-like profile provides excellent stability, distributed impact loading, and highly predictable directed impact forces. The control mechanism provides a foolproof timed parachute release and instant thrust response thanks to the tripwire activation system. The drone racing motors provide a thrust system that is precise, controllable, and high-power density. The modular internal design based on 3D printed parts is simple to manufacture, repair, and modify. The Arduino microcontroller is low-cost and easily programmable. The only point of failure was the parachute mounting system, which could be easily modified using an I-bolt and shock cord to improve stability and maintain parachute contact with the vehicle. With the inclusion of a better parachute mount, the current vehicle could be effectively used for high school level microgravity experiments.

We recommend continuing this academic and scientific exploration by pursuing phase 2 of the plan developed by FSI. With the feasibility study completed (phase 1), FSI and its collaborators at UCF can now focus on the design and construction of a drop vehicle made to be suitable for STEM outreach, along with sets of microgravity experiments to be conducted using the newly designed drop vehicles. Phase 2 drop vehicles might even be able to retain most of the critical design choices made during phase 1, only with a few key changes in order to assist the user with operation and maintenance of the vehicle. Seeing as phase 1 only aimed to explore the physics and theory of operation of such a vehicle and not the actual user experience, such consideration have been neglected in phase 1 and must be further refined with more research.

Simple modifications could go a long way in improving the design. Larger motors coupled with increased pitch propellers could increase thrust for longer drop durations. Ducted fan propulsion would streamline the thrust profile and provide increased efficiency of the thrusters. Closed loop control could react to environmental conditions in order to “self-adjust” to maintain its microgravity environment. The developed vehicle was optimized for mechanical performance and has much room for improvement aerodynamically. With a greater budget, this concept can be applied in a custom made aerodynamic outer shell which would minimize turbulence and drag effects. Active stabilization methods could be implemented to eliminate lateral movements, and possible devices include gyroscopes and active control surfaces. The impact forces upon landing were not excessive but were beyond the goal of 3 G's. In order to move towards this goal, a larger parachute could be installed, or viscous damping could be used to reduce the initial impulse forces.

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Appendix A: Customer Requirements

User needs (listed below) were determined over the course of multiple meetings with Mike Conroy, which is the team’s main point of contact with Florida Space Institute (FSI). FSI first presented the project with a basic overview of the multi-phase plan before acquainting the team with specifics regarding Phase 1. After extensive deliberation within the team and through discussions with Mike Conroy, the requirements were put in a list based on priority and the exact goals of Phase 1 were made clearly distinct from the development of the project as a whole. In order to succeed, it is of utmost importance that the goals of Phase 1 are not overshadowed by the more ambitious goals relating to the development of a final product.

Below is a prioritized list of user wants and needs.

- Quality microgravity simulation with an acceleration of less than 10-2G’s
- Ability to house a 2U CubeSat
- Ability to achieve at least 3 seconds of microgravity
- Drop Vehicle weight of ≤ 16lbs (4lbs for payload)
- Include payload mass simulator
- Easily removable instrumentation package

Appendix B: System Evaluation Plan

Table B1: Evaluation Legend for Weighted Evaluated

Value	Rating
1	Very Unsatisfactory
2	Unsatisfactory
3	Adequate
4	Satisfactory
5	Very Satisfactory

Table B2: Control System Concept Selection

	Weighted Importance	**No Loop**		**Open Loop**		**Closed Loop**	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Financial Cost	20	5	1	2	0.4	2	0.4
Simplicity	40	5	2	3	1.2	1	0.4
Accuracy	40	3	1.2	4	1.6	5	2
	100		**4.2**		**3.2**		**2.8**

Table B3: Thrust System Concept Selection

	Weighted Importance	**Electric Motor**		**Rocket**		**Cold Gas**	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Financial Cost	30	3	0.9	2	0.6	2	0.6
Max Thrust	20	3	0.6	4	0.8	1	0.2
Control	30	5	1.5	1	0.3	3	0.9
Reusability	10	5	0.5	2	0.2	5	0.5
Weight	5	3	0.15	4	0.2	1	0.05
Size	5	4	0.2	5	0.25	2	0.1
	100		**3.85**		**2.35**		**2.35**

Table B4: Chassis Concept Selection

	Weighted Importance	**Wood Carpentry**		**Lasercut Wood**		**Lasercut Acryllic**		**Aluminum**		**3D Printed**		**PVC**	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Financial Cost	25	5	1.25	5	1.25	4	1	3	0.75	5	1.25	5	1.25
Weight	25	2	0.5	2	0.5	3	0.75	4	1	3	0.75	2	0.5

Strength	40	3	1.2	3	1.2	4	1.6	4	1.6	3	1.2	3	1.2
Configurability	10	4	0.4	5	0.5	5	0.5	3	0.3	5	0.5	4	0.4
	100		**3.35**		**3.45**		**3.85**		**3.65**		**3.7**		**3.35**

Table B5: Aerosurface Concept Selection

	Weighted Importance	**Fiberglass**		**3D Printed**		**Canvas**		**Bent Wood**		**Metal Sheet**		**Plastic Wrap**	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Financial Cost	20	3	0.6	2	0.4	3	0.6	4	0.8	2	0.4	4	0.8
Drag	40	4	1.6	3	1.2	3	1.2	4	1.6	3	1.2	3	1.2
Design Options	30	2	0.6	4	1.2	3	0.9	1	0.3	2	0.6	2	0.6
Ease of Manufacturing	10	3	0.3	4	0.4	4	0.4	3	0.3	2	0.2	5	0.5
	100		**3.1**		**3.2**		**3.1**		**3**		**2.4**		**3.1**

Table B6: Deceleration System Concept Selection

	Weighted Importance	**Parachute**		**Power Descent**		**Airbags**		**Cannon**		**Spike**		**Foam**		**Crumple Zone**	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Financial Cost	10	4	0.4	3	0.3	3	0.3	2	0.2	4	0.4	5	0.5	4	0.4
Deploym	30	3	0.9	3	0.9	4	1.2	5	1.5	5	1.5	5	1.5	5	1.5

ent time														
Decelerating Force	25	4	1	5	1.25	4	1	5	1.25	4	1	2	0.5	3	0.75
Reliablity	25	4	1	3	0.75	3	0.75	2	0.5	2	0.5	2	0.5	3	0.75
Weight	5	5	0.25	4	0.2	3	0.15	2	0.1	3	0.15	4	0.2	2	0.1
Size	5	5	0.25	4	0.2	2	0.1	2	0.1	4	0.2	4	0.2	1	0.05
	100		**3.8**		**3.6**		**3.5**		**3.65**		**3.75**		**3.4**		**3.55**

Table B7: Severity Rating Scale for FMEA

Effect	Criteria: Severity of Effect	Ranking
Hazardous - Without Warning	Destruction of payload and vehicle; irreparable; no microgravity	10
Hazardous - With Warning	Destruction of payload with no microgravity; subsystems are damaged; additional drops are unsustainable	9
Very High	Damage to payload or vehicle but microgravity achieved; subsystems are damaged; additional drops are ill advised	8
High	Repairable damage; affects flight; affects microgravity condition; subsystems are damaged	7
Moderate	Subsystems do not work or sustained some damage	6
Low	Damage to replaceable parts (fins, cones, internal structure)	5
Very Low	Minor cosmetic damage (small dents or scratches)	4
Minor	Run does not occur due to external events	3
Very Minor	Negligible effect	2
None	No Effect	1

Table B8: Probability Rating Scale for FMEA

Probability of Failure	Occurrence in Drops	Ranking
Very High: Failure is almost inevitable	Occurs 90-100% of drops	10
		9
High: Generally associated with processes similar to previous processes that have often failed	Occurs 70-80% of drops	8
		7
Moderate	Occurs 40% - 70% of drops	6
	Occurs 20% - 40% of drops	5
	Occurs 15% - 20% of drops	4
Low	Occurs 10% - 15% of drops	3

Very Low	Occurs 5% - 10% of drops	2
Failure is unlikely	Occurs ≤ 5% of drops	1

Table B9: Detection Rating Scale for FMEA

Detection	Criteria: Likelihood of detecting failure mode	Ranking
Almost Certain	Failure mode can immediately be detected	10
Very High	Very high likelihood of detecting failure mode	9
High	High likelihood of detecting failure mode	8
Moderately High	Moderately high likelihood of detecting failure mode	7
Moderate	Moderate likelihood of detecting failure mode	6
Low	Low likelihood of detecting failure mode	5
Very low	Very low likelihood of detecting failure mode	4
Remote	Remote likelihood of detecting failure mode	3
Very Remote	Very remote likelihood of detecting failure mode	2
Almost Impossible	No known controls available to detect failure mode	1

Table B10: FMEA for EGBM Gold Team

Process Step/Input	Potential Failure Mode	SEVERITY (1-10)	OCCURRENCE (1-	DETECTION (1-1	Potential Failure Effects	Action Recommended
What is the process step or feature under investigation?	In what ways could the step or feature go wrong?				What is the impact on the customer if this failure is not prevented or corrected?	What are the recommended actions for reducing the occurrence of the cause or improving detection?

			10)	0)		
Landing Rebar Deceleration	Inadequate deceleration before impact	8	2	6	- Damages internal structure - Damages payload - Damages or destroys vehicle	- Refined testing/FEA to determine worst case of maximum forces on framing - Create stronger internal framing structure - Change material of framing structure or fuselage
	Pierces through internal framing	8	5	6		
Parachute Deployment	Does not deploy or deploys late	8	2	4	- Causes unsuccessful landing - Broken nose cone and/or internal components - Damaged or destroyed vehicle	- Backup parachute - Sew patches for rips and holes - Refinement/testing
	Does not expand properly in a timely manner	7	4	5		
	Becomes defective (rips/holes)	5	3	3		
Motors	Insufficient thrust to reach target	9	4	7	- Lack of quality microgravity - Causes unsuccessful landing - Electronics/motors become unusable - Damage to control system preventing parachute from deployment	- Use previous flight results to adjust voltages and RPM accordingly to meet target microgravity value - Stress testing board of electronic system
	Unequal performance in motors	9	3	6		
	Electrical fire due to high current in motors	9	3	7		
Accelerometer	Does not work	7	2	9	- Data does not capture therefore cannot determine whether microgravity was achieved	- Backup power supply - Test prior to use
Drop Release Mechanism	Does not work	4	3	8	- Run does not occur - Data not captured in the run	- Testing

Appendix C: User Manual

C1: Choosing Variable Values

This vehicle is controlled by a predetermined speed profile. In order to accurately operate the vehicle, the programming must be adjusted according to the planned experiment. This program runs on a timer. This programmed timer consists of three important variables: fallTime, fallDuration, and gap. The variables fallTime and fallDuration count the milliseconds since the microcontroller was last reset. The fallTime is continually updated until the vehicles connection to the drone has been broken. The fallDuration is continually updated as long as the microcontroller has a power source. The gap calculates the difference between the two previously mentioned variables to measure the time since the drop began.

There are three distinct sections during the drop. The initial section begins when the vehicles connection to the drone is broken and ends when the timer reaches a predetermined time. This predetermined end time is controlled by the variable "parachuteDelay". This initial section is when the motors are spinning, propelling the vehicle downwards. The speed profile is already included in the program and should not have to be adjusted. This vehicle was designed to be assisted by the motors for up to three seconds. The speed profile cannot be assumed as accurate for motor run times longer than three seconds. The variable parachuteDelay is measured in milliseconds. This value will control the length of time that microgravity will be achieved. This is the most critical value for the experiment. A value should be chosen that will allow for data gathering but leave enough time for the parachute to open and slow the vehicle before impact.

Once the variable gap, or the time since the drop began, has reached the value of parachuteDelay, the code moves to the next section. In this section the motors are stopped, and the servos are opened to allow the parachute to deploy from the parachute tube. This section ends when the timing variable "servoStop" has been reached. This variable is calculated as a user defined value added to parachuteDelay. This user defined value must be large enough to allow the servos enough time to fully open. If the value is not large enough, the servos may not open to the full position before servoStop is reached, causing a malfunction. Once gap has reached the value of servoStop, this section is over.

The final section of the drop is when the microcontroller ceases to send signals to the motor and the servos in order to conserve battery. This section begins when the value of gap has passed the value of servoStop. Nothing in this section of code requires changes.

MICROCONTROLLER CODE:

```
#include <Servo.h>;
const int kPinLed1 = 4;
const int parachuteDelay = 3000;              //Delay after RELEASE to open parachute tube
const int servoStop = parachuteDelay + 3000;    //Time when servos shut off to save battery
const int endAll = servoStop + 5000;           //Time of Motor shut off

Servo ESC1;     // create servo object to control the ESC
Servo ESC2;
Servo ESC3;
Servo ESC4;
```

```
void setup() {

//Motor Setup
  ESC1.attach(6,1000,2000);  // (pin, min pulse width, max pulse width in microseconds)
  ESC2.attach(9,1000,2000);
  ESC3.attach(10,1000,2000);
  ESC4.attach(11,1000,2000);

  ESC1.write(5);    // Send the signal to the ESC to activate
  ESC2.write(5);
  ESC3.write(5);
  ESC4.write(5);
  delay(7000);
  Serial.begin(9600);

  pinMode(kPinLed1,INPUT);
  digitalWrite(kPinLed1,HIGH);
}

int speedgood = 40;

void loop() {
long fallTime = millis();           //Will mark time of drop
long fallDuration = millis();       //Will update current time
long gap = fallDuration - fallTime;

   while(digitalRead(kPinLed1) == LOW){      // While LED1 is connected, program stays in this
loop.
    fallTime = millis();                  //Both timers update while in this loop.
    fallDuration = millis();
  }


  while(gap < parachuteDelay){   //During the fall, but before parachuteDelay

//Timer
    fallDuration = millis();
    gap = fallDuration - fallTime;
```

```
//Motor Drive
   ESC1.write(speedgood);    // Send the signal to the ESC
   ESC2.write(speedgood);    // Send the signal to the ESC
   ESC3.write(speedgood);    // Send the signal to the ESC
   ESC4.write(speedgood);    // Send the signal to the ESC

//Motor Write
  speedgood = gap*0.07 + 40;

  }

  while(gap < servoStop){   //Once parachuteDelay is reached, but before servoStop
//Motor Stop
   ESC1.write(0);    // Send the signal to the ESC
   ESC2.write(0);    // Send the signal to the ESC
   ESC3.write(0);    // Send the signal to the ESC
   ESC4.write(0);    // Send the signal to the ESC


//Parachute Release
   /*servo.write(0);                  //New Servo positions, they move opposite because they...
   servo2.write(180);*/

//Timer
   gap = fallDuration - fallTime;
   fallDuration = millis();
  }

  while(gap < endAll){               //After reaching servoStop
//Motor Detach
  ESC1.detach();
   ESC2.detach();
   ESC3.detach();
   ESC4.detach();

//Parachute Servo Detach
   servo.detach();
   servo2.detach();

//Timer
```

```
    gap = fallDuration - fallTime;
    fallDuration = millis();
  }

  while(gap >= endAll){                //End of system

//Timer
    gap = fallDuration - fallTime;
    fallDuration = millis();
  }
}
```

C2: Preparing Hardware

A number of wired connections must be made to operate the vehicle properly. Each of the electronic speed controls have a white and black wire. The black wire must be connected to the microcontroller ground, while the white wire must be connected to pins 6,9,10 and11. The order is not important. The battery has connections that connect it to the motors and to the microcontroller. The positive connection to the microcontroller should connect to the Vin pin and the negative connection should go to ground. The battery should not yet be connected. The circuit that connects the vehicle to the drone should be connected to pin 7 and ground. The servos are connected to pins 3 and 5 and ground.

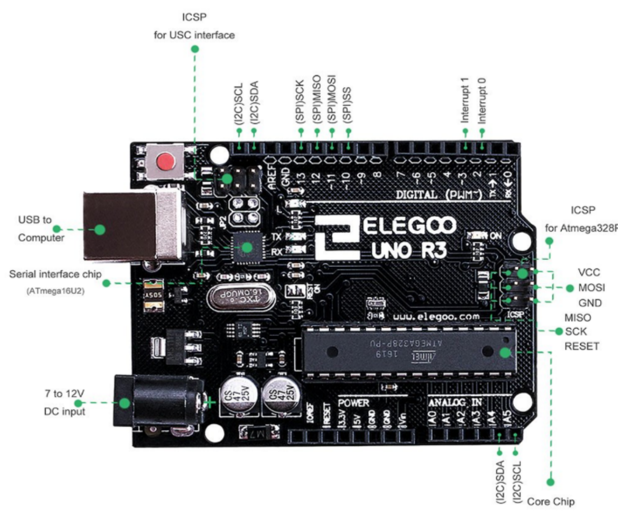

Figure C1: Microcontroller purchased for control system

C3: Final Setup

The last steps to prepare the control system is to upload the code to the microcontroller through a computer's USB port, disconnect the USB cable, and then connect the battery to the microcontroller and motors. It is critical to disconnect the microcontroller from the computer before connecting the battery as this could seriously damage the microcontroller. Once the battery has been connected, the internals can be placed inside the body of the vehicle. While the battery is connected, remain clear of the propellers as a malfunction could cause them to spin.

Extra caution should be taken with the circuit that connects the vehicle to the drone as breaking this circuit will start the programming, causing the motors to spin and the parachute to deploy.

C4: The Drop

Once the vehicle has been prepared, it can be lifted by the drone and dropped. This process is automated and requires no further action. Participants must stand a safe distance away from the drop site as the vehicle will be falling very quickly. Once the parachute deploys, winds can carry the vehicle a large distance at a speed that could cause injury if there is an impact. To be safe, this experiment should only be conducted on days where there is little wind. Participants should also stand upwind from the drop site if possible. In the case of a parachute malfunction, the vehicle will impact the ground at high speed and could potentially fling pieces of material at high speeds. Standing behind a barrier that could shield participants from shrapnel is advised. Participants should also clear the area while the vehicle is being lifted in case the vehicle is dropped or falls from the drone prematurely. Even an impact from ten feet could cause serious injury.

C5: Recovery

Once the vehicle has landed, the team can approach it. If the motors are not spinning, remove the internals and disconnect the battery. While the battery is still connected, always use caution and remain clear of the propellers as there is the possibility of a malfunction that causes the motors to spin. Once the battery is disconnected, the vehicle is safe and the data can be retrieved.

Appendix D: Cost Analysis and Manufacturability Analysis

The vehicle design was primarily focused on achieving quality microgravity and efficient reproductions. These factors drove the design to be relatively straightforward and intended not to overcomplicate the systems involved. With these decisions in mind, the cost to manufacture the vehicle are highly cost effective, allowing the group to be 100 dollars under budget, and having a very effective and similar prototype, as well as a Final Vehicle. The vehicle can be easily reproduced at an estimated final cost around 500 dollars.

Critical system elements included in this vehicle are very manageable. Therefore, it was decided to make our own system elements and simply buy the materials needed to produce them. The two critical systems involved in the design of our vehicle are the propulsion system, and the parachute system. The propulsion system incorporates the use of 4 DC motors in order to provide enough thrust to overcome drag. This system is powered by a lithium battery, and the amount of thrust is controlled through electronic speed controllers and coded using a microcontroller board. The parachute system incorporates the release of a parachute being held by the use of servo motors. Once the vehicle is at a low enough altitude, the servo motors, based on a predetermined flight path based on time, will release the parachute. By the use of the parachute and rebar, the deceleration system should allow for the vehicle to survive the drop, and be able to be reproduced efficiently. The materials used are relatively inexpensive, and we were able to make these systems ourselves without too many complications, allowing us to save a sum of the budget, instead of spending it on having a third-party company produce the system entirely.

Appendix E: Expense Report

Table E1: Itemized list of purchases

Item	Quantity	Unit Price	Subtotal	Shipping	Total
Fuselage	2	$5.31	$10.62	-	$10.62
3D Printer Filament	1	$19.99	$19.99	-	$19.99
Accelerometer	1	$89.00	$89.00	$10.66	$99.66
4 Piece Brushless Motors	1	$56.99	$56.99	-	$56.99
4-piece Brushless Electronic Speed Controller	1	$45.89	$45.89	-	$45.89
Arduino	1	$19.80	$19.80	$2.41	$22.21
Tattu Lipo Battery Pack	1	$13.99	$13.99	-	$13.99
Lipo Fast Charger	1	$49.95	$49.95	-	$49.95
Parachute 3ft	1	$27.29	$27.29	$6.95	$34.24
Propellers	1	$12.99	$12.99	-	$12.99
Y Splitters	3	$9.99	$29.97	-	$29.97
XT60 Connectors	1	$7.99	$7.99	-	$7.99
3D Printer Filament	1	$19.99	$19.99	-	$19.99
Carbon Fiber Motor Arms	1	$14.99	$14.99	-	$14.99
Connector Adapter	1	$7.99	$7.99	-	$7.99
Assorted Screws	1	$13.99	$13.99	-	$13.99
Parachute 6ft	1	$106.95	$106.95	$10.31	$117.25
Lipo Battery Pack	1	$14.99	$14.99	-	S14.99
3D Printer Filament	2	$17.98	$35.98	-	$35.98
Backup Brushless Motors	1	$56.99	$56.99	-	$56.99
Shock Cord	1	$10.94	$10.94	-	$10.94
6in Spring	1	$8.80	$8.80	-	$8.80
McMaster Spring	1	$9.95	$9.95	-	$9.95
Arduino Backups	2	$11.65	$23.30	-	$23.30
ESC	2	$45.89	$91.78	-	$91.78
Motor Servos	1	$20.59	$20.59	-	$20.59
Rebar #3	3	$1.97	$5.91	-	$5.91
Rebar #4	1	$2.39	$2.39	-	$2.39
Total Project Cost	**36**	**$845.33**			

Appendix F: Design Matrices

Table F1: Mechanical Engineering Design Competence Evaluation

MECHANICAL ENGINEERING DESIGN COMPETENCE EVALUATION						
Rate this *design project* in illustrating effective integration of mechanical engineering topics:						
Project Title: Earth-Based Gravity Machine						
	Please rate the relative importance of the given topic in this design project					
ME Design Areas	Critical/ Main contributor	Strong Contributor	Necessary but not a primary contributor	Necessary but not a primary contributor	Only a passing reference	Not Included in this Design Project
Thermal-Fluid Energy Systems	X					
Machines & Mechanical Systems			X			
Controls & Mechatronics	X					
Materials Selection		X				
Modeling & Measurement Systems		X				
Manufacturing	X					

Table F2: Mechanical Topics Utilized in this Senior Design Project

Mechanical Topics Utilized in this Senior Design Project			
Project Title: Earth-Based Gravity Machine			
Topics	Criticality	Sections and Page(s)	Comments
Thermal-Fluid Energy Systems	Critical	Section 7, pg. 22 Section 10, pg. 30	CFD Analysis
Machines & Mechanical Systems	Not Important		
Controls & Mechatronics	Critical	Section 3, pg. 11 Section 5.4, pg. 14 Section 6.1, pg. 15	Arduino microcontroller used to control the timeline of mechanical processes,

		Section 8, pgs. 24–25 Section 10, pg. 28 Appendix B: Table B2, pgs. 40–43 Appendix C, pg. 41	including servo and motor power.
Materials Selection	Important	Section 6.3, pg. 17 Appendix B, pgs. 35-36	Weighted evaluations were conducted for each system and chosen materials were discussed in section 6
Modeling & Measurement Systems	Important	Section 7, pgs. 18–22	Thrust modeling crucial to balance drag forces, and accelerometer measurement determines the success of the experiment.
Manufacturing	Critical	Section 6, pgs. 15-17 Section 7, pg. 22 Section 11, pg. 31 Appendix B, pgs. 35-39 Appendix D, pg. 45	3D printing allows for low cost, easily modified and repaired manufacture

Table F3: Aerospace Engineering Design Competence Evaluation

AEROSPACE ENGINEERING DESIGN COMPETENCE EVALUATION						
Rate this *design project* in illustrating effective integration of mechanical engineering topics:						
Project Title: Earth-Based Gravity Machine						
	Please rate the relative importance of the given topic in this design project					
Aeronautical	Critical/ Main contributor	Strong Contributor	Necessary but not a primary contributor	Necessary but a minor contributor	Only a passing reference	Not Included in this Design Project
Aerodynamics	X					
Aerospace Materials			X			
Flight Mechanics				X		
Propulsion	X					
Stability & Control				X		
Structures		X				

Astronautical	Critical/ Main contributor	Strong Contributor	Necessary but not a primary contributor	Necessary but a minor contributor	Only a passing reference	Not Included in this Design Project
Aerospace Materials		X				
Altitude Determination & Control				X		
Orbital Mechanics						X
Rocket Propulsion						X
Space Environment						X
Space Structure						X
Telecommunications						X

Table F4: Aeronautical and/or Astronautical Topics Utilized in this Senior Design Project

Aeronautical and/or Astronautical Topics Utilized in this Senior Design Project			
Project Title: Earth-Based Gravity Machine			
Topic	Criticality	Sections and Page(s)	Comments
Aerodynamics	Strong	Section 5, pgs. 14 – 15	Understanding of how Drag will affect the vehicle and payload in achieving microgravity directed the design process
Aerospace Materials	Strong	Section 5, pgs. 13 – 15 Section 6, pgs. 16 – 19 Appendix B: Table B5, pg. 36	Aluminum was chosen as for the fuselage as it's cheap and has good manufacturability.
Flight Mechanics	Minor	Not included	Fins were only used to assist in overcoming Drag. The control system used only acted to activate the Motors and to release the Parachute
Propulsion	Critical	Section 3, pgs. 10 – 11 Section 5, pgs. 14 – 15 Section 7, pgs. 22 – 25 Section 10, pgs. 31 – 33	
Stability & Control	Critical	Section 8, pgs. 27 - 28 Section 9, pgs. 29 – 30 Section 11, pg. 34 – 35	Landing Rebar center of gravity helps realign the vehicle after

			Parachute deployment. However, this is the only assurance that
Structures	Strong	Section 6, pgs. 17 – 19 Section 7, pgs. 20 – 21	Internal support is need to keep the Rebar in place where it will not come into contact with the Payload (Accelerometer) and Control system. As well as continue to allow test to be done without repeatedly replacing parts.