ADD

Autonomous Drone Delivery Systems

ADD Systems CDR

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Executive Summary

After submitting a proposal in Fall 2018 to build a drone delivery service, the ADD team followed through and constructed the intended project. For four months, the ADD team rapidly prototyped a mechanism that could be attached to a Phantom 3 Advanced drone and could be used to autonomously deliver packages weighing at least .5 lbs.

We demoed the final version of our project to our client, Dr. Anthony Choi, on March 28, 2019. The drone flew a course of 245 yards and was in the air for a total of 2 minutes. On the course, the drone flew at a height of 11 yards and at the drop off location the drone lowered to a height of 5.5 yards. At the drop off location the drone delayed for two seconds in order to open trapdoor and release the package. After the delay the drone flew to the home location.

From the PDR, we did not have to make many modifications to our design. The main stress point of the building process came from the total weight of the payload system. The DJI website lists the Phantom 3 Advanced max payload at 2.8 lbs, but upon testing, the drone crashed with a payload of 2 lbs. Most of the manufacturing and testing process was spent trying to limit the weight. After taking a recommendation from our client, we decided to construct the box out of balsa wood instead of PLA.

Throughout the manufacturing process, we faced multiple setbacks. We made several modifications to our final circuit design, and the waiting time in between prints somewhat delayed the progress of our project. We also burned a microcontroller and the re order delayed our project a couple days. We also found it incredibly difficult to fly the drone in wind, so often times we had to wait to find the optimal flying day.

Overall, our team and client views the project as a success. We were able to meet all the deliverables for the project. We also were able to complete all tests associated with the project. Our team concluded that our delivery system could carry a package of 1.5 lbs. We did not test past 1.5 lbs because that placed the total weight of the payload at a little over 2 lbs. The battery life of the drone did not decrease drastically with the increased payload weight. Our team recommends that 2-3 flights could be completed successfully on a single full charge.

If another team were to take on the project in a subsequent semester, our team recommends using a drone with a higher payload capacity. We would also recommend further reinforcing the payload box, and possibly using a stronger material. Our team believes that we maxed out the project when fit for the Phantom 3 Advanced drone. In the following sections, we outline our complete design, manufacturing, and testing process.

Introduction

Problem Statement

Ideally, autonomous drones would control the local delivery of small, light packages, allowing for the bypass of common shipping problems like gas prices, traffic congestion, travel time, and human error. However, a low cost, scalable solution for the transportation of packages by drones does not yet exist. Companies like Amazon, UPS, and IBM are all currently seeking an autonomous drone delivery system. For the project, we were given a list of deliverables, and we built a unique final product.

Conceptually, a human or robot in a warehouse could somehow attach a package to a drone and the drone would be programmed with the coordinates of a destination. The drone would then fly to the destination, drop off the package, and return to its starting location in order to repeat the process. Clearly, this process presents several complex problems that have yet to be solved.

Limitations on drone flight time, weight of the payload, cost of development, etc. have prevented an industry wide, scalable solution. In recent years, the focus of using drones for shipping has been directed at last mile delivery. Delivery of small, light packages such as emergency medical supplies, pill prescriptions, first aid kits, food, and other items by drone have the ability to transform how we deliver consure products. Still, regulations by the FAA, competition from industry giants like Amazon, and overall complexity have prevented a solution that is reusable, scalable, and easily implemented.

Project Description

After meeting with Dr. Choi, we learned that he was requesting a system to allow a drone to deliver a 0.5 lb object over a distance of 100 yards through an autonomous flight path. When deconstructing the problem, the ADD team came up with several specifications. First, the drone must fly to a specific destination and return to its initial position autonomously. Second, the drone must be able to support an object with a weight of at least 0.5 lbs for the duration of the flight. Third, the drone must drop off the of the object safely and securely at a predetermined waypoint. Lastly, the drone must cover a round trip of 200 yards (100 yards each way).

Our team decided to design a solution that was reusable, durable, and simple. Since we were working with Dr. Choi’s grant with NASA, we were told we were allowed to spend what was needed in order to meet our deliverables. In order to meet the deliverables, we purchased an autonomous flight program (Litchi), created a payload carrying box out of balsa wood, and used an inclinometer to measure the Phantom 3 Advanced drone camera angle to trigger a motor to open a trapdoor. The complete delivery system was detachable and reusable, and the only user interaction with the system is when the package is placed in the box.

Figure 1: Phantom 3 Advanced Drone

Deliverables

The deliverables given by our client, Dr. Choi, were:

1. The drone must fly a round trip of 200 yards
2. The drone must carry a package weighing at least 0.5 lbs
3. The drone must drop a package off at specified waypoint.

All of the deliverables were to be completed autonomously. With the originally given deliverables, our team was able to surpass expectations. Theoretically speaking, we devised a system that can make deliveries within the maximum range of the drone, only limited by the total battery life. We were also able to fly with a package weight of 1.5 lbs.

PDR Review

Goal

The goal of the ADD Systems team was to find a low cost, scalable solution for autonomous drone delivery for Dr. Choi. ADD Systems had been tasked with developing and delivering an innovative way to use a drone to autonomously transport a package of a half pound over a distance of 100 yards. The flight of the drone had to be completely autonomous. The drone had to find a drop off location, and release the payload at the point. The drone then had to return to home making the total flight distance 200 yards.

In order to meet the goals of the project, the ADD team devised designs that related to Dr. Choi's goals. Since we were dealing with a complex system, ADD divided the design into seven major segments:

1. The drone.
2. The method of autonomous flight.
3. The payload system.
4. The method in which the payload system released the package. The payload component is a device that harnessed an object during flight and had to be able to release the object safely at a specific location. The device needed to be spacious and light. In order to be considered practical our design needed to be able to open and close.
5. Any external devices mounted to the payload system to aid in the opening and closing of the box.
6. The sensor that communicates with the mechanism that opens and closes the box.
7. The microcontroller which handled system communication between the sensor and any other external components.

In order to have a system that meet the project goals, each segment of our solution had to communicate and operate in unison. Each of the segments relied upon each other to meet the project goals. The next step of the design process was to outline the operational requirements of the entire system.

Operational Requirements

In order to ensure that our system would be fully operational, our team developed the segments individually so that they could be tested before they were combined. Once the segments of the design were nearly perfected, they will be individually tested before combining and attempting an autonomous delivery. All functionality using manual flight was tested before running our system with the autonomous flight program. The steps for a successful project are outlined as follows:

1. The payload system had to be attached to the drone.
2. The package had to be enclosed in the payload system.
3. The drone had to take off with the payload system attached.
4. The drone had to fly autonomously to a predetermined waypoint.
5. The drone had to stop at the waypoint and descend to a predetermined height.
6. The drone had to drop the package at the waypoint.
7. The payload system had to remain intact and attached to drone after the drop off.
8. The drone had to ascend and continue the autonomous flight.
9. The drone had to fly back to the home location
10. The drone had to land autonomously.

Each of the segments presented different feasibility and merit criteria and different engineering analysis techniques. The feasibility criteria, merit criteria, and engineering analysis techniques helped us select a preferable design to build in test over the previous semester.

Team Description

The ADD Systems team is composed of three Mercer University Engineering Students. Graham Guthrie is a senior computer engineering student, Jordan Hughes is a mechanical engineering student, and Stone Phillips is a senior electrical engineering student. As engineers, all three members have undergone a rigorous course load with focus in math, science, and technology. Through academic learning, hands-on time in lab, and enterprise endeavors, all three members of the team have excellent time management skills (all three members have been prepared to offer a product that works). The team as a whole has collaborative work experience and have spent time working on product development teams. Full bios of the team can be found in Appendix E.

Roles and Responsibilities

Each of the ADD team members had specific tasks when coming up with a design and building our system. As a computer engineering student, Graham was tasked with devising a plan for the sensor to communicate with the payload mechanism. Graham aided in the selection of a flight software, an ideal sensor for communication, and a suitable microcontroller. Relying on previous experience in programming embedded systems, Graham was able to devise a method of communication between the drone, Litchi, the inclinometer, and motor. Graham programmed the microcontroller in order for the payload system to open. He also programmed the flight program to send a specific camera angle to the drone.

As electrical and computer engineering students, Graham and Stone relied on their knowledge of electronic components and circuit design to create a wiring diagram for the system.

As an electrical engineering student, Stone was responsible for determining a particular motor to power the trapdoor of the payload system. Stone was able to find a motor that would be able to hold the weight of the door and the package for the duration of the flight. He also made sure that the motor would be able to be programmed to power the movement of the trapdoor at specific point in time. Stone devised a solution of including the motor and a separate power supply to the circuit containing the microcontroller, the inclinometer, the switch and the 9V battery. Stone thought it would be smart to use two different power supplies to separate the loads of the circuit and to increase the functionality of the circuit. Throughout the build process, Stone was responsible for the designing and the fabrication of the printed circuit board. Stone also contributed to how the motor would power the movement of the payload door and the placement of all the circuit components on the payload system.

As an mechanical engineering student, Jordan Hughes was responsible for the designs of the payload system and opening system. He used Solid Edge to create 3D models of each design and used the program to calculate volume of designs and weight of designs. The opening system was also roughly simulated using Solid Edge as well to ensure the door would open and close as desired. He also calculated the torque required for the motor to work with the given design. During the build process, Jordan was responsible for fabricating the payload system design, including the box attached to the drone and the trap door. Jordan also helped with the placement of circuit components onto the payload system.

Methods and Work Accomplished

The Autonomous Drone Delivery Systems team used a method that allowed the team to test and build different aspects of the product simultaneously. The iterative development process allowed the team to be informed of any design changes that would need to be made as soon as possible. The project's construction process was divided into three major parts. The software, hardware, and mechanical components were divided among all team members and several parts of the development process had overlapping components.

The team followed the schedule outlined in Fall 2018 for the construction and testing process. After receiving all parts, the team began working on the construction on the project. Graham started on the software side by working with the Arduino Nano microcontroller. He programmed the microcontroller to allow communication between the inclinometer and the servo motor. Graham worked with a motion processing library when coding the microcontroller. All of the code for the project can be found in Appendix D2. Graham tested the inclinometer by manually tilting the sensor to see if it would activate the rotation of the motor. Graham found out through testing his program, that an LED would help him exponentially. The LED helped give a visual signal as to when the inclinometer needed to be tilted. He also discovered that if you tilted the inclinometer too early, that it would throw off the calibration of the sensor and it would pollute the signal being sent to the microcontroller. Several delays were added to the program in order to increase the accuracy of readings. When programmed and timed correctly, the inclinometer sent an accurate signal to the motor to trigger rotation.

When Graham finished his initial program for the payload system, Stone took the circuit and thought of ways to make the motor activate the trapdoor in the most efficient way possible. Stone kept the radius of the attachment to the motor shaft as small as possible, so the motor would be able to lift the optimal amount of weight. Stone also noticed that the length of the motor shaft would play an integral role into the payload system design.

While Graham was working on the initial program and Stone was working on the circuit, Jordan designed and constructed 2 box designs out of 1/4 inch thick balsa wood. The main difference in the designs were the interlocking teeth on the sides to ensure the separate pieces of wood were securely attached to one another. After some tests, it was decided to increase the thickness of the balsa wood to 3/8 inch thick to increase the rigidity of the design. The final payload design schematics are pictured in Appendix D4.

The team was restricted in the development process because the payload system would be attached directly beneath the drone. The team was tasked with fitting all the circuit components on the payload system without interfering with the movement of the camera, without causing hazardous weight distribution, and without interfering with the package release. A long motor shaft would take up too much space and would not allow proper placement of the PCB (printed circuit board) and the motor. When Stone devised a solution for the motor shaft, he tested to make sure the motor would be able to lift the half pound it would need to carry in a real case scenario. Stone tested the torque of the motor and the motor successfully lifted the half pound weight while being powered by the constructed circuit.

Once the team confirmed the software and the hardware components were working properly, Stone began the construction of the PCB. Stone used EAGLE, a PCB design software to draw the circuit board onto a computer. Once a digital file of the circuit was created, it was sent to the Electronics Fabrication Lab at Mercer University and Jeremy Barker, the Electronics Technician, printed the circuit board using a CNC machine. Jeremy was a huge help in this process because he was readily available for multiple PCB prints as there were multiple PCB revisions along with a few errors made in the soldering process of the PCB. The final wiring diagram can be found in Appendix D3.

After the construction of the final PCB and after making sure the circuit worked properly on its new platform, the team collectively decided the placement of each of the hardware components. As mentioned before, the placement of the components was key to the project's success. The team had to make sure the inclinometer could placed properly to the side of the camera. The camera was an integral part to the project considering the camera needed to have a full range of motion to effectively tilt the inclinometer to power the movement of the trapdoor. The final design is displayed in Appendix D5.

After all components were individually tested, the team flew the drone several times manually before using the flight program, Litchi. The team ran payload tests to determine how much the drone could lift. The team also measured the battery life of the drone when carrying different weights.

The team concluded the semester by flying the drone autonomously with Litchi. The team used the Mercer soccer field for demo flights. Screenshots of the Litchi interface can be found in Appendix D1. The team used a bag of quarters as the payload package. The final demo flight for our client Dr. Choi lasted 2 minutes and covered a total distance of 245 yards.

Key Activities and Decisions

In the early stages of the design process, the group came up with several key ideas in order to make the final product possible. First, the group needed to harness a half pound object in a payload system. The payload system was essentially a box that is attached to legs of the drone, which sits directly underneath the drone. The payload system has a trapdoor at its base, where the half pound object rests. Since the drone has a payload system attached to its legs, the drone lands directly onto the payload system with the payload system being the new base for the entire aircraft. This was a clever idea to allow the drone to carry an object in flight and still allow the drone to have lift-off and landing capabilities. After the final demo, our client asked for an expanded landing base to prevent crash landings.

Second, in order for the drone to fly autonomously, the group needed a flight program that used GPS coordinates and a Google Maps user interface. Due to limited time to complete the project deliverables, the group needed a quick efficient solution for autonomous flight. Our group found the Litchi flight program app on the Apple App Store. Litchi synchronizes with several DJI drones. It also allows the user to fly the drone to any specified way point within a given radius. Litchi also allowed for several programmable actions at each waypoint and altitude control between waypoints. Litchi was the perfect solution for the group's needs.

Lastly, the group needed to a way to open and close the trap door automatically in order to make the drone delivery solution completely autonomous. Since the Phantom 3 Advanced offered no free version of external output, the group needed to brainstorm a different solution. The team's best solution was to use a sensor to send a signal to the servo motor to activate the movement of the trapdoor. The team came up with the idea of using the camera to be the source of the signal. As previously mentioned, the Litchi flight program allows a user to program the camera movement at a specific location and time.

The mounting of a sensor to the camera and Litchi feature allowed the team to devise a way of opening and closing the trap door at any specific location at any point in time. Graham decided an inclinometer would be the best sensor to use in order to create a signal transmission from the movement of the camera. The inclinometer would transmit a signal to the microcontroller whenever the inclinometer tilted 30 degrees. This would power the movement of the trapdoor. Throughout the entirety of the construction process the team came across several design successes, failures, and adequate revisions.

Design Successes

Since we completed all of our deliverables, our overall design is viewed as a success. There were several key components of our design that let to its success. Since one of our main limiting variables was the weight of everything, the design of the payload carrying system greatly contributed to the overall success of the project. Building the payload carrying system out of balsa wood is one of the main factors as to why our project was able to work. The box-like payload system was also great because it was able to be attached directly the legs of the drone and could sit directly underneath the drone. This design was a great design to encapsulate small objects and it did not interfere with the landing and take-off capabilities of the drone.

The other main successful component of the design was the inclinometer attached to the drone camera. By using the camera movement, we were able to communicate with external from the drone. Using the camera helped make our design completely removable from the drone. Theoretically, through the use of the inclinometer, different instructions could be communicated to any external device mounted to the drone.

The way the team mounted all of the components to the payload system also contributed to the success of the project. With the mounting of the batteries inside, the team made use of the space on top of the box to mount the remaining components. The team was able to use a limited amount of space to balance the weight of all the components of the design.

Design Failures and Revisions

Even though the team views the overall design as a success, several failures and resulting revisions were encountered along the way. Originally the payload system was to be 3D printed using PLA and it would have weighed ~0.52 lbs. If the team used PLA, then the weight would not have been ideal, as reducing the weight of the payload system would allow for a heavier package. The material was changed to balsa wood, which is a much lighter material and is commonly used for model aircrafts. After changing the material and modifying the design, the final weight of the payload system was .116 lbs.

Another key failure with the design presented in the CDR was the material used to raise and lower the trap door. Initially fishing line was to be wound onto the motor to raise and lower the trapdoor. However, the line tangled during every test and we could not find a solution to work for the fishing line. The material was changed to yarn to resolve the tangling issue. A weight was also added to the end of the yarn to aid in keeping the string taut.

The placement of the string was also an issue. We originally planned to have two connection points on the payload box that would wind string to one central motor. Due to time constraints and tangling issues, the two points were switched to one single point in the middle of the box. Although using a central location in the middle of the box may not be an optimal design, we did not encounter any setbacks by placing the string in the middle of the box. In the future, this may be a segment of the design that can be optimized by a subsequent team.

Another design failure was with the printed circuit board. The circuit board had several external components and internal components. The external components were the components that were not directly soldered to the PCB, but that they were connected via wire connection. These components were, the inclinometer, the servo motor, and the two battery sources. The internal components were the components that were directly soldered to the board and these components were the microcontroller, the three resistors, and the LED. The first PCB print Stone made was an unorganized model. The board had several pads installed to where the external components could be connected; however, these pads were installed throughout the board with no real organization. For example, the inclinometer needed 5 pads on the PCB in order to have a proper connection with the microcontroller. Instead of all these pads being right beside each other, they were scattered all over the PCB.

The next issue with the PCB were with the wire connections. These wires were soldered on one end to the board with the other end of the wire hanging free. This was so these wires could attach to the external components. These external components could not be directly attached to the PCB, so initially, the free wires seemed like a good idea. However, after moving the PCB several times while trying to figure out how it would be placed onto the payload system, the wires ripped out of the board. The solution to this poor design was an organized PCB so the wires for the external components could all be attached in the same place on the board. The other solution to this design was to make a bread-board-like PCB in the sense that the board would have several female ends installed on the board, so the wires could plug into the board with a male end. This would keep our board permanent and would only have to replace external components if anything were to go wrong.

While conducting flight tests, the drone occasionally fell over once it had landed. To resolve this issue, a fork like design was added to the bottom of the payload system to stabilize the drone during landing. In the following section, all of the components of our final design are discussed in detail, as well as the tests our team performed.

Final Design and Construction

Our final design changed in several ways from the design presented in the PDR. Foremost, the payload system is made out of balsa wood. Jordan used a laser cutter to cut the balsa wood in order to get the shape he initially designed in the PDR phase. The box-like payload system has a trapdoor at its base. The trap door takes up the entire base of the box and is attached to the back wall of the box with hinges and epoxy. The entire weight of the payload system came out to be 8.52 oz.

The circuit Stone designed resides on top of the payload box. Stone fabricated the PCB using EAGLE and a couple of the components on the circuit were changed from the original design. The design was sent to the electronics fabrication lab to be printed using a CNC machine.

These components were mounted onto the box with hot glue because glue is relatively lightweight. If we would have attached the PCB with screws, it would have damaged the balsa wood box. The components attached to the PCB include the microcontroller, LED, servo motor, and inclinometer.

The servo motor and the inclinometer are attached outside the payload system as well. The servo motor was mounted with hot glue. The servo motor string runs through a hole in the top of the box and is attached to a single point on the base of the trap door. The inclinometer is attached to the side of the camera using electrical tape. Each of the components not mounted with hot glue can be easily removed.

The box-like payload system is attached to the legs of the drone by zip-ties, so we could keep our product completely separated from the drone to where the drone can still be used for other purposes. The payload system is attached in a fashion to were the payload system sits directly underneath the drone. After speaking with our client, future teams may need to make a system that does not interfere with the ultrasonic sensors on the bottom of the drone.

On the inside of the payload system, are the batteries. The 9 V and 6 V batteries are mounted on the ceiling of the top panel of the payload system, so they are mounted directly beneath the microcontroller and the servo motor. The batteries are held in containers so they can be easily replaced. They connect to the PCB through wires and holes in the front of the payload box.

In order to construct the entire system. Each segment of the design was carefully mapped out and planned before it was made permanent. Jordan made several test balsa wood boxes so the team could map out the correct locations of each of the components. After each position was decided, Graham hot glued the components onto the box, and then he glues the free wire in order to limit interference. Before the end of the semester, the team will reinforce the bottom of the box and add landing gear to help stabilize the drone during landings.

Figure 2: Final Product Design

Tests and Checks Performed

Several tests and checks were developed to test each component of the design to ensure the project's success. Each of the tests were designed to ensure the system works efficiently and successfully. The list below describes the tests and checks performed:

Checks:

1. The drone must fly autonomously to a predetermined waypoint.
    a. The ADD team has tested this by synchronizing the Litchi flight program with the drone. The team took the drone out to Mercer Soccer Field and used Litchi to make the drone fly autonomously across the field and come back to its initial position. The drone was able to fly to 4 waypoints at a distance of over 200 yards and complete the mission autonomously.

2. The payload system must be attached to the drone, the drone must take off with the payload system attached, and the payload system must remain intact and attached to drone after the drop off.
    a. After laser cutting the balsa wood box design, the box was attached to the drone with zip ties. We then flew the drone to test how well the drone flew with the attached box. There was no visible restrictions to flying the drone with the box attached.

3. The camera and sensor must be able to communicate with arduino and trigger the bidirectional movement of the motor.
    a. First, our team connected the inclinometer, the microcontroller, and the motor together via a breadboard circuit. Then our team powered the circuit with the two batteries and held the inclinometer in one of the group members hands. The circuit was powered and we tilted the inclinometer to see if the sensor would signal the rotation of the shaft of the motor. The code Graham wrote worked and

all of our connections were proper, so we decided that we could continue building out the hardware and software components of the project.

4. The motor must be strong enough to hold the trap door in place during the entire flight.
    a. Our team constructed the circuit as it was in Check 3. We then attached the electrical components to the payload system and checked to see if the motor could hold the trapdoor in place. The trapdoor did not move, and the strength of the motor was verified.

5. The motor must be strong enough to lower the trapdoor to release the half pound object.
    a. The same procedure was implemented as described in Check 3, except we tied one end of a piece of fishing line to the motor shaft and the other end to a ziplock bag containing half a pound of quarters. We held the inclinometer and tilted it to signal the rotation of the motor shaft. After doing this, we waited to see if the motor was strong enough to move the half pound weight.

6. The motor must be strong enough to raise the trapdoor to its initial position.
    a. The same procedure will be implemented as described in Check 5. If Check 5 passed, then we were able to conclude Check 6 would pass. This is because 0.5 lbs weighs more than the balsa wood door.

7. The system works together manually with the payload system design
    a. The team took the constructed circuit from Check 3 and mounted the PCB, the motor, and the batteries onto the payload system. We then attached the inclinometer to the side of the camera with electrical tape. After everything was attached, we flew the drone a few feet off of the ground and manually tilted the camera to see if it would signal the movement of the trapdoor. The camera was able to move freely. The motor lowered the door and raised it.

8. All components must work for the autonomous delivery of a .5lb package
    a. Once all previous tests were completed, all systems were combined and attached to the drone for an autonomous delivery attempt at the Mercer Soccer field. We then used the Litchi flight program to see if the drone could deliver the half pound package autonomously. The system was able to work repeatedly.

Tests:

1. How does the weight of the package affect the lifetime of the drone battery?
    a. Attach the payload system to the bottom of the drone.
    b. Fly the drone manually where the drone will hover about 5 feet off of the ground.

c. Fly the drone for 3 minutes and then land the drone.
d. Video record the test for the entire 3 minute flight and then an additional 45 seconds after landing (3 minutes and 45 seconds of footage).
e. Keep track of the battery life percentage on the dji drone app and watch how the percentage decreases over time.
f. Repeat steps a through 5 for the following package weights: 0, 0.5, 1.0, and 1.5 pounds.

2. Find the current draw from the 9V and 6V battery when connected to the entire circuit to help determine the lifetime of each battery.
   a. Construct the circuit as mentioned before onto a breadboard and connect the DMM in series with the power supplies to see how much current is drawn.
   b. Take the results to make a calculated estimate of the lifetime of each battery.

3. Find the maximum package weight the drone can fly with.
   a. Step 1a.
   b. Fly the drone and check to see if there is normal functionality
   c. Step 1f.

<u>Results and Discussion</u>

Test Results

The testing process for our project contained mostly checks. The construction of everything properly consumed a majority of the team's time. After building each respective piece of our project, we ensured that it was adequate enough to move to the next step. When everything was constructed, we began a more in depth and relevant testing process. Outside of making sure the drone delivered the package successfully, our testing process related to finding the maximum capabilities of our system. We made sure to fly several successful test flights before demoing the final product to our client Dr. Choi. The remaining paragraphs outline our testing process in relation to the previously mentioned tests. The testing data and supporting calculations can be viewed in Appendices B and C, respectively.

The most insightful test we conducted was a look at how package weight affects the lifetime of the drone battery. Our team found that the battery life was linear with respect to time. Also, as more weight was added, the slope became increasingly negative, as expected. For the test, we flew the drone and payload system with several different weights inside. The max flight times based on the tests for 0, 0.5, 1.0, and 1.5 pounds were estimated to be 17, 15.6, 12.5, and 10.1 minutes respectively. Graphs showing the behavior of the drone battery can be found below:

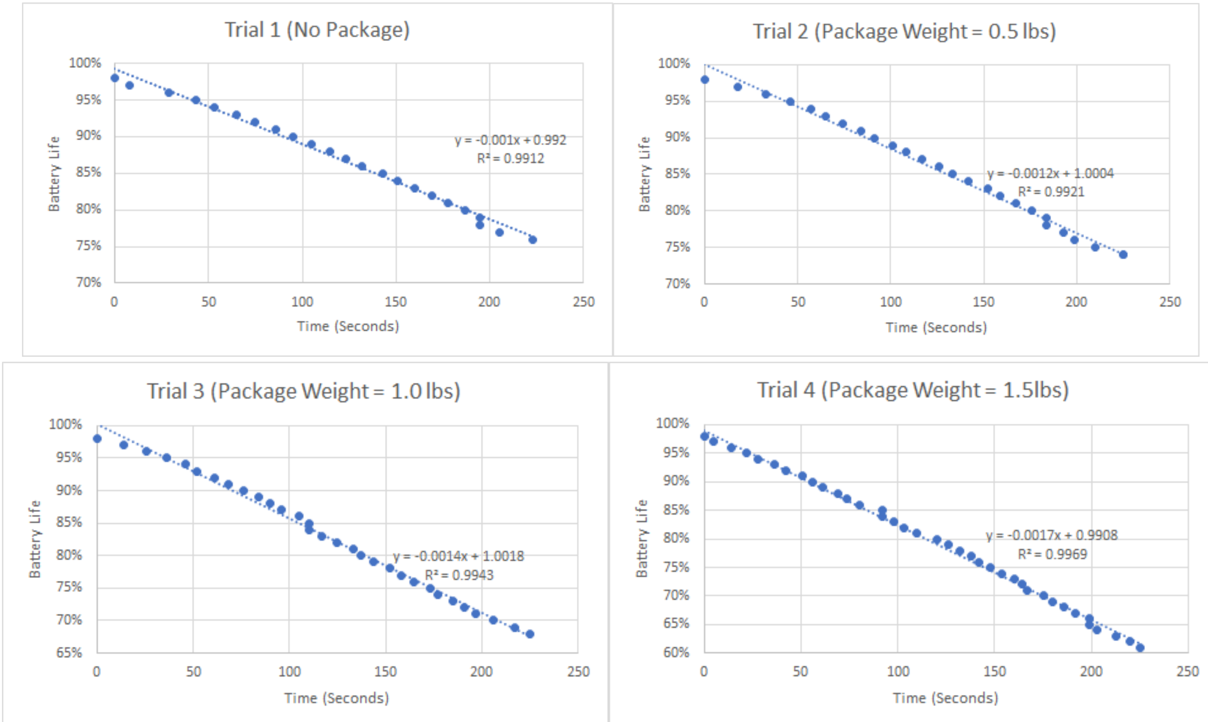

Figure 3: Battery Life Test Results

One issue we ran into when testing the battery life of the drone was that the DJI GO app does not accurately display the depletion of the drone battery. The drone battery life decreased linearly for all 4 tests; however, the DJI GO app showed that the battery life of the drone still decreased at a significant rate after landing the drone. After this discovery, we decided to retest the battery life of the drone battery by flying the drone for 3 minutes and then continuing to record the depletion of the battery 45 seconds after landing. We felt that the drone battery did not decrease much more after this point of time. We felt that the battery life percentage displayed on the app, at that point in time, was an accurate representation of how much battery life had been consumed from the flight.

The other tests we conducted were measuring the current draw from the 9V and the 6V battery. The purpose of these tests was to show us how much current was being drawn from each of the batteries for every second of the flight. Stone tested the current draw from the 6V and the 9V for each of the actions the circuit would perform. When testing the current draw from the 9V battery, Stone built the entire circuit and measured how much current was being drawn when the LED displayed a green light, a red light, and a white light. Each light is displayed for a certain amount of time during the actually flight of the drone and the payload system and each light draws different amounts of current. Stone took this into account and measured how much of the battery capacity was used during one flight. Then, he divided the total battery capacity of the 9V battery by the battery capacity used during the flight. Stone did the same thing for the 6V battery. He measured how much current was drawn when the motor was stalled, when the motor was lowering 0.5lbs, and when the motor was rotating with no load at all. Lastly, he measured how much battery capacity was used during one flight and divided that into the total capacity of the 6V battery. The results of these tests show that the 9V battery would last about 500 flights and the 6V battery would last about 11,700 flights. After seeing the results of these tests, it is clear to see that these batteries will last for a very long time. These measurements and calculations can be found Appendix C2.

After demoing to our client, we asked if there were any specific tests he would like us to run. He wanted to know what the maximum package weight our payload system could handle when attached to the drone. We ran this test at the same time as the battery depletion test. Starting a 0 lbs inside the payload system we increased the weight of the package by .5 lbs until reaching 1.5 lbs. The drone and payload system were able to take off with a package weighing 1.5 lbs. There were no warnings and the drone was able to keep all flight functionality. We did not want to increase the weight beyond 1.5 lbs because we had flown the drone with a total weight of 2 lbs during the PDR process and it crashed. We could not afford to crash the drone with the payload system attached due to time constraints and limited resources.

For future teams, it would be beneficial to test the maximum distance the drone would be able to fly, especially since our team found the maximum battery life of each of the components.

Changes and Updates from PDR

The main change the ADD team made from the PDR was the material used to build the box. The proposed material was PLA and the box was to be printed. We quickly ran into problems with this design due to weight. The weight of the PLA box would have been 0.52 lbs Our client recommended using a box made out of balsa wood. Using a laser cut balsa wood box reduced the weight drastically. The weight of the box made from balsa wood was 0.116 lbs.

Another design change, we had to make was the placement of the sensor on the camera. We originally proposed the sensor be mounted to the backside of the camera. When first mounting the camera to this position, the force of the wires pushed the camera too far forward and caused the gimbal to glitch. If we were to go with the sensor mounted to the back of the camera, we would not be able to control its movement, so we needed to devise another solution. We decided to move the sensor to the side of the camera. Moving to the side greatly reduced the force of the wires on the camera, and it increased the range of motion of the camera.

The final design change we had to make from the PDR was the material and placement of the string used to open and close the door. Originally, we planned on mounting the string to two points on each side of the box. When running initial tests, the team ran into several tangling issues due to the lack of tension in the fishing line. The team decided to switch to yarn and attached a light weight to the end of the yarn to keep tension constant throughout the opening and closing process. Due to time constraints, the team abandoned the idea of using two attachment points on the door of the box. Instead, we used a single point in the middle of the box. Although the placement in the middle seems like it may affect the release of the package, the team did not run into any issues when testing.

Revised Cost

From the PDR, the proposed cost for the project was $98.77. After constructing the project, we finished with a revised number. Although we purchase all the parts outlined in the PDR, we ran into some setbacks that increased our original cost. We had to purchase multiple Arduino Nano microcontrollers because we burned through one of them. Due to Dr. Choi's budget we were able to accommodate all unexpected parts. Additional quantities of some of the parts were purchased if they were considered essential to the project in order to reduce the need to reorder. We also were able to find multiple cheaper products than what was originally proposed. A full updated parts list can be seen in the table below:

Purchased Parts List and Cost	
Litchi Flight Program	$22.99
2x 9V Battery	$16.40
9V Battery Holder	$2.99
4x 1.5 Lithium Double A Batteries	$6.49
4 AA Battery Holder	$7.49
Mpu 6050 Inclinometer	$7.95
2x Servo Motor	$23.99
3 x Elegoo Arduino Nano	$13.86
Polyester Sheet	$15.99
Balsa Wood	$12.00
Wires	$9.79
Battery Leads	$5.58
Plastic Hinges	$5.26
Fishing Line	$5.42

Zip Ties	$5.18
Total	**$161.38**

Table 1: Final Cost

Ethical and Community Impact

Implementing a full scale drone delivery service has the ability to reshape the global community. The original proposal for this project was to create a service for a local Macon hospital in order to deliver pills and emergency medical supplies. By using a drone, a health professional could bypass traffic, reduce the chance of getting into an accident, conserve time, and reduce the cost of resources, like gas.

Outside of the health community, a drone delivery service would have a strong positive impact on the environment. Although there are gas powered drones, a majority of drones are electric. By replacing common delivery mechanisms like freight trucks, mail carriers, and ships with electric powered drones, emissions could be reduced drastically. The speed of delivery could also be magnificently improved, because the process would bypass the need for roads.

The world is years and most likely decades away from using drone delivery on a full scale. However, it can be expected that in the very near future drones will be used on segments of the delivery process.

There are several areas that drone delivery impacts ethically. The FAA takes precautions on allowing pilots to drop objects from drones. The FAA states that any pilot must take precautions to avoid injury or damage to any person or object [1]. Companies have to receive special permission in order to develop drone delivery technology. In the future, when this technology is implemented, extensive codes and standards will need to be written in order to manage and control the use of the sky. For now, our team believes the FAA should encourage further development and progress in the field of drone technology and capabilities.

Recommendations for Future Work

For future iterations of the project, our team recommends a drone that is Litchi compatible and has a higher payload capacity. The Inspire 2 by DJI can hold a payload of 4 lbs and is compatible with Litchi. Since it is compatible with Litchi, camera movements can still be used to program the opening of a payload system.

With a larger drone that has a larger payload capacity, a larger box could be made in order to facilitate multiple package deliveries. In order to support multiple deliveries, the payload system will probably need to be modified. Using camera motion to trigger the opening of the payload system could technically be used to encode any kind of message from the drone to the payload system. This opens the possibility of multiple compartments on the payload system. Also, a payload system design that did not block the ultrasound sensors on the drone could be beneficial for a smoother flight.

Another recommendation for this project would be a different circuit configuration. Our group thinks it would be beneficial to use only one power source for the arduino circuit instead of two. When looking at the test results section, it is clear to see that the 6V and the 9V battery will last for an extremely long amount of time. Our team thinks it would be beneficial to try to design a circuit that allows the arduino microcontroller and the servo motor to be powered by the 9V battery alone. We think this would be beneficial because this could reduce the weight of the payload system. This would allow the drone to carry a heavier package. Since the servo motor has an operating voltage between 4.8V and 6V, there would need to be a voltage regulator or some sort of a voltage drop to decrease the voltage from 9V to the operating voltage of the motor. This design change would only be beneficial if the PCB would still be small enough to fit on top of the payload system and not interfere with the motor shaft or the movement of the camera.

Conclusion

Even though we were able to meet all the deliverables for the project. Our devised system for drone delivery is still far from what would be considered necessary for large scale operation. This project was originally designed with pill delivery in mind for a health care facility in Macon. Our client redesigned the project with the package being anything weighing 0.5 lbs.

We were able to prove the concept for the first iteration of the project. The biggest limiting factor with using the Phantom Advanced 3 was the weight. The spec sheet of the drone claims it should be able to carry double its normal takeoff weight. We found it difficult to fly the drone with any payload weighing more than 1.25 lbs.

We also ran into several other limiting factors that slowed our development process. The drone was not stable when flying in wind, the force of the wires attaching the inclinometer affected the gimbal’s range of motion, and the tension of the string used to pull up the trapdoor on the box was difficult to manage.

Overall, our team deems the project as a success. There is a lot of potential for future work with the project, and we hope another team continues to build upon the foundation we laid.

References

[1] "Federal Aviation Administration." *FAR Part 91 Sec. 91.15 Effective as of 09/30/1963*, rgl.faa.gov/Regulatory_and_Guidance_Library/rgFAR.nsf/0/AD2EBDA6370BB404852566CF0061287A?OpenDocument.

[2] Adafruit Industries. (n.d.). Continuous Rotation Servo. Retrieved from https://www.adafruit.com/product/154

[3] Energizer. "Energizer L522 Ultimate Lithium Product Datasheet."

[4] Energizer. "Energizer L91 Ultimate Lithium Product Datasheet."

[5] China Young Sun LED Technology Co. "RGB LED Datasheet."

[6] Invensense. (n.d.). *MPU-6000 and MPU-6050 Product Specification Revision 3.4* [PDF]. Invensense, Inc

[7] Getting Started. (2018, October 16). Retrieved from https://www.faa.gov/uas/getting_started/

Appendices

A. Component Specifications

A1. Continuous Rotation Servo Motor - FeeTech FS5103R [2]:

- Operates between 4.8 and 6 volts
- Max current draw = 1 A
- Weight = 40 grams
- At 6V, Stall Torque = 2.777 lb-in

A2. Energizer 9V Lithium Battery [3]:

- Capacity = 750mAh
  - Can draw 750 mA for one hour before battery dies.
- Weight = 1.2 ounces = 33.9 grams

A3. 6V Battery [4]:

- Comprised of 4x1.5V Lithium Energizer Batteries
- Capacity of 1.5V Lithium Battery = 2.9Ah

A4. RGB LED [5]:

- Forward Current = 20 mA
- Typical Forward Voltage (Red pin) = 2.0V
- Typical Forward Voltage (Blue pin) = 3.2 V
- Typical Forward Voltage (Green pin) = 3.2V

A4. Weights of Remaining Components [6]:

- Total Weight Payload System (Including Electrical Components): 0.53125 lb
- Weight of Circuit Components:
  - Energizer 9V Lithium Battery = 0.064 lb
  - 4x1.5v Energizer Lithium Double A batteries = 0.132 lb
  - Arduino 4 AA battery holder = 0.02 lb
  - Continuous Rotation Servo - FeeTech FS5103R = 0.088 lb
  - Arduino Nano = 0.015 lb
  - Mpu 6050 Inclinometer = 0.005 lb
- Weight of Package = 0.5 lbs
- Total weight drone HAS to carry = 1.03125 lbs

B. Test Data

B1. PCB Current Measurements

Experiment Run	Battery	Components Used in Experiment	Current Draw Between Microcontroller and 9V
1	9V	Arduino Nano	~25 mA
2	9V	Arduino Nano LED (Green) LED (White)	 ~31 mA ~39 mA
3	9V	Arduino Nano Inclinometer LED (Green) LED (White) LED (Red)	 ~36.5 mA ~45 mA ~40 mA
4	9V	Arduino Nano Inclinometer Servo Signal LED (Green) LED (White) LED (Red)	 ~36.5 mA ~45 mA ~40 mA

Table 2: 9v Current Measurements

Note: The "Components Used" were the active components in the circuit being used to test the current draw from the 9 volt battery. The LED is listed multiple times because different currents were drawn from the battery based off the different light colors emitted from the LED.

Experiment Run	Battery	Servo Motor Activity	Current Draw Between Servo and 6V
1	6V	Rotating	~125mA
		Rotating Down with 0.5 lb load	~98mA
		Rotating Up with 0.5 lb load	~164mA
		Stationary	~3.5mA

Table 3: 6v Current Measurements

Current Drawn From 9V Battery (130 Second Flight Time)		
LED	**Time**	**Current Drawn**
White	10 seconds	45mA
Red	118 seconds	40mA
Green	2 Seconds	36.5mA

Table 4: Flight Current Measurements

C. *Supporting Calculations*

C1. Expected Drone Battery Life With Respect to Varying Payloads

(Reference Data from Appendix B1)

Trial	Weight of Payload	Time Elapsed	Drone Battery % Depletion	Expected Battery Life of Drone
1	0.0 lb	225 seconds	22 %	~ 17.045 minutes
2	0.5 lb	225 seconds	24 %	~15.625 minutes
3	1.0 lb	225 seconds	30 %	~ 12.5 minutes
4	1.5 lb	225 seconds	37 %	~10.135 minutes

Table 5: Drone Battery Life

Note: Expected Battery Life = {[(100%)/(Battery % Depletion)]*(Time Elapsed)}/(60 seconds)

C2. 6V and 9V Battery Life Based off Circuit Measurements From Appendix B2

Current Drawn from 6V Battery (130 second flight):

= [(126s*3.5mA) + (2s*98mA) + (2s*125mA)] = 887 mAs

6V Battery Capacity = 2.9 Ah = 2900 mAh = 10440000 mAs

→ 6V Battery life = (10440000mAs)/(887mAs) = 11,770.01 flights

Current Drawn from 9V Battery (130 second flight):

= [(10s*45mA) + (118s*40mA) + (2s*36.5mA)] = 5243 mAs

9V Battery Capacity = 750 mAh = 2700000mAs

→ 9V Battery life = (2700000mAs)/(5243mAs) = 514 flights

C3. Torque Calculation for Continuous Rotation Servo Motor - FeeTech FS5103R:

Stall torque = 2.777 lb-in

- Torque = weight*radius*sin(90)
- Weight of package = 0.5 lb
- Total weight motor must hold in place = ~ 0.5 lb

  $\rightarrow$ 2.777 lb-in = (0.5 lb)*r

  $\rightarrow$ r $\leq$ 5.554 in

C4. LED Resistance and Current Calculations (Using data from Appendix A4):

Calculations for Resistor Values:

LED Red Pin: (5V-2V)/(20mA/2) = 3V/0.01A = 300 ohm resistor
LED Blue Pin: (5V-3.2V)/(20mA/2) = 1.8V/0.01A = 180 ohm resistor
LED Green Pin: (5V-3.2V)/(20mA/2) = 1.8V/0.01A = 180 ohm resistor

Resistors Used Based Off Capability:

LED Red Pin: 330 ohm
LED Blue Pin: 220 ohm
LED Green Pin: 220 ohm

Current Drawn by LED:

Red Pin: 3V/330 ohm = 9mA
Blue Pin: 1.8V/220 ohm = 8mA
Green Pin: 1.8V/220 ohm = 8mA

D. Drawings/Fabrication Document

D1. Demo Test Flight with Litchi

Figure 4: Demo Litchi Flight Path

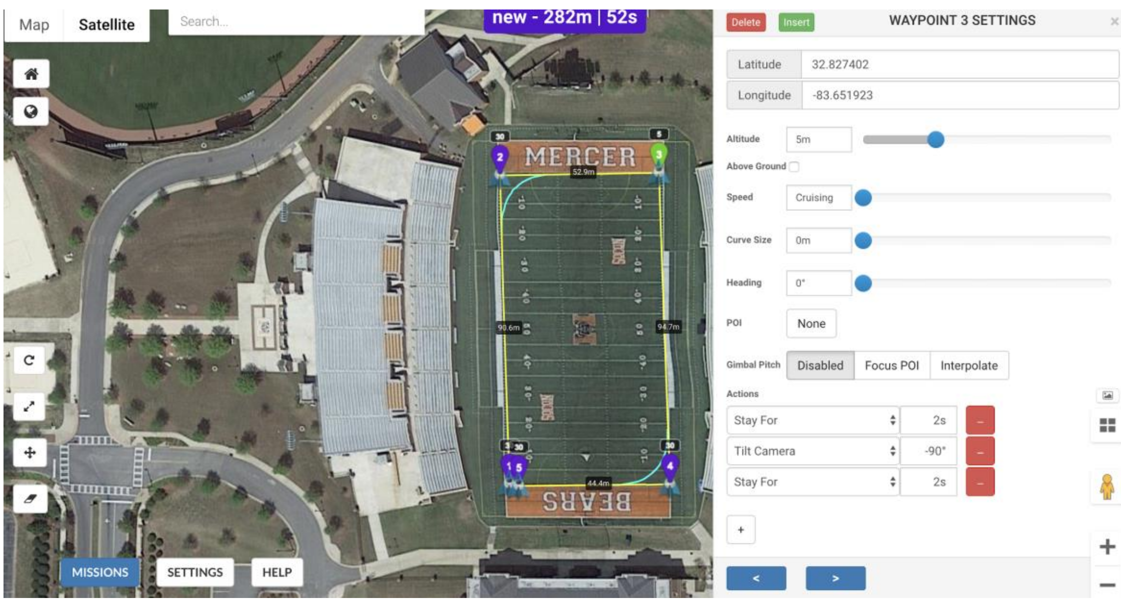

Figure 5: Litchi Commands Display

D2: Complete Microcontroller Code

```
#include <I2Cdev.h>
#include <Servo.h>
```

```
#include <MPU6050_tockn.h>
#include <Wire.h>

Servo myservo;
MPU6050 mpu6050(Wire);
int valx;
int valy;
int valz;
int onButton = 3;
int redPin = 4;
int greenPin = 5;
int bluePin = 6;

bool doorTrigger = true;
float initAngle;

// On/Off Button Setup:
int ledState = LOW;

void setup() {
  //Button Setup
    pinMode(onButton, INPUT);

    //Led Setup
    pinMode(redPin, OUTPUT);
    pinMode(greenPin, OUTPUT);
    pinMode(bluePin, OUTPUT);
    setColor(255, 0, 0);

  setColor(255, 51, 153);
  Serial.begin(9600);
  Wire.begin();
  mpu6050.begin();
  mpu6050.calcGyroOffsets(true);
  delay (1000);

  unsigned long findInitAngle = millis();
  while(millis() - findInitAngle < 3000){
     mpu6050.update();
    initAngle = mpu6050.getAngleX();
  }
}

void loop() {
    mpu6050.update();
```

```
    int OnOffReading = digitalRead(onButton);

    if( findIncline() && doorTrigger){
          myservo.attach(9);
          myservo.write(90);
          setColor(0, 0, 255);
          lowerDoor();
          delayDoor();
          raiseDoor();

          ledState = !ledState;
          doorTrigger = false;
      }
      else{
        setColor(255, 0, 0);
        myservo.detach();
      }

}

void setColor(int red, int green, int blue)
{
  #ifdef COMMON_ANODE
    red = 255 - red;
    green = 255 - green;
    blue = 255 - blue;
  #endif
  analogWrite(redPin, red);
  analogWrite(greenPin, green);
  analogWrite(bluePin, blue);
}

bool findIncline(){
  boolean inclineAbove30 = false;
   if((abs(mpu6050.getAngleX()) - abs(initAngle)) > 30)
      inclineAbove30 = true;
   return inclineAbove30;
}

bool returnedToHome(){
  boolean inclineAtHome = false;
   if((abs(mpu6050.getAngleX()) - abs(initAngle)) < 5)
      inclineAtHome = true;
   return inclineAtHome;
}
```

```
void lowerDoor(){
  unsigned long startToLower = millis();
  while(millis() - startToLower < 2000){
    myservo.write(180);
  }
  myservo.write(90);

}

void delayDoor(){
  unsigned long doorDelayStart = millis();
  while(millis() - doorDelayStart < 1500){
    myservo.detach();
  }
  myservo.attach(9);
  myservo.write(90);

}

void raiseDoor(){
  unsigned long startToRasie = millis();
  while(millis() - startToRasie < 1925){
    myservo.write(0);
  }
  myservo.write(90);

}
```

Note: Along with the main program code, several test code snippets were written. Code was written to test the servo motor and the inclinometer. For the motion processing library for the MPU 6050, I used the library which can be found at https://github.com/tockn/MPU6050_tockn.

D3. Wiring Diagram

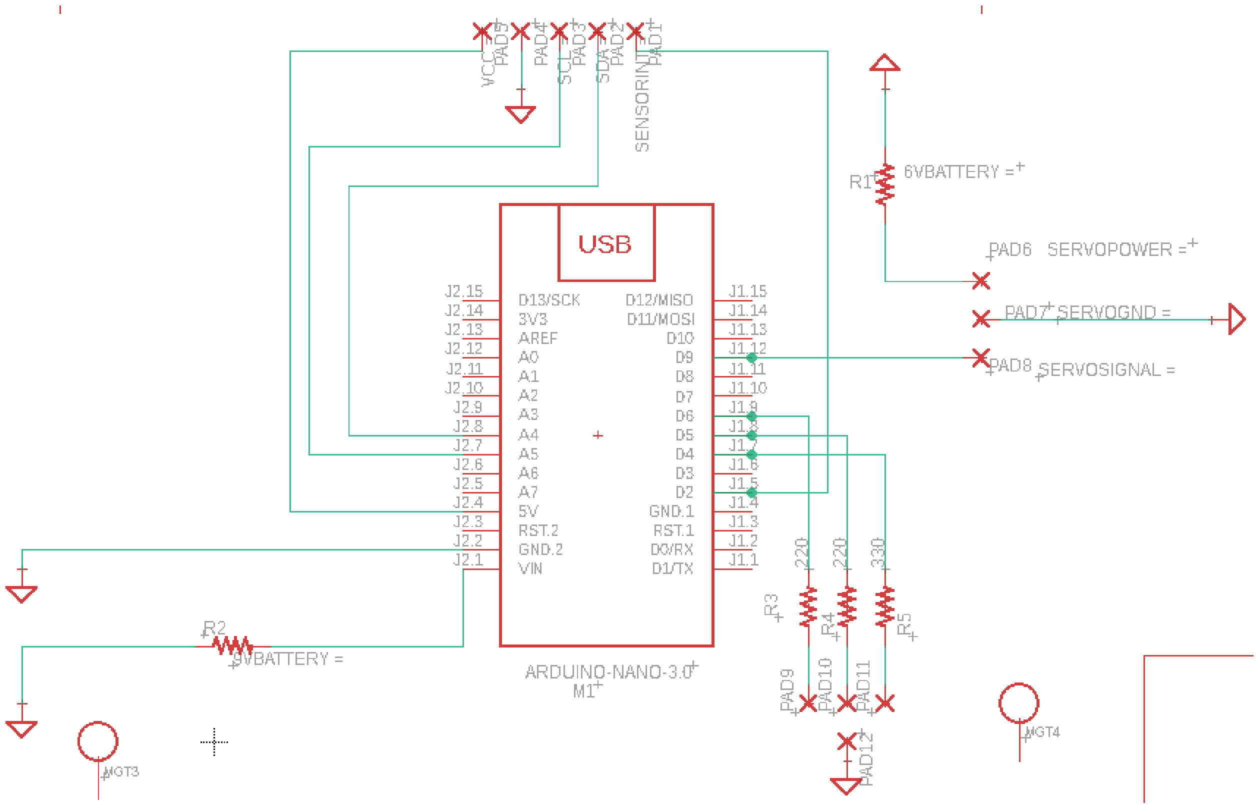

Figure 6: Wire Diagram

Note: Pads 1, 2, 3, 4, and 5 are the Sensor Connector Pads. Pads 6, 7 and 8 are the Servo Motor Connector Pads. Pads 9, 10, 11, and 12 are the LED Connector Pads. R1 is the 6V battery and R2 is the 9V battery. R3 and R4 are 220 ohm resistors. R5 is a 330 ohm resistor.

D4. Final Payload Design

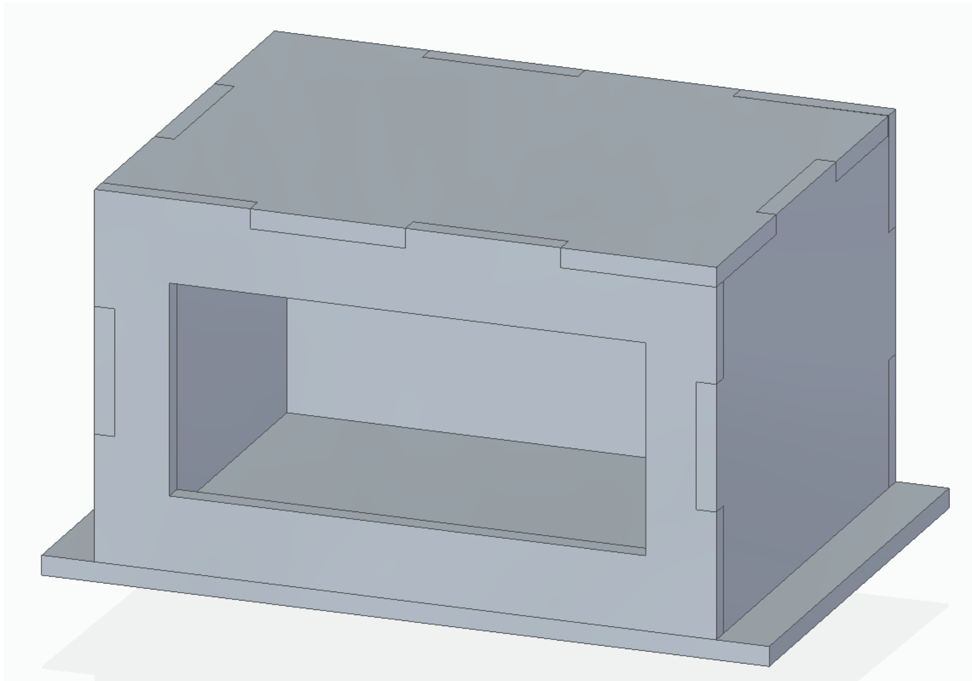
Figure 7: Box Front View

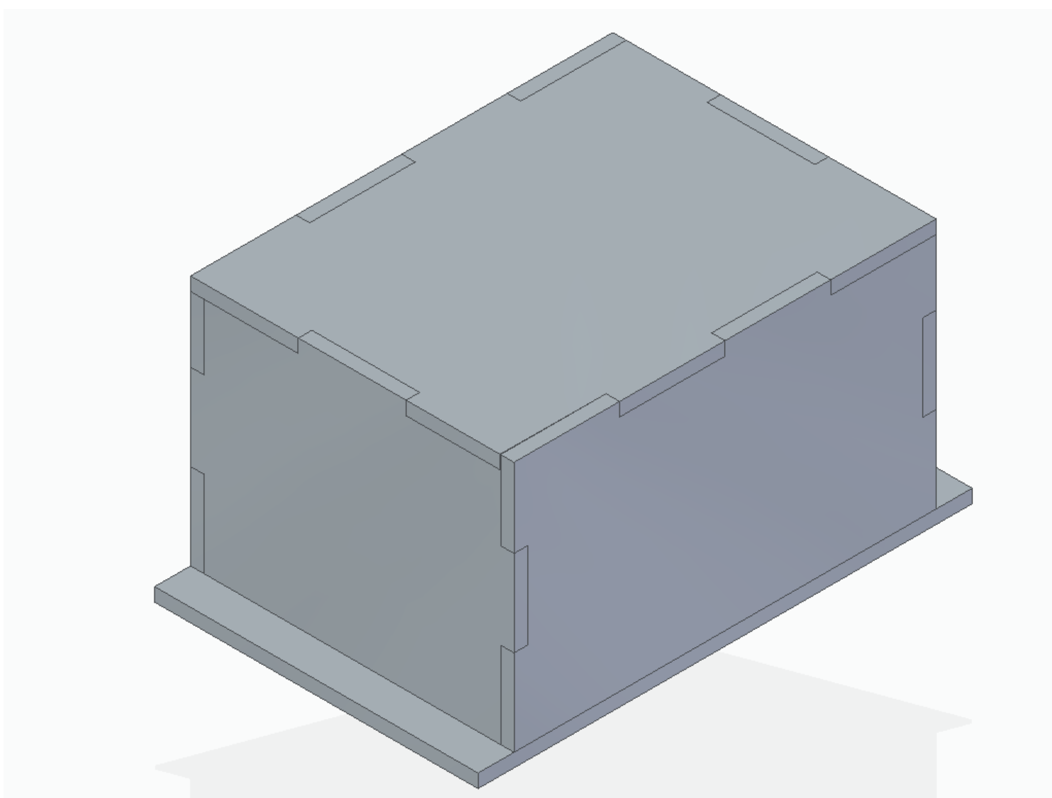
Figure 8: Box Back View

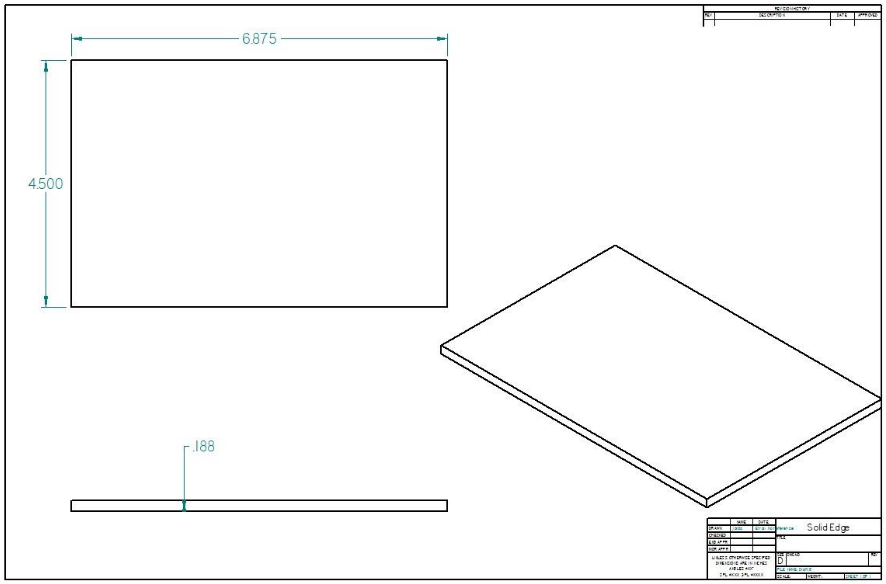

Figure 9: Trap Door Schematic

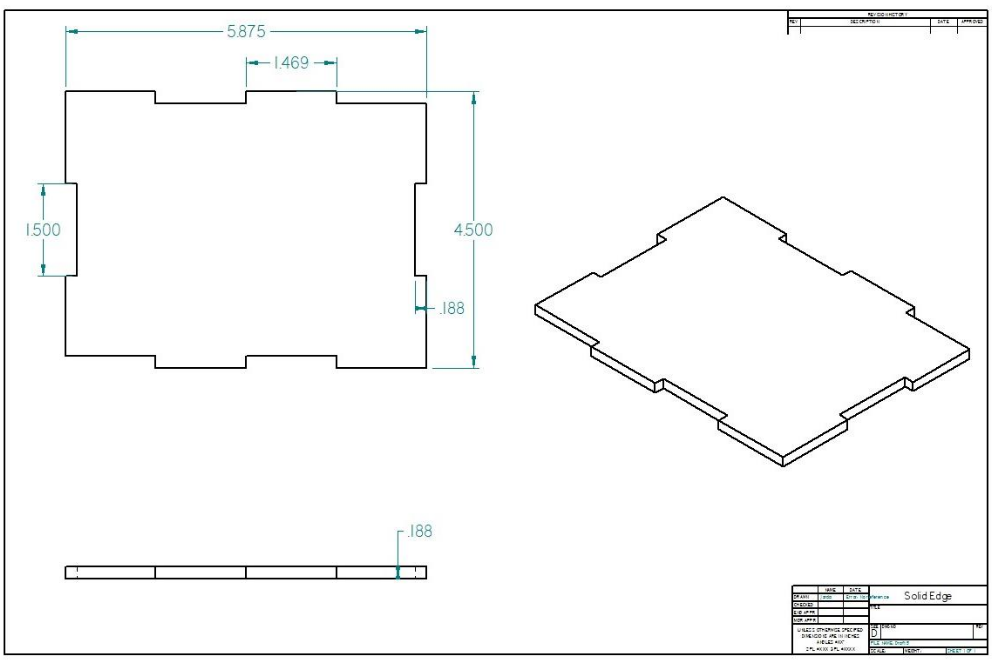

Figure 10: Top Box Schematic

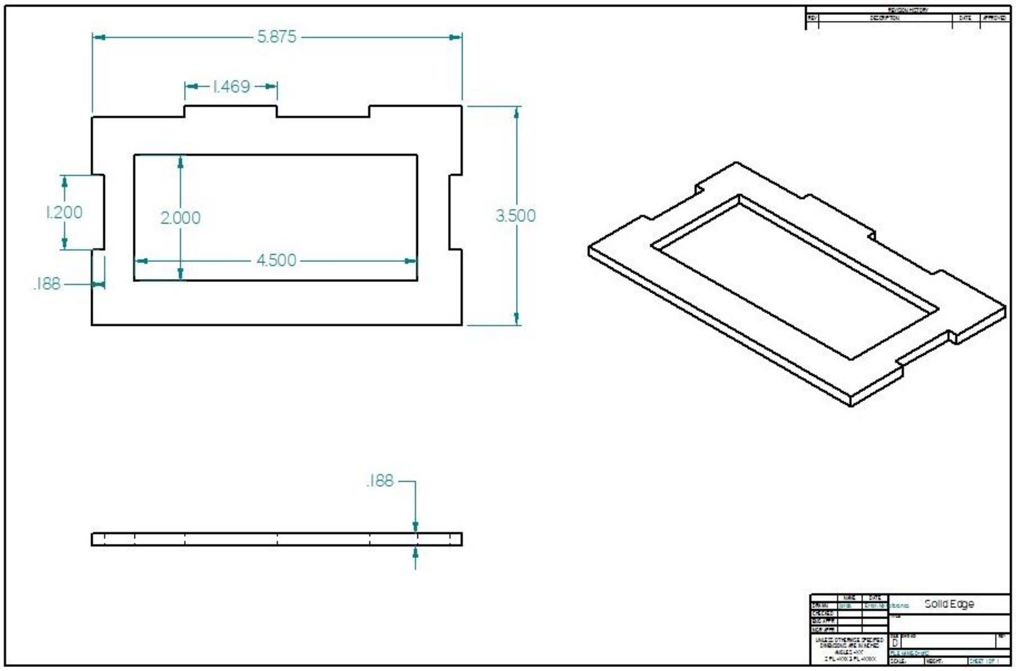

Figure 11: Load Door Schematic

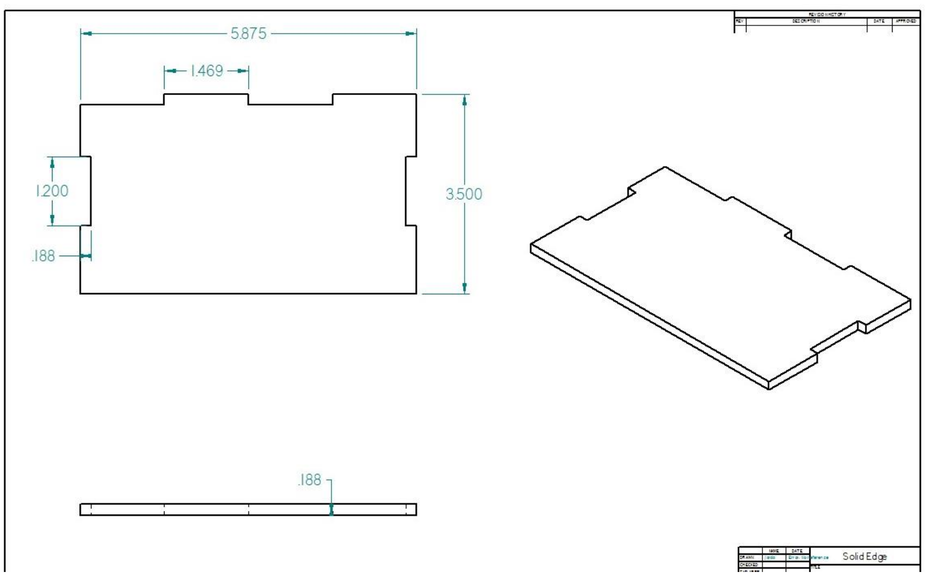

Figure 12: Side Box Schematic 1

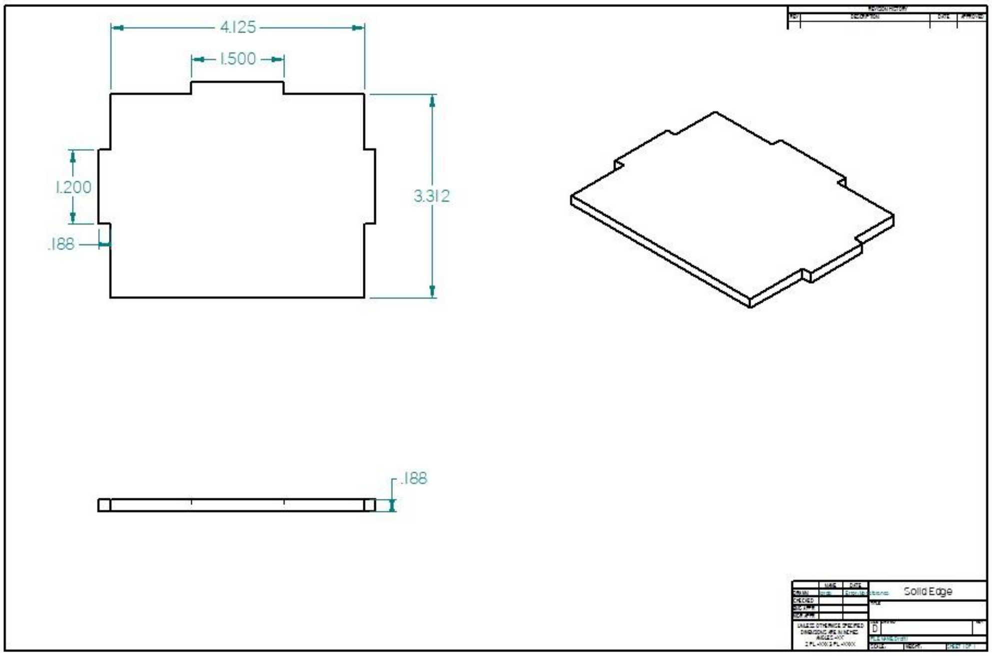

Figure 13: Side Box Schematic 2

D5. Final Product

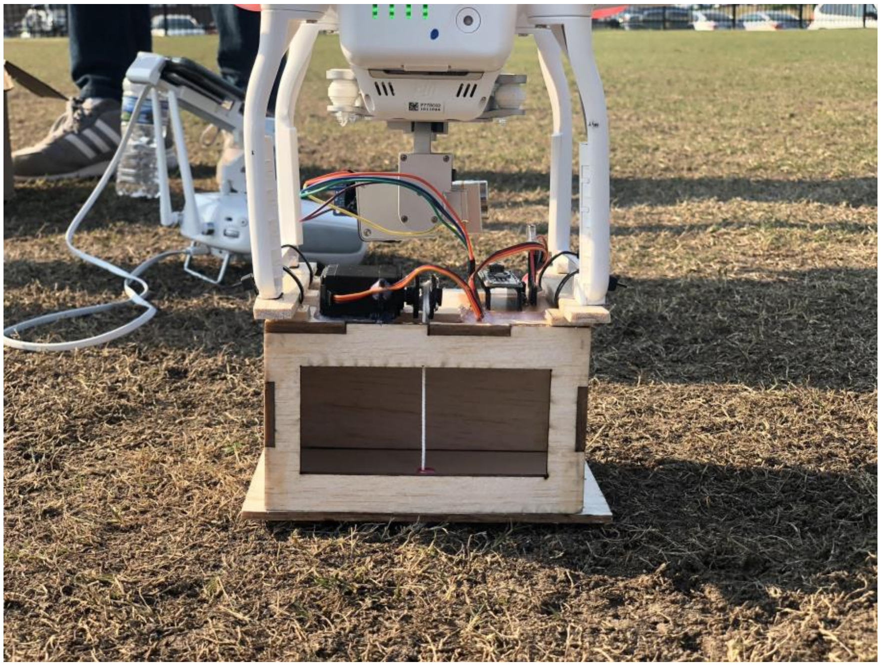

Figure 14: Final Design Back

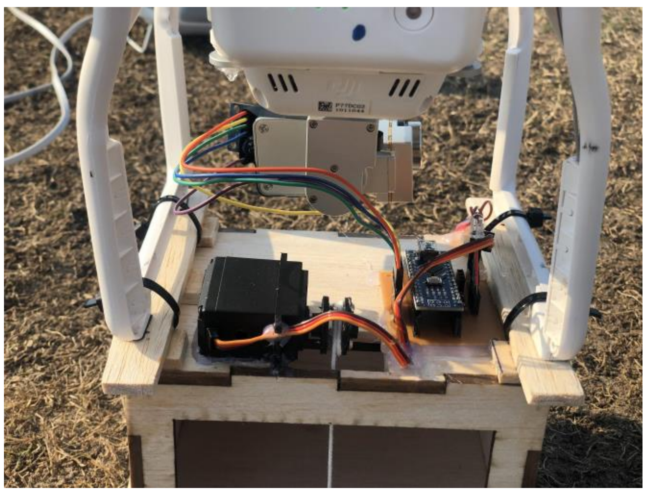

Figure 15: Final Design Top

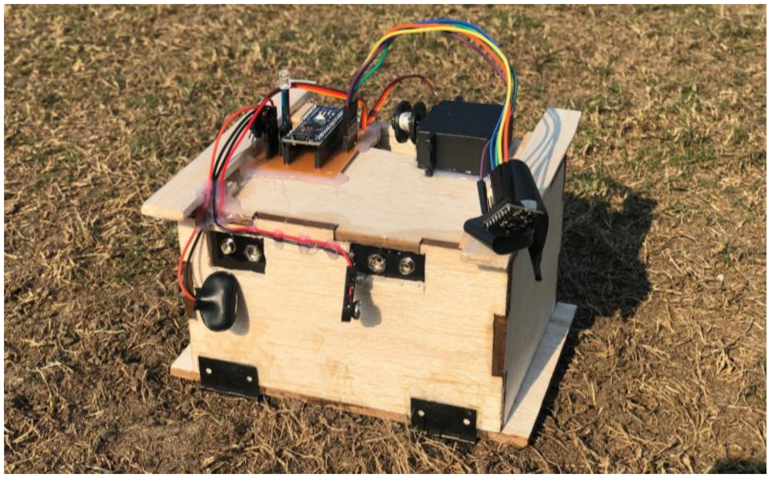

Figure 16: Final Box Detached

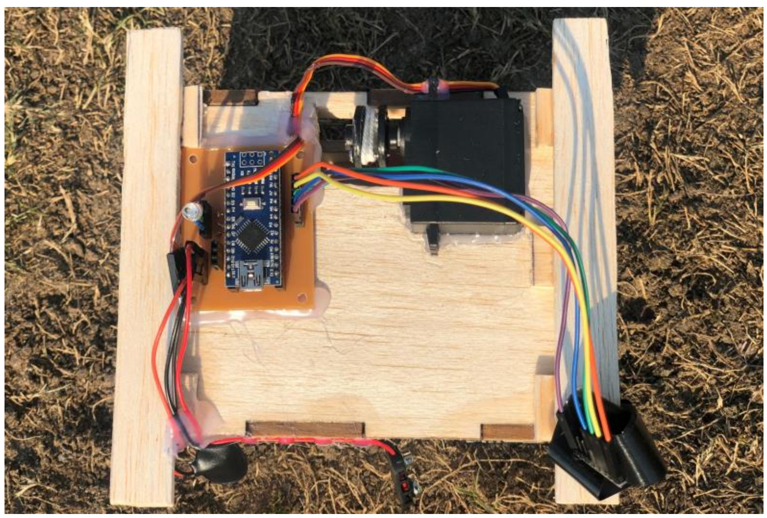

Figure 17: Final Box Detached Top

D6. Free Body Diagram

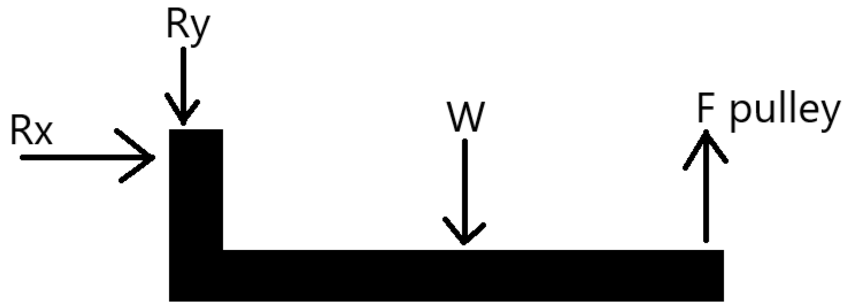

Figure 18: Free Body Diagram

E. Team Bios

Stone Phillips is a Senior Electrical Engineering major at Mercer University. Throughout Stone's college career, Stone has maintained an exceptional GPA while also gaining experience in the electrical engineering field through multiple internships. Stone has developed a keen interest in the aerospace field through college and through his most recent internship at Honeywell Aerospace. For the project, Stone was tasked with supplying power to the delivery mechanism for the drone as well as creating an interface for software communication. His knowledge of project development and hardware systems played a key role in the success of ADD Systems.

Jordan Hughes is a Senior Mechanical Engineering major at Mercer University. Jordan's interests pertaining to the project include autonomous system design, robotics, and revolutionary technology. His experience inside of the classroom includes work with different types of robotic systems (LEGO NXT, K'Nex, Arduino, etc.), programming (C++ and Matlab), and 3D Modeling. Outside of the classroom, Jordan worked with Heatcraft Worldwide Refrigeration on a project pertaining to shipping efficiency, which gave insight on the commercial/consumer side of the project. Jordan was responsible for the mechanical design of the payload, 3D models throughout project, and element analysis, as well as helping with programming the payload and drone movement.

Graham Guthrie is a Senior Computer Engineer at Mercer University. While at Mercer, Graham has maintained an outstanding GPA. Outside of the classroom, Graham has completed multiple internships, including his most recent role as a software engineering intern at The Home Depot. For the project, Graham was tasked with the developing software for the drone and the payload mechanism. Through coursework, Graham has experience with programming embedded systems. He has used microcontrollers with many different forms of I/O devices which will be beneficial when connecting the drone to the payload system. For the autonomous movement of the drone, Graham relied on his extensive programming experience and his strong analytical skills to devise an algorithm that helped the drone move without a controller. Graham provided quality software for the project and with the help of his teammates, he kept track of deadlines to ensure the project is completed by the set date.

F. Codes and Standards: FAA Regulations on Unmanned Aircraft Systems (UAS) [7]

F1. Fly under the FAA's small UAS rule (Part 107):

- Unmanned aircraft must weigh less than 55 pounds, including payload, at takeoff
- Fly in Class G airspace
  - Class G airspace is designated as an uncontrolled airspace. This area consists of the area between the surface of the ground to class E airspace.
- Keep the unmanned aircraft within visual line-of-sight
- Fly at or below 400 feet
- Fly during daylight or civil twilight
- Fly at or under 100 mph
- Yield right of way to manned aircraft
- Do not fly directly over people
- Do not fly directly over people (The term "over" refers to the flight of the small unmanned aircraft directly over any part of a person.)

F2. Fly under the Special Rule Model for Aircraft (Section 336):

- Fly for hobby or recreation ONLY
- Register your model aircraft
- Follow community-based safety guidelines and fly within the programming of a nationwide community-based organization
- Fly a model aircraft under 55 lbs. unless certified by a community-based organization
- Fly within visual line-of-sight
- Never fly near other aircraft
- Notify the airport and air traffic control tower prior to flying within 5 miles of an airport
- Never fly near emergency response efforts

F3. Rules for model aircraft registration:

- 13 years of age or older (if the owner is less than 13 years of age, a person 13 years of age or older must register the model aircraft)

- A U.S. citizen or legal permanent resident

F4. Other Resources

- Code of Federal Regulations, Title 14, Chapter 1, part 107
- Fact Sheet - Small Unmanned Aircraft Regulations (Part 107)
- Pilot’s Handbook of Aeronautical Knowledge
- Advisory Circular, AC 91-57, Department of Transportation, FAA