Project Pegasus

Final Project Report

Project 1558: Localized Package Delivery Drone

Lockheed Martin

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Executive Summary

The goal of this project was to design and build a drone that would pick up and deliver packages. Based on the project requirements and team preferences, a flying solution was selected. The decision was made to use an RC helicopter as the flying device, and the package pickup device was an 80/20 aluminum frame, with a tempered hardboard floor, containing a chain and sprocket system. This was used along with a rack to pick up and deliver packages controlled via key FOB that communicated to an Arduino Rev 3 motor shield. The RC helicopter was controlled using a 14-channel Futaba controller. Additionally, upgrades were made to the tail rotor and motor to ease the function of lifting the package pickup device, which was attached to the bottom of the helicopter. The package pickup device uses two chain-and-sprocket systems to move the rack in a square path with the larger chain system having the square path and the smaller chain system connecting two larger chain systems to ensure they move at the same rate. There are a total of 4 larger chain systems (two on each side) and 2 smaller chain systems (one on each side).

The design can pick up three packages with a weight limit of 5 lbs. total for the packages. In addition, the smallest package the system can pick up is 1”x1”x0.5” and the biggest package is 6”x6”x4”. As the device can fly as instructed by the pilot, it will be able to pick up packages on the second floor. It can be used outdoors and indoors. However, it cannot be operated at night or if there is any precipitation.

In addition, to prove that the system is stable and functional with the intended package weight, finite element analysis has been done on several elements: the chassis of the helicopter, the floor of the package pickup device, as well as the 2 most vital aluminum beams to ensure that they will be able to bear the load. The F.O.S. for all these components was well over 5. To supplement the analysis, there is additional video proof of the helicopter flying as well as picking up packages of varying sizes.

A link to an electronic repository containing all software source files, CAD files, electrical schematics, and other electronic files associated with this project will be provided to the sponsor by UTDesign.

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1.0) Introduction

The problem statement for this project is to create a drone capable of delivering packages to various locations. The testing plan is being used to evaluate the prototype's ability to fulfill the threshold requirements set forth by the clients and the objective requirements the team decides to take on. The objective requirements were stretch goals, therefore the team put more emphasis on certain objectives such as being able to carry three packages and deliver them to different places as well as being able to pick up 15 lbs.

The testing plan will use a Compliance Matrix to organize different tests that will be performed with the prototype and to document the results of the tests. The first column of the compliance matrix specifies the test that will be performed on the prototype. The second column will define the acceptable outcome of the test. The third column shows the method or tool being used to measure devices performance. The fourth column will document the results of the test and the fifth column will show if the test was passed or not. The sixth column will be for any additional information gathered from the test.

The Compliance Matrix will serve as a comprehensive document for tracking the prototype's progress and identifying areas for improvement. By following this plan, the team will be able to ensure that the drone meets the necessary requirements and is capable of delivering packages efficiently and reliably. In addition, the Compliance Matrix will help to clearly identify which requirements were met and proof of how they are met.

2.0) Design Alternatives

The prompt for this design challenge was to build a device that could pick up and deliver a package in a localized area. The team agreed that an air-based solution would better meet the high-tier requirements, so the device needed flying capabilities.

2.1) Flying Devices

Examples of conceptual flying devices can be seen below in Figure 1. These designs were evaluated against the requirements that pertained to the flying device. Examples of these requirements include ability to operate in windy conditions (Specification 1.13), operate in snowy conditions (Specification 3.9), operate in day or night (Specification 2.16), minimum pick-up zone size (Specification 3.12). More specifically, the designs were evaluated for which tier the design could achieve.

One example is the pick-up zone requirement for instance. The base requirement would award 1 point, while each succeeding tier awards an additional point. However, not all requirements awarded 1 point for each tier. Examples of exceptions to this include the sound requirement (Specifications 1.3, 2.3, 4.1) and the minimum package size requirement (Specifications 1.5, 3.1), which rewards higher points because that tier is considered harder to achieve. All the requirements were structured like this with varying tiers and corresponding points.

Using the relevant requirements and considering the likelihood of a design fulfilling the requirement, flying device design was judged on which was most likely to award the greatest point in each individual requirement. Some of the trade-offs that were considered for flying devices were the flight time to pick-up, number of packages that could be carried, and ability to pick-up and drop-off packages in any order. However, the most important trade-off that was considered was the weight that the flying device could carry with these quadcopter and VTOL aircraft designs.

Since all the flying devices used the brute force flying method, the team was pushed to find a flying method that incorporated both basic flying principles: Bernoulli's Equation and Newton's Third Law. After a new round of design iterations, a solution incorporating both was not found. This is when one of the sponsors suggested fixed-wing rotary aircraft because of the superior hover efficiency as shown below in the figure. After this, the helicopter design was compared against the relevant requirements, and found that it would achieve the base requirements, the stretch goals that were determined internally, and greatly reduce the complexity of the project. It was agreed upon that a helicopter design was the best.

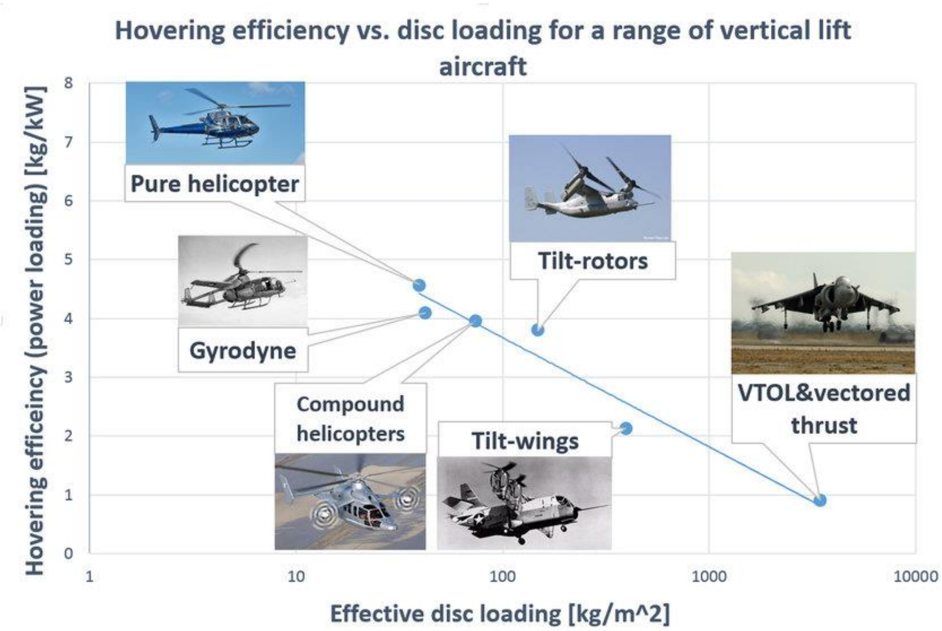

Figure 1) Helicopter vs VTOL hovering efficiency

2.2) Standardized Package Carrying Designs

In conjunction with the quadcopter design, some of the early design iterations of the quadcopter were paired with a standardized carrying device that could ease the complexity of picking up packages that could vary greatly in size, shape, weight, or quantity. Designs included a basket-carrying quadcopter, a net quadcopter, a basket-and-hook quadcopter, and a claw quadcopter. Such designs can be seen below in Figure 2. The design recommended during the PDR was the basket quadcopter. These designs were evaluated against the requirements that pertained to the package device. Examples of these kinds of requirements are package weight requirements (Specifications 1.6, 2.5, 3.2), package shape requirements (Specification 2.6), and multi-package requirements (Specifications 2.10, 3.5, 3.6, 3.7, 4.4, 4.5). Using the relevant requirements, the best pick-up method was determined by comparing each design to each tier of the requirements and considering the likelihood of the design achieving this tier consistently. Some of the trade-offs that were compromised were package weight, quantity of packages, and quantity of servicing zones. The sponsor influenced the package device portion of the project profoundly. The sponsor stated that the difficulty of any pick-up method that was performed during hover would be practically impossible to achieve, given the flight expertise of the team. Therefore, the task was reframed into developing a pick-up method that would decouple these two actions: flight and pick-up. Furthermore, the sponsor gave design suggestions in the form of "what if" questions. Examples of these questions are: "What if the package device used one motion to perform the task?", "What if it picked up packages on one side and dropped them off on the other?", "For a multipackage device, what if you could drop off any package at any time?". These suggestions directed the subsequent design iterations.

Figure 2) Early Standardized Package Designs with hooks, nets, and baskets

2.2) Modular Package Carrying Designs

Another package design type that was considered was the modular design. The main basis for this concept is a complete singular functioning design. Then, producing multiple devices and using them individually to achieve a multi-package feature on the device. An advantage of these designs is that they simplified the design and building process. The disadvantage is that these designs prove to be large and bulky, and waste weight, materials, and resources on the design. This was determined by comparing the materials needed to construct a 3-package version and the materials needed to construct a non-modular 3-package design. As such, the modular package designs were discarded. Examples of such designs can be seen below, in Figure 3 and Figure 4.

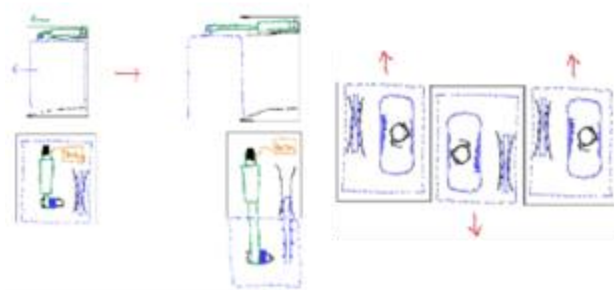

Figure 3) Modular "Dustpan" Design

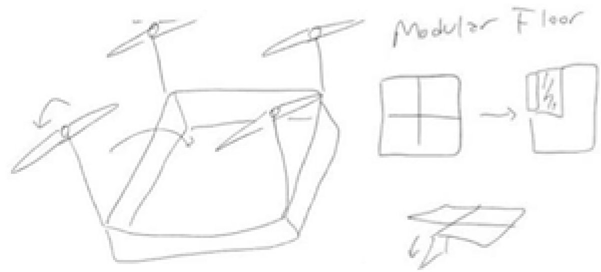

Figure 4) Quadcopter with Modular Floor

2.3) Wall-E Package Carrying Design

An early rendition of the chosen design is the "Wall-E" since its functions similarly to the Disney cartoon robot, Wall-E. As seen in Figure 5, the design incorporates a single input motion, a decoupled flying and picking up action, and a separated entrance and exit side.

The idea of this design is that the blue "rack" is mounted to a track system, outlined in green. As the rack goes around the track, it will pick-up packages, move packages, and drop off packages. When picking-up a package, the rack will be on the top side of the track and will go horizontally out past the package and then vertically descend around the package. As the rack moves to the left on the bottom part of the track, the package will get drug into the device for storage. Each cycle of the rack will move the package one slot deeper into the device. There are three package slots in the device, therefore it will take 3 rack cycles to bring a package in and push the same one out. An advantage to this design is that the landing accuracy required to align the package with the device is decreased. This design was evaluated against the relevant requirements the same way the previous package devices were before. It was determined by the funnel method that this design fulfilled all the base requirements and stretch goals. This design passed the team vote and was officially the design for the project. Detailed implementation was allowed to begin on the Wall-E design.

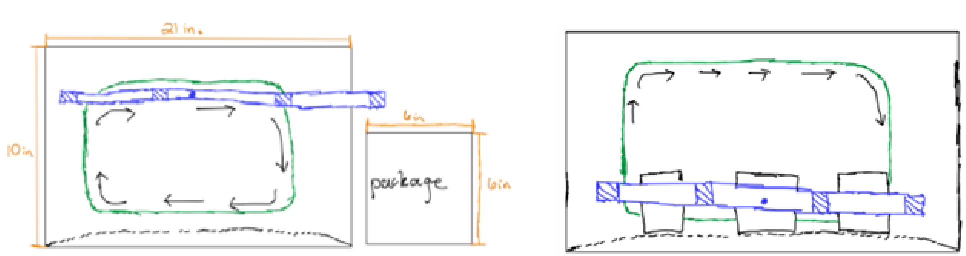

Figure 5) Early Concept of Wall-E Design

3.0) Final Design Solution

3.1) Description of Design

The full assembly has 2 major sub-assemblies, the flying device, and the package pickup assembly.

3.1.1) Flying Device

The flying assembly consists of using an Align Trex 600 helicopter with a 750mx brushless motor and an upgraded 3 tail rotor blade (105mm size blades) system. This selection of the helicopter allows the option for the device to pick up loads of up to 25 lbs. after full assembly of device. The helicopter main rotor blade was modified to allow for an increased pitch range to produce more lift. The helicopter is paired with a Futaba 14SG receiver which contains 14 channels to operate the helicopter.

3.1.2) Package pickup assembly:

For the package pickup sub-assembly, it can be split up into 3 additional subassemblies which include the frame, chain and motor assembly, and Arduino assembly. In Figure 6, there is a 3D rendering of the full package pick-up device.

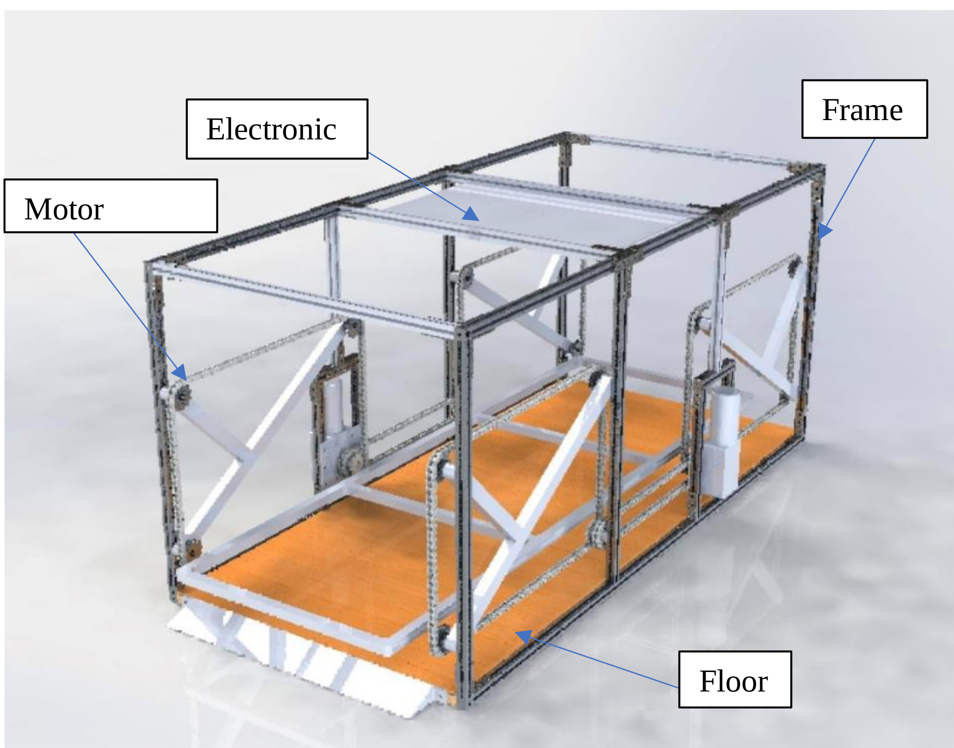

Figure 6) 3D Rendering of Package Pick-up Device

3.1.3) Frame sub-assembly:

The frame materials were selected based off the materials property, in which the stiffness, strength, and weight were top priority. The frame sub-assembly consists of a multitude of parts which include 10mmx10mm aluminum slotted beams, straight brackets, corner brackets, right angle brackets, T-brackets, M3 machine screws and nuts, 10mmx10mm wooden dowels, wooden sheet, 10mmx10mmx10mm square corners, and wood glue.

The flooring of the frame is made from wooden dowels and a wooden sheet. There are 5 wooden dowels under the wooden sheet at a length of 13 inches separated evenly with the ends made of the aluminum beams which are cut by 13 inches. The wooden sheet is wood glued onto the wooden dowels with the dimensions of 28.57 inches by 13 inches. There are 4 corner brackets that are placed on the ends of the wood flooring that connect the panel to the aluminum beams. They are held together by 6mm M3 square head machine screws and M3 nuts.

The shell of the frame is made from slotted aluminum beams to allow us to easily modify any dimensions if needed. The corners of the frame have corner brackets and right-angle brackets for added structural support. Drawings for this component are Figure 26 in the Appendix.

3.1.4) Chain and Motor Assembly:

There are a total of 4 larger chain systems in a square path shape divided evenly into two sides. On one side, there are 2 larger chain systems separated at 7 in. The path has a length of 10 in. from the sprocket origin and 6.25 in. Height from the sprocket origin. The sprockets are offset from the wall 0.43 in. to allow for a double sprocket to drive each side. The square path is attached to the outer sprocket teeth of the two-sprocket assembly, so the other chain system does not interfere with the rack rotation. The smaller chain system is connected to a worm gear motor attached to a two-headed sprocket piece. The chain is connected to the inner sprocket teeth and extends 7 in. to the side where another two-headed sprocket piece is located and is also connected to the inner sprocket teeth. This allows the motor to spin both sprockets simultaneously to ensure both square paths are rotating at the same speed. The larger chain systems were modified so one pin would be replaced with a 50mm (about 1.97 in) M2 machine screw to allow us to connect the rack to the chains with the square path. This would allow the rack to move in the square path that the larger chain system provided. The motor spins at a rate that allows the rack to move one full square cycle in 90 seconds. Since the motors are on opposite sides, one motor runs in reverse while the other runs forward, however, this does not affect the speed at which they move. Drawings for this component are Figure 25 in the Appendix.

3.1.5) Arduino sub-assembly:

The Arduino assembly consists of using AA lithium-Ion batteries, an Arduino uno Rev3, a key fob and receiver, and a motor shield. The Arduino is connected to a motor shield that is also connected to the motor assembly which is powered by the batteries. The key fob is paired with a receiver that is also connected to the Arduino to give commands when one of the key fob buttons are activated. This activation is what allows the motor system to operate as intended. There are 4 buttons on the key fob: A, B, C, and D with each button having different operations. The A button activates the system to complete one full cycle, the B button activates the system to complete one full cycle in reverse, the C button allows for either side to realign with the other, and the D button stops any of the current operations from continuing for an emergency stop.

Figure 7 shows a friendly view of the same wiring diagram in Section 8.1.1. On the breadboard, the left black square is the RF sensor, and the right black rectangle is the motor driver integrated circuit. The motor is on the far right, while the Arduino microcontroller is at the bottom in blue. Lastly, the remote used to send signals on the far left. The Arduino and Motor shield are connected on top of each other with pin connectors. The Worm gears are connected to the motor shield's terminal which the power supply is also connected to. This allows for the electronics to be powered during operation. The receiver is connected to the motor shield to allow for the key fob to send signals to the motor shield.

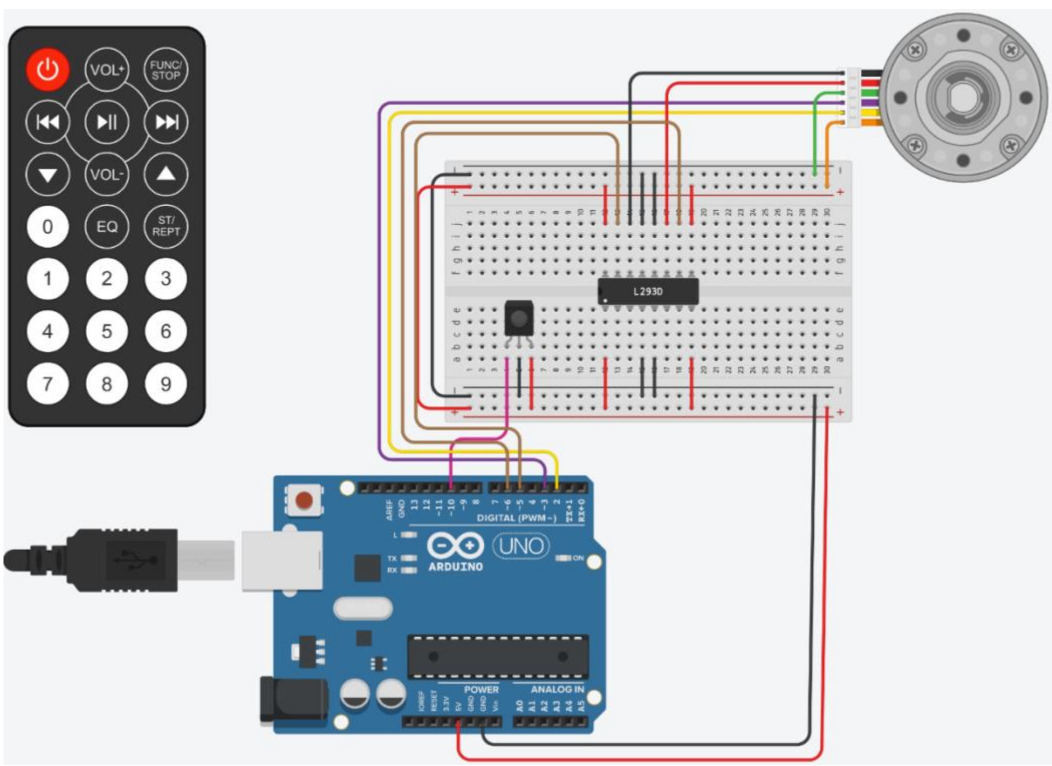

Figure 7) Friendly view of Wiring Schematic

Figure 8 shows the basic setup design of the software that will be installed onto the Arduino microcontroller. The set-up method will initial data that is necessary for the system to function. The loop method will run all the actions that are needed for the system to function properly.

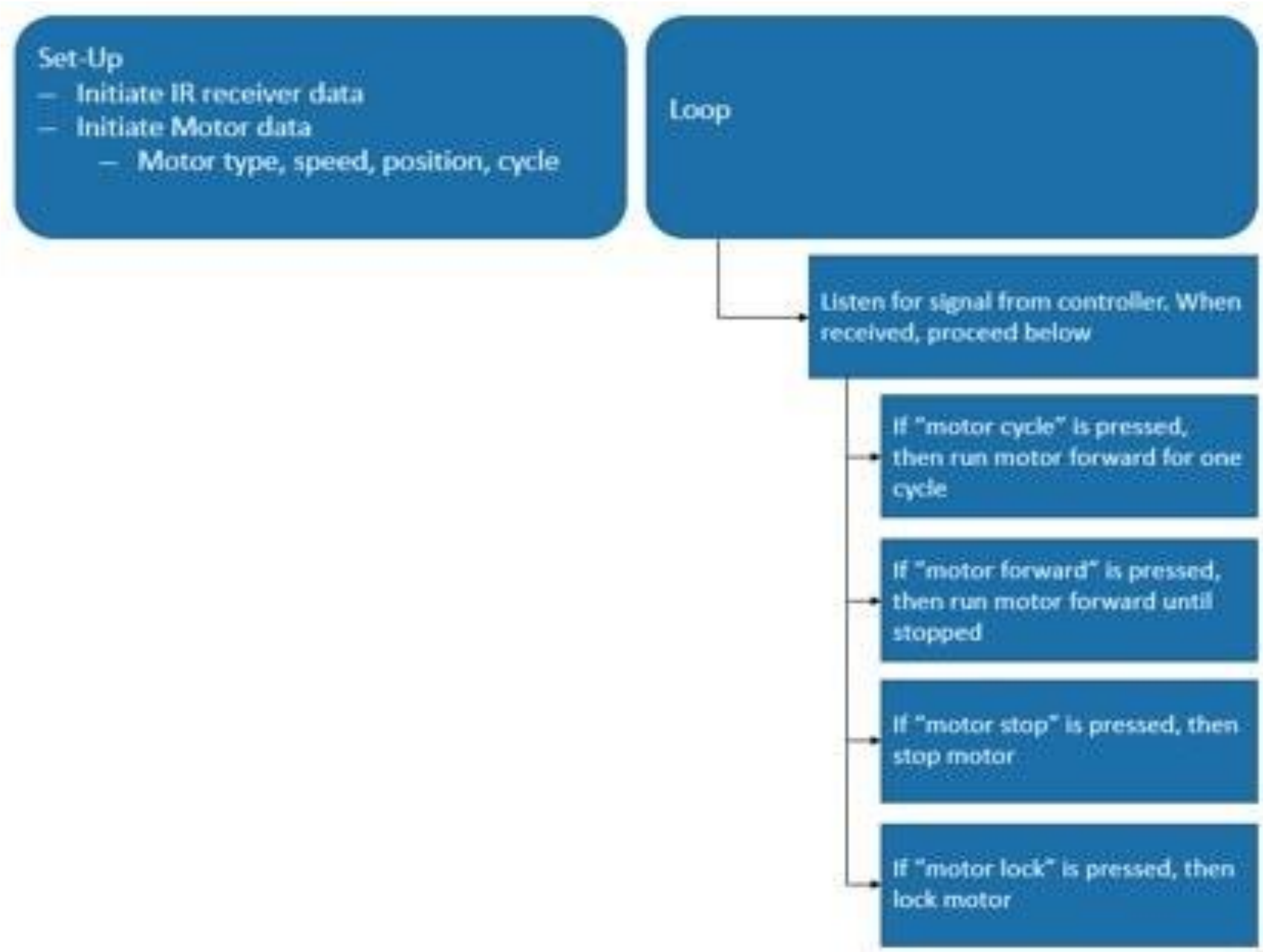

Figure 8) Software Flowchart

3.1.6) Rack Pickup/Drop-off

The rack pickup/drop-off mechanism [4], pictured in Figure 9, will move along the gear system and bring one package into the frame as well as dropping off any package in the third slot. The rack is made of layers of tempered hardboard adjoined with slow-cure epoxy. Brushes are used to pick up the smallest package sizes and push them along the system. The three compartments are 9x9 to give enough clearance to pick up a 6x6x4 inch package. The 9"x9" compartment will allow the operator additional space to increase the chances of picking up the package. In addition, there will be an Arduino controller to send the signal to the package pickup device signaling the pickup or drop off a package. It will be placed on the underside of the plate attached to the helicopter.

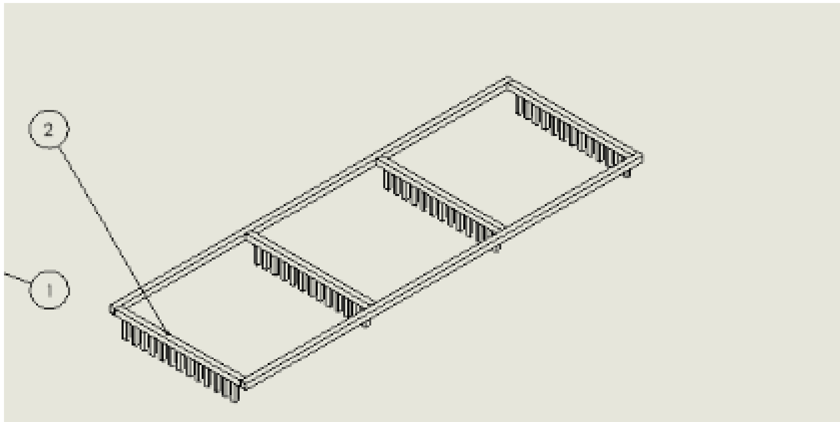

Figure 9) Rack Pick-up/Drop-off

3.2) Design Justification

3.2.1) Worm gear motor justification

The worm gear motor that was used for this project is rated at 70 kg/cm and there is one for each side of the rack. To prove that this was enough torque for the application, an FBD was drawn, as seen in Figure 10, and calculations were done based on the size of the sprocket and the potential max weight of the package. The force the motor needed to overcome was the friction force from the package and with an assumed worst coefficient of friction of .4 and a max weight of 15 lbs. the motors needed to overcome a 6 lb. force to move the largest package. With a 70 kg/cm, or 390 lb./in torque rating and a .5 in radius sprocket this is easily achieved by the motors

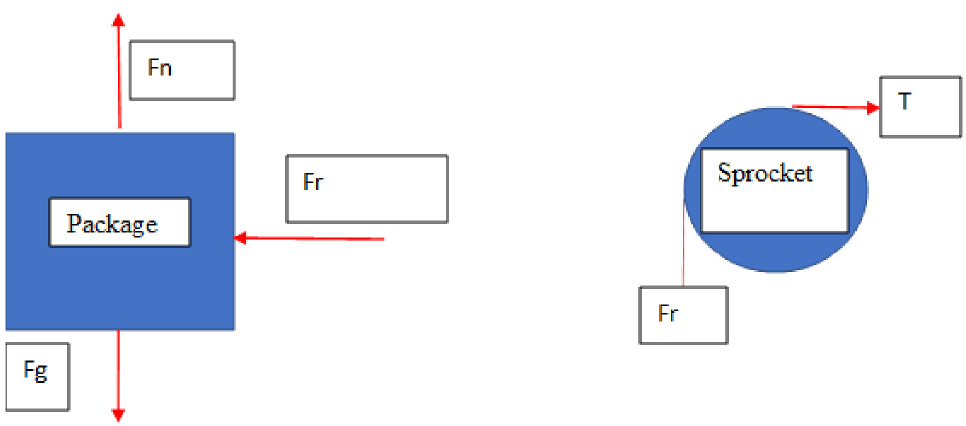

Figure 10) Free Body Diagrams of Package and Sprocket

3.2.2) Helicopter Lift Justification

MATLAB was utilized to calculate the overall lift produced by the blades since the sections of the blades farther away from the center are moving at a greater velocity in relation to the surrounding air, as seen in Figure 11.

```
clear all;
clc;
%all si units           %Dimensions
omega = 2500*2*pi/60;   %rpm to rad/s
r = 0;                  %m
v = omega*r ;           %m/s
Density = 1.175;        %kg/m^3
Cl = 1.0;               %none
length = .055;          %m
lift = 0;               %N
liftG = [1 2 3];        %for graphing
c = 1;
%Finds lift of each increment of the wing and adds them together
for i = 0:.001:.52
     v = omega*r;
     lift = lift + .5*Cl*Density*v^2*(.055*.001)
     r = r + .001;
     liftG(c) = .5*Cl*Density*v^2*(.055*.001);
     c = c + 1;
end
```

Figure 11) MATLAB code used to calculate potential lift of helicopter.

The total lift obtained per blade is 104.099 N, resulting in a total of 46.76 lb. Based off the calculations, the Trex 600E can lift 46 lbs. The entire device with everything included (Helicopter, Package pickup device, Rack, and Batteries) is 18.8 lbs. and will be picking up a maximum of 5 lb. packages making it a total of 23.8 lbs. Based on the calculations, the helicopter has enough lift to pick up itself and all the parts of the system.

Theoretical lift calculations are based on idealized conditions, assuming that the lift generating surface is perfectly smooth, rigid and without deformations. However, in real life, several factors can affect lift and cause deviations from theoretical predictions. For example, friction between a lift-producing surface and the surrounding fluid can reduce lift by dissipating energy and creating turbulence. Eccentricity or uneven weight distribution can also affect lifting capacity because it can create an imbalance that reduces the production efficiency of the lift. In addition, blade deformation due to stresses and strains can affect lift by changing surface geometry and force distribution.

3.2.3) Chassis Structural Analysis

After the subject matter experts and client voicing concern over the structural integrity of the chassis, a Finite Element Analysis was performed, in Figure 12 and 13, on the chassis of the helicopter made of carbon fiber and the top plates connecting to the rotor are made of 6061 T6 Aluminum alloy. In this FEA, a load of 140N was applied to the four screw holes on the bottom and fixed the sides of the chassis. 140N was chosen as the load, which is roughly 30 pounds, to make sure even at the upper limit of the weight the chassis will not fail. After the test, the conclusion was that the chassis is strong to hold up even more than 30 pounds as the Yield Strength was 9.35e+8 Pa and the largest stress the chassis would be under is 5.810e+7 Pa.

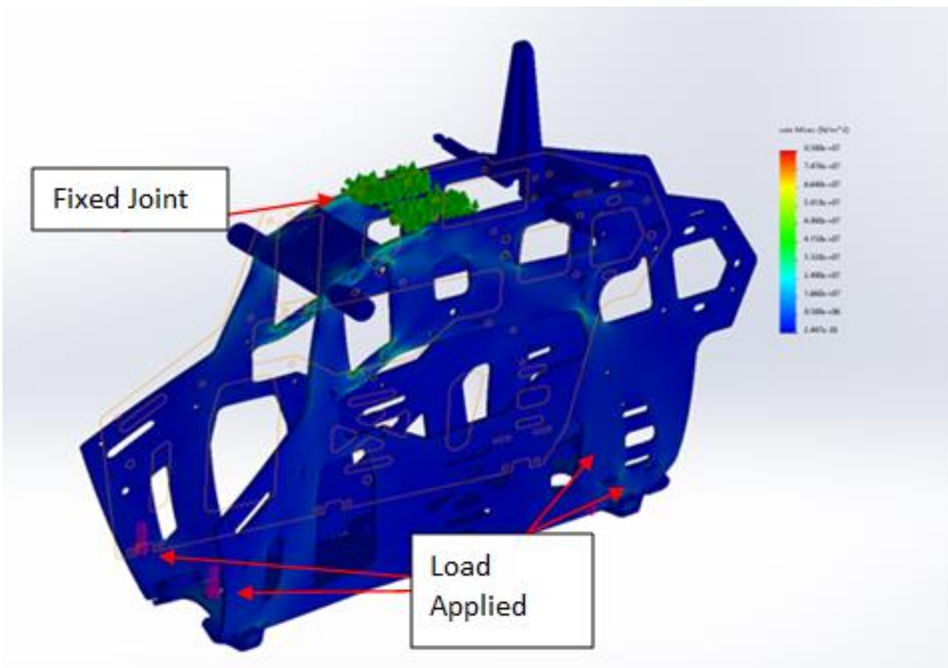

Figure 12) Stress Analysis of Helicopter Chassis

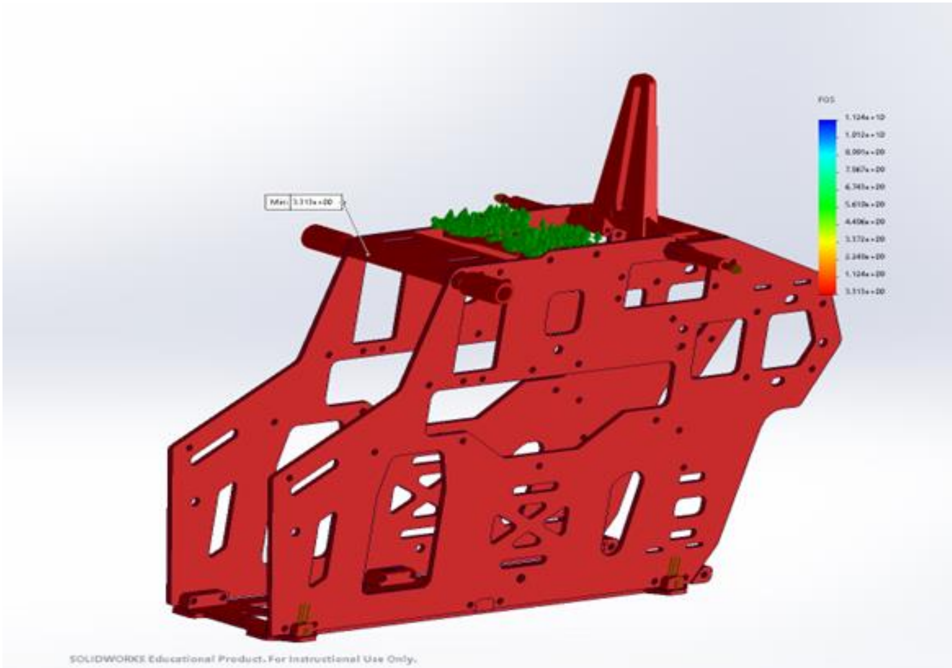

Figure 13) Factor of Safety Analysis of Helicopter Chassis

The minimum factor of safety was 3.313. This is safe however many components were taken away to make the FEA as simple as possible, and as more parts are included in the model it will become more structurally stable. In conclusion, the results from the FEA show that the chassis of the helicopter is very capable of withstanding expected loads during normal operation.

3.2.4) Pick-up Device Structural Analysis

Due to the significant difference in material strength between aluminum and balsa wood, the balsa components were seen as potential weak points and thus required further analysis. A static study was conducted where a 30lb load would be distributed over a small area, in the middle of the floor to simulate a worst-case scenario. The model is fixed by the surfaces that are attached to the frame. The results are shown in Figure 14 and resulted in a minimum factor of safety of 2.4, showing that the floor should be strong enough to withstand any loads it would be subjected to in normal operation.

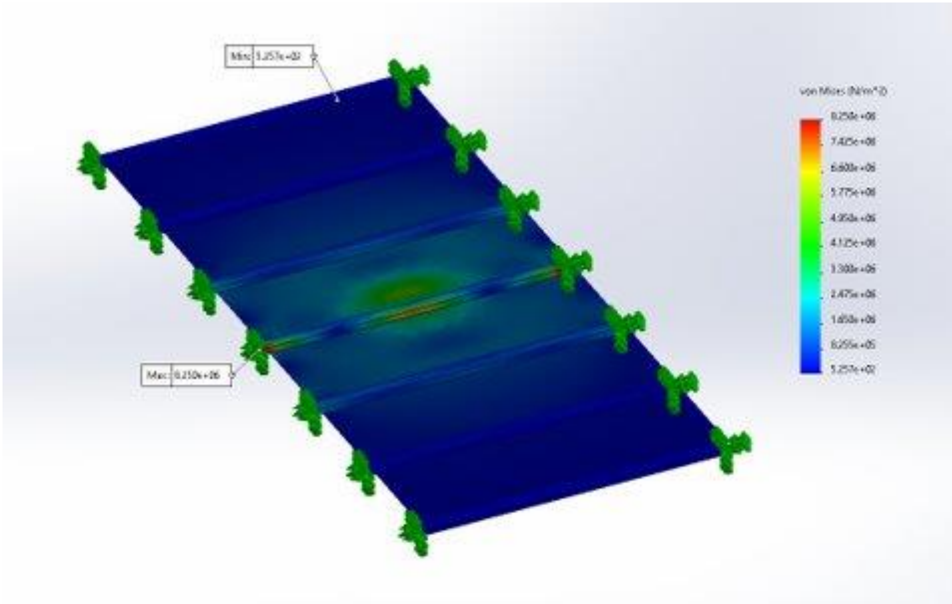

Figure 14) Stress Analysis of Floor in Package Pick-up Device

The structural stability of the aluminum was also questioned. To prove they were strong enough for any loads the device would encounter during operation, a static simulation was run to prove analytically, the aluminum is strong enough. In the simulation seen in Figure 15, both ends of the beams were fixed and a total of 30 lb. was applied where the helicopter is attached to the package pickup device to simulate the worst-case scenario for these load-bearing beams.

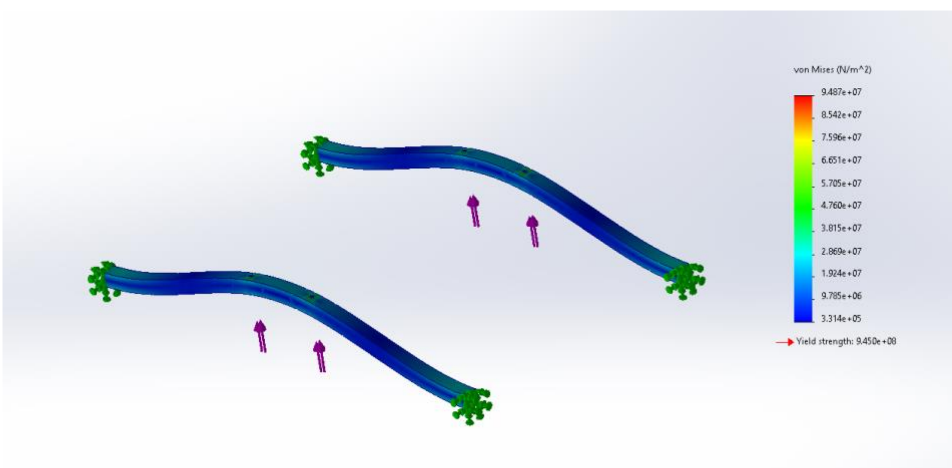

Figure 15) Static Displacement Analysis of interface tubing

From the analysis, the minimum factor of safety of 10 and a max displacement of .3mm. This shows the material used is strong enough to not yield during operation and that the deflection of the beams will not interfere with any other parts of the design.

3.3) Standards

There are many standards that engineers must consider when starting a project. For example, when using Lipo batteries, some relevant standards like IEEE 1725: standard for rechargeable batteries for cellular telephones or IEEE 1625 standard for rechargeable batteries for multi-cell mobile computing devices should be looked at. For this project, it was not necessary to use these standards as the helicopter was manufactured to operate with certain lipo batteries which the main company had involved their own set of standards they found. Another standard that this project could consider would be ASME B291.1: Roller chains, Attachments, and sprockets. This standard was used to help design the sprocket and chain assembly to achieve quality performance.

3.4) Safety and Reliability

Several features were incorporated into the design of the product to guarantee its safe and dependable operation. First, to make sure the sprocket and chain assembly could withstand the required loads and stresses, they were designed and tested. In order to achieve quality performance and reduce the danger of failure, ASME B291.1 requirements were adhered to.

Second, safety was considered in the design of the pickup device. The wood flooring and aluminum slotted beams offer a stable and safe platform for the transportation of packages. To prevent items from sliding during shipping, the wood flooring was coated with a non-slip coating, and the beams were carefully chosen for their strength and endurance.

Thirdly, careful consideration was given to the use of LiPo batteries to ensure dependable and secure operation. The batteries were obtained from reliable suppliers that follow IEEE guidelines for multi-cell rechargeable batteries for mobile computing devices. Before every use, the battery charger for the helicopter and the receiver were both pre-inspected to make sure they were in good condition and free from damage.

Finally, the main safety concern for the design is the main rotor blades of the helicopter. To ensure there is no injury or damaged property it is necessary to pilot this product with nothing in a 10ft radius besides any packages staged to be retrieved.

Although no FMEA was performed for this project, it is possible to calculate a critical RPN value for each potential failure mode to identify which failure modes require the most urgent corrective action. This would enable design modifications to lower the likelihood of failure and raise the product's level of safety and dependability.

4.0) Design Validation

4.1) Compliance Matrix

This is the compliance matrix for the product. Its purpose is to document each requirement, threshold and objective that the device needs to complete. The specification and accepted outcome are followed by how the specification was tested and the result of the test as well as its final pass or fail score.

Table 1) Threshold Requirements Compliance Matrix

Threshold Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass/Fail	Notes
1.1	Drone is no larger than 3' x 3' x 3'	Volume occupied by drone is no larger than 3’ x 3’ x 3’	Inspection using measuring tape, SolidWorks	Unit is small enough	Pass	N/A
1.2	Drone weighs less than 40 lbs.	Weight is less than 40 lbs.	Inspection with weight scale	18.75 lbs	Pass	N/A
1.3	Drone is quieter than 120 dB at full power ~10' away	Drone is quieter than 120 dB at full power ~10' away	Inspection with decibel meter	Unit is significantly quieter than a plane taking off	Pass	N/A
2.1	Drone should be capable of picking up a 1" x 1" x 0.5" min package size	Drone picks up a 1" x 1" x 0.5" package with no issues	Verify by testing	Unit can achieve this task	Pass	N/A
2.2	Drone should be capable of picking up a 6" x 6" x 4" max package size	Drone picks up a 6" x 6" x 4" package with no issues	Verify by testing	Unit can achieve this task	Pass	N/A

Threshold Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass/Fail	Notes
2.3	Drone should pick up package(s) weighing up to 5 lbs.	Drone picks up a 5 lb. package with no issues	Analysis, as well as testing	Unit can pick up packages up to 15 lbs	Pass	N/A
2.4	Drone should not damage package(s)	Package is undamaged after pickup and delivery	Inspection of characteristics of design	Unit does not damage packages when operated properly	Pass	N/A
2.5	Drone should pick up package(s) from a single loading zone	Drone picks up a package from one loading zone.	Inspection of package pickup method	Unit can achieve this task	Pass	N/A
2.6	Drone should drop off package(s) from 5 drop off zones	Drone drops off package at multiple drop off zones.	Inspection of system procedures and operational capabilities	Unit can achieve this task	Pass	N/A
3.1	Drone can operate in environments from 40F to 100F	Drone operates in any temperature range between 40F and 100F	Evaluation and inspection of individual components to show functionality in temperature range. Include vendor spec	All individual components are verified for this temperature range	Pass	See section 4.3
3.2	Drone should operate indoors or outdoors	Drone can operate both indoors and outdoors	Inspection- no design characteristics will inhibit either indoor or outdoor performance	Unit can achieve this task	Pass	N/A

Threshold Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass/Fail	Notes
3.3	Drone should operate at daytime	Drone operates during daytime	Inspection	Unit can achieve this task	Pass	N/A
3.4	Drone should be capable of operating in winds up to 5MPH	Drone operates in 5MPH wind with no issues	Inspection, summary of system operation, prior testing	Unit has flown successfully in 10+ mph winds	Pass	Videos available upon request
4.1	Drone should pick up package within 5 minutes of need indication	Drone picks up package within 5 minutes of indication	Inspection of system speed	Unit runs a pick-up cycle in 90 seconds	Pass	Allows flying time tolerance of 210 seconds
4.2	Drone should drop off package within 10 minutes of pickup	Drone drops off package within 10 minutes from pickup	Inspection of system speed	Unit runs a drop-off cycle in 90 seconds, up to 270 seconds	Pass	Allows flying time tolerance of 330 seconds
4.3.1	Drone should be capable of picking up within a 4' diameter clear zone	Drone picks up package in a 4' diameter clear zone	Inspection, 3d model drawing	Unit can achieve this task	Pass	N/A
4.3.2	Drone should be capable of delivering within a 4' diameter clear zone	Drone drops off package in a 4' diameter clear zone	Inspection, 3d model drawing	Unit can achieve this task	Pass	N/A

Threshold Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass/Fail	Notes
4.4.1	Drone should pick up package from ground level	Drone picks up package from ground level	Verify by test	Unit can achieve this task	Pass	N/A
4.4.2	Drone should drop-off package from ground level	Drone drops off package at ground level	Verify by test	Unit can achieve this task	Pass	N/A

Table 2) Objective Requirements Compliance Matrix

Objective Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass /Fail	Notes
1.2.2	The unit shall weigh no more than 25 lbs	Weight is less than 25 lbs.	Inspection with weight scale	Unit weighs 18.75 lbs	Pass	N/A
2.4.1	The unit shall be capable of picking up "packages" that do not have square corners.	Picks up packages that do not have square corners	Inspection of system functionality, test	Unit picked up several non-square corner packages on Test day	Pass	N/A
2.5.4	The unit shall be capable of picking up "packages" from any location within the pre-defined mission area.	Picks up packages at any location requested	Inspection of system operational procedures	Unit can achieve this task	Pass	N/A

Objective Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass /Fail	Notes
2.6.4	The unit shall be capable of dropping off packages at any location within the pre-defined mission area.	Drops off packages at any location requested	Inspection of system operational procedures	Unit can achieve this task	Pass	N/A
2.7.4	The unit shall be capable of carrying three packages to three destinations.	Picks up three separate packages, delivers to three destinations	Inspection of system operational procedures, demonstration	Unit has 3 package slots and cyclical package pickup system	Pass	Verified during Test day
2.7.6	The unit shall be capable of picking up additional packages to be delivered to multiple destinations.	Picks up additional packages and delivers to various destinations	Inspection of system operational procedures, demonstration	Unit has 3 package slots and cyclical package pickup system	Pass	Verified during Test day
3.2.2	The unit shall be capable of operating both indoors and outdoors in a single mission.	Operates indoor and outdoor in one mission	Inspection- no design characteristics will inhibit either indoor or outdoor performance in a single mission	Unit can achieve this task	Pass	N/A
3.4.2	The unit shall be capable of operating in winds up to 10 MPH	Drone operates in 10 MPH wind with no issues	Inspection, summary of system operation, prior testing	Unit has flown successfully in 10+ mph winds	Pass	Videos available upon request

Objective Requirements Compliance Matrix						
Ref.	Final Specifications	Acceptable Outcome	Verification Method	Test Result	Pass /Fail	Notes
4.4.3	The unit shall be capable of picking up from locations on the second floor of a building.	Picks up package from an elevated position, similar to a second floor of building	Inspection, demonstration	Unit has flown to elevations of 10+ feet successfully, and capable of landing and picking up packages at that height	Pass	It is valid to note although capable, opportunities were not provided to demonstrate
4.4.6	The unit shall be capable of delivering to locations on the second floor of a building.	Drops off package from an elevated position, similar to a second floor of building	Inspection, demonstration	Unit has flown to elevations of 10+ feet successfully, and capable of landing and delivering packages at that height	Pass	It is valid to note although capable, opportunities were not provided to demonstrate

4.2) Verification Methods

What follows is the detailed testing for each of the requirements achieved by this device. All reference numbers relate back to Table 1 and 2 above.

Ref 1.1

The project specifies that the drone should not be larger than 3’x3’x3’ prior to operation. The drone can deploy or articulate devices/components during operation. The verification process will proceed as follows, as seen in Figure 16:

Figure 16) Helicopter blade position and angle

1. Fold helicopter blades to have a 45-degree angle between the two main blades.
2. Rotate the folded blades behind the nose of the helicopter as shown in figure 1.
3. The drone will be placed diagonally in a 3’ x 3’ x 3’ box prior to operation with the tail in one end of the box.
4. See if drone fits within the box prior to operation.
5. Begin operation and start up drone from this starting position.

Ref 1.2

The project specifies that the drone should not weigh more than 40 lbs. This can be verified by performing the following steps, as seen in Figure 17.

1. Place drone onto a weight scale
2. Record weight shown.
3. Inspect and determine if the weight of drone is greater than 40 lbs.

Figure 17) Weight measurement of the complete system

Ref 1.3

The project specifies that the drone should be quieter than approximately 120 dB from a range of ~10’ from device. The verification process will proceed as follows:

1. Place drone on ground
2. Stand ~10’ away from drone
3. Have sound tester ready for use.
4. Turn on drone and then receiver from figures 2 and 3.
5. Hover drone at 4 ft above ground.
6. Record dB while drone is operating.
7. See if recorded dB is greater than 120 dB.

Ref 2.1

The project specifies that the drone should pick up a package that is at least 1” x 1” x 0.5” in size. The verification process will proceed as follows:

1. Place a 1” x 1” x 0.5” package at 3” in front of drone.
2. Turn on drone device along with AA battery pack container.
3. Press the key fob “A” button once to pick up package as shown.
4. Observe the device picking up the package.

Ref 2.2

The project specifies that the drone should pick up a package that is at most 6” x 6” x 4” in size. The verification process will proceed as follows:

1. Place a 6” x 6” x 4” package 3” in front of drone.
2. Turn on drone device along with AA battery pack.
3. Press the key fob “A” button once to pick up package.
4. Observe the device picking up the package.

Ref 2.3

The project specifies that the drone should pick up a package(s) weighing up to 5lbs. The verification process (hand calculation and analysis) will proceed as follows:

In order to demonstrate the helicopter's capacity to lift the intended weight, it is necessary to determine the amount of lift it can produce. This calculation begins by determining the Reynolds number, Figure 18, for the air in which the helicopter will be operating, at a temperature of around 70 degrees Fahrenheit.

$$Re = \frac{\rho u L}{\mu}$$

Re = reynolds number
ρ = density of the fluid
u = flow speed
L = characteristic linear dimension
μ = dynamic viscosity of the fluid

Figure 18) Reynolds Equation used to calculate projected lift

Air density at 1 bar and 22°C is 1.175 kg/m^3

L = blade cord = .055 m

μ = 1.19 kg/m/s

The range of the Reynolds number is determined to be between 2.0 to 3.0 x 10^5 due to the fluctuating velocity of the blade. It is important to consider the changing rotor speed when calculating the lift. The website airfoiltools.com can provide us with the coefficient of lift (CL) based on the blade's angle of attack. A coefficient of lift of 1.0 can be achieved at an angle of attack of approximately 10°, which is close to the maximum angle of attack that can be utilized without causing stalling.

After determining the suitable angle of attack from Figure 19, the next step is to input the relevant values into the lift equation.

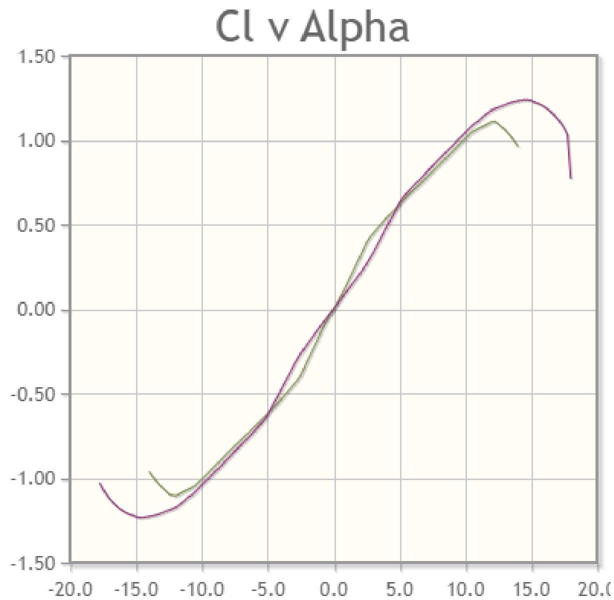

Figure 19) Lift Coefficient vs Rotor Angle of Attack

MATLAB, as seen in Figure 20, was utilized to calculate the overall lift produced by the blades since the sections of the blades farther away from the center are moving at a greater velocity in relation to the surrounding air.

```
clear all;
clc;
%all si units              %Dimensions
omega = 2500*2*pi/60;      %rpm to rad/s
r = 0;                     %m
v = omega*r ;              %m/s
Density = 1.175;           %kg/m^3
Cl = 1.0;                  %none
length = .055;             %m
lift = 0;                  %N
liftG = [1 2 3];           %for graphing
c = 1;
%Finds lift of each increment of the wing and adds them together
for i = 0:.001:.52
     v = omega*r;
     lift = lift + .5*Cl*Density*v^2*(.055*.001)
     r = r + .001;
     liftG(c) = .5*Cl*Density*v^2*(.055*.001);
     c = c + 1;
end
```

Figure 20) MATLAB code used to calculate potential lift of the helicopter.

The total lift obtained per blade is 104.099 N, resulting in a total of 46.76 lb.

Ref 2.4

The project specifies that the drone should not permanently damage the package during operation. The verification process will proceed as follows:

1. Place a package 3” in front of drone.
2. Turn on drone device along with AA battery pack as shown in figures 2, 3, and 4.
3. Press the key fob “A” button once to pick up package.
4. Allow the rack to make one full cycle.
5. Press the key fob “A” button once to move package to next slot.
6. Repeat steps 4 and 5 until the package is out of storage.
7. Inspect the package for any permanent damage.

Ref 2.5

The project specifies that the drone should pick up package(s) from a single loading zone. The verification process will proceed as follows:

1. Place helicopter at least 4’ away from designated loading zone in a clear operating zone.
2. Turn on drone device, receiver, along with AA battery pack as shown in figures 2, 3, and 4.
3. Fly helicopter to designation.
4. Land in front of the package at 3” maximum.
5. Run the package delivery device cycle to pick up the package(s) by pressing key fob “A”.
6. Allow the rack to make one full cycle.
7. Fly to the next loading zone with the package inside.

Ref 2.6

The project specifies that the drone should drop off package(s) from 5 different drop off zones. This is shown in Figure 21. The verification process (Analysis of system procedures and operational capabilities) will proceed as follows:

Figure 21) Sequence images of package exiting the rear of the package device

Based on system drop off procedure, nothing is preventing drop off in at several varied locations

Ref 3.1

The project specifies that the drone can operate in environments from 40F to 100F. The verification process (Analysis, Inspection) will proceed as follows:

The components that make the helicopter fully function in 40F degree temperatures as well as 100F temperatures are the Arduino and the Lipo batteries. According to their manuals, the Arduino Rev 3 can withstand temperatures from –40F to 185F. The Lipo Batteries function properly in temperatures from 32F to 104F. All other parts of the helicopter will function if these two components are in range of its Min and Max temperatures. One last component that is also important is the two Servo Motors. Heat has an impact on both the permanent magnet and the winding of these motors. At about 160ºC, neodymium magnets begin to demagnetize and lose strength. Unfortunately, the effect is permanent, and cooling the motor does not undo it. An insulating varnish covers the winding, offering stability in addition to insulation. Above 160ºC, the varnish begins to soften, and the winding may become deformed. This rubbing wears down the insulation and results in a short circuit and motor failure. The varnish and insulation may melt at extremely high temperature increases, resulting once more in a short circuit.

Ref 3.2

The project specifies that the drone can operate indoors or outdoors. The verification process (inspection and analysis) will proceed as follows:

No design characteristics will inhibit either indoor or outdoor performance. No exhaust prohibiting operation in enclosed space. No communication or transmission issues either. The vehicle does not rely on solar energy or guidance of the sun. The helicopter and rack system are both powered by independent battery systems. The helicopter system can be controlled well enough for safe flight indoors. Since the device needs no adjustments to be able to operate indoors and outdoors, the device can operate in both environments in a single mission.

Ref 3.3

The project specifies that the drone can operate during the daytime. The verification process will proceed as follows:

The package delivery drone is designed to operate in the daytime. Additionally, it will be able to operate during the nighttime since there are no components of the device that are dependent on factors only found during the daytime. The navigational system is fully dependent on the operator. The power sources found onboard are batteries. No power source is dependent on daytime factors, such as solar panels. Since the device needs no adjustment to operate during the nighttime, the dive can operate in both daytime and nighttime.

Ref 3.4

The project specifies that the drone can operate in winds up to 5 mph. The verification process will proceed as follows:

1. Locate safe, outdoor operating environment.
2. Check local wind speeds or measure wind speeds to ensure 5 mph winds are present.
3. Place packages in the environment.
4. Fly device to packages.
5. Pick-up packages.
6. Fly to next location.

Ref 4.1

The project specifies that the drone should pick up package within 5 minutes of need indication. The verification process (analysis) will proceed as follows:

The package delivery drone is designed to operate as quickly as possible. The furthest range this device is expected to operate in is 100 yards. One cycle of the rack system is calculated to be 89 seconds. This means that the device must travel 100 yards in 3 minutes and 31 seconds to the pick-up location. To achieve this, the helicopter must travel at approximately 0.5 yards per second. This speed is equivalent to 1 mph.

A fully stocked TREX 450 RC helicopter with full battery charge and no package device is reported to be 45mph. The helicopter for this device is the TREX 600, a more powerful version of the 450. Therefore, it is safe to assume that the TREX 600 will achieve travelling speeds of 45 mph and greater.

Considering the 1 mph travel speed necessary to travel the distance in the allotted time and the forward speed capabilities of the TREX 600, it can be concluded that this package delivery drone will be able to reach a pick-up destination, 100 yards away, within 5 minutes of indication.

Further verification can be done by operating the device in such conditions.

Ref 4.2

The project specifies that the drone should drop off package within 10 minutes of pickup. The verification process (analysis) will proceed as follows:

One cycle of the rack system is demonstrated and tested to be 89 seconds. After pickup, the package pickup device must run 3 more times after pickup to deliver the package. This means the drop off process will take 4.5 minutes. Considering the flying device can meet the allotted time in less than 5 minutes, this requirement will be met within 10 minutes of pickup.

Ref 4.3.1

The project specifies that the unit shall be capable of picking up within a 4' diameter clear zone. The verification process (analysis) will proceed as follows:

Figure 22 illustrates the delivery drone in a 4’ diameter zone. This top-down view of the 3d model verifies that the device can pick up a package within a 4’ diameter clear zone.

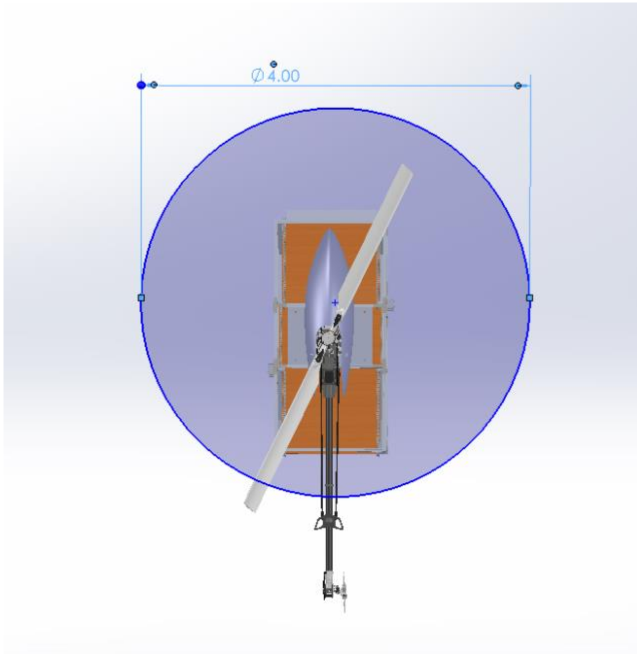

Figure 22) CAD inspection of helicopter rotor diameter

Note: The Package shall be in the clearance zone without any other items. The unit does not need to be confined to this clearance zone.

Ref 4.3.2

The project specifies that the unit shall be capable of dropping off a package within a 4' diameter clear zone. The verification process (analysis) will proceed as follows:

Figure 22 illustrates the delivery drone in a 4’ diameter zone. This top-down view of the 3d model verifies that the device is capable of dropping off a package within a 4’ diameter clear zone.

Note: The unit does not need to be confined to this clearance zone.

Ref 4.4.1

The project specifies that the drone should pick up packages from ground level. The verification process will proceed as follows.

1. Place package on ground level
2. Place drone in starting location at least 4’ away from package location.
3. Turn on drone and receiver.
4. Fly the drone to the package location and land in with the package in front of drone.
5. Press the key fob “A” button to pick up package at ground level.
6. Allow the rack to make one full cycle.

Ref 4.4.2

The project specifies that the drone should drop-off packages from ground level. The verification process will proceed as follows:

1. Place drone at starting place.
2. Place package into drone in the first slot of the rack.
3. Turn on drone and receiver along with AA battery pack.
4. Fly drone to a destination on ground level.
5. Press the key fob “A” button to move package into next slot.
6. Allow the rack to make one full cycle.
7. Repeat steps 5 and 6 until package is moved out of storage.

4.3) Discussion of Test Methods

The testing was conducted using a variety of verification methods, including inspections, measurements, and actual testing of the device's functionality. The results of these tests are presented in the "Test Result" column in the threshold requirements compliance matrix table and indicate whether the device met the specified criteria.

In terms of the relevant data, there are several key metrics that were measured or evaluated during the testing process. For example, the weight of the drone was measured to ensure that it was under 40 lbs., and the noise level was evaluated using a decibel meter to ensure that it was quieter than 120 dB at full power ~10' away. Other metrics that were evaluated include the device's ability to pick up and drop off packages of various sizes, its operating temperature range, and its ability to operate in winds up to 5 MPH.

Overall, the results of the testing indicate that the package pickup device met all the specified criteria and was deemed to be functional and reliable. This is reflected in the "Pass" column, which indicates whether the device passed each individual test.

The testing that was performed provides a strong indication that the package pickup device is functional and reliable and meets the specified criteria for operation. In addition to testing, several analyses were performed, such as to determine that the drone could operate between 40F and 100F, the drone’s ability to pick up packages within 5 minutes of indication, as well as the drone’s ability to pick up more than 5 lbs.

For example, the latter involves hand calculation and analysis of the drone's lift capacity. The calculation involves determining the Reynolds number for the air in which the drone will be operating, which was found to be between 2.0 to 3.0 x 10^5. Using the airfoiltools.com website, a coefficient of lift of 1.0 was found to be achievable at an angle of attack of approximately 10°.

MATLAB was utilized to calculate the overall lift produced by the blades, resulting in a lift capacity of 46.76 lbs., which is more than enough to lift a package weighing up to 5lbs.

Overall, the demonstration and testing of the drone's capability, along with the analysis and inspection of the drone's temperature limits, speed capabilities, and lift capacity show that the drone can perform its intended function. These results provide confidence in the drone's ability to perform its intended function reliably and effectively.

5.0) Prototype Construction

5.1) Bill of Materials

Table 3) Bill of Materials

Item #	Item Description	Vendor/URL	Model/Part #	Qty	Unit Cost	Total Price
1	Double Sprockets w/D shape hole ~8mm	UTDesign	NA	2	$0.25	$0.50
2	Double Sprockets w/.375 diameter hole	UTDesign	NA	2	$0.25	$0.50
3	Ramp	UTDesign	NA	1	$2.00	$2.00
4	Electronic Housing	UTDesign	NA	1	$1.00	$1.00
5	Funnel Rod Connector	UTDesign	NA	2	$1.00	$2.00
6	Rack Screw Support	UTDesign	NA	6	$0.25	$1.50
7	Sprocket Support Bracket	UTDesign	NA	4	$1.00	$4.00
8	6mm m3 square head bolts 250 count	Amazon	NA	200	$0.06	$12.76
9	10mmx10mm straight braket for t slot beam 12 count	Amazon		4	$0.80	$3.20
10	3m 6mm wood screws	Home Depot		20	$0.40	$7.98
11	T bracket	Amazon		16	$0.67	$10.65
12	Corner bracket	Amazon		24	$0.80	$19.18
13	M3 regular nuts	Amazon		222	$0.03	$6.65
14	Arduino UNO Rev3	Amazon	7630049200050	1	$28.50	$28.50

Item #	Item Description	Vendor/URL	Model/Part #	Qty	Unit Cost	Total Price
15	Arduino Motor Shield Rev3	Amazon	7630049200371	1	$29.00	$29.00
16	Bringsmart 12V 12RPM DC high-torque, worm-gear motor. Rated for 70kg*cm	Amazon		2	$29.99	$59.98
17	Black 4-button keyfob remote controller	AdaFruit	1095	1	$6.95	$6.95
18	3V CR2016 Lithium Coin batteries	Energizer 2016 Batteries (2-Pack), 3V Lithium Coin Batteries 2016BP-2 - The Home Depot	2016BP-2	1	$3.44	$3.44
19	Amazon lithium ion AA High Batteries	Amazon	N/A	8	$1.85	$14.80
20	8x AA Battery Holder Box with Switch	Amazon	N/A	1	$6.99	$6.99
21	Madison Mill 0.5-in dia x 36-in L Square Poplar Dowel	Lowes	N/A	1.86	$1.99	$3.70
22	Align Trex 600E Pro helicopter	Align	AGNRH60E10X	1	$800.00	$800.00
23	Futaba T8FG Super 14ch Transmitter	Futaba	T8FGS24M1	1	$200.00	$200.00
24	Spektrum 22.2V 5000mAh 6S Smart LiPo Battery	Hobbytown USA	SPMX40006S50	1	$120.00	$120.00
25	acetal Resin white roller chain sprocket: .966 in Pitch Dia. 1/4 bore size, .375 width	SDP/SI	A 6M 7-2512	16	$3.75	$60.00
26	1-4 inch x 4ft brushes for rack	NorthShore Commercial Door		1	$8.44	$8.44

Item #	Item Description	Vendor/URL	Model/Part #	Qty	Unit Cost	Total Price
27	1500 x 10mm x 20 m aluminum bream	Maker Beam	101024	5	$15.17	$75.85
28	Maker Beam Corner Cube	Maker Beam	100270	4	$1.39	$5.56
29	Edgelec breadboard jumper wires, 20cm length, assorted kit	Amazon		14	$0.06	$0.81
30	103mm tail blade 3 blade set	AlignTrexShop		1	$43.99	$43.99
31	Align 550E/600E Three-Blade Tail Blade Set	Amain Hobbies		1	$66.99	$66.99
32	Brushless Motor	Heli Direct		1	$146.99	$146.99
33	Feathering Shaft	Heli Direct		1	$8.99	$8.99
34	Drive Gear	Heli Direct		1	$24.99	$24.99
35	Motor Mount	Heli Direct		1	$11.24	$11.24
36	Pinion Gear Mount	Heli Direct		1	$13.99	$13.99
37	Bearing	Heli Direct		1	$7.99	$7.99
38	#25 Roller Chain	Red Boar Chain	#25-1R-10FT	16	$1.68	$26.88
39	#25 connecting link	Red Boar Chain	25-C/L	6	$0.99	$5.94
40	Tempered Hardboard sheet	Home Depot	N/A	563	$0.01	$3.17
41	M2 by 50 mm screws 50 count	Walmart		4	$0.25	$1.00
42	M2 nuts	Walmart		8	$0.07	$0.52
43	Reinforcement Brace	Heli Direct		1	$26.99	$26.99
					Total Cost:	$1,820.61

5.2) Fabrication Process

For the fabrication of this device, there are no unusual manufacturing methods used for the creation of this product. The aluminum extrusion, wooden dowels, and hardboard are all cut to size according to their drawings. The ends of the cut aluminum extrusion are tapped with an M3 tap so the connector cubes can be attached, and the rest of the aluminum rods can be attached. The floor is assembled and attached together with M3 wood screws, purchased brackets, and wood glue. The straight, T, right angle, and corner brackets are attached with the T-head M3 screws and nuts as shown in drawings. The 25mm long T headed, M3 screws are used to hold the sprockets in place with some 3D printed parts meant to go over the M3 screws. A pin is removed in the chains, so

M2.5 screws can attach the rack to the chains. The rack is made by laser cutting layers of hardboard and using wood glue to bind the layers together. After this drill holes in the sides of the rack and attaching the rack with the added pin joints on the chain and the M2.5 nuts are used to keep the rack in place on the screws. The helicopter is attached to the package pickup device with M3 screws and brackets for extra structural stability.

6.0) Cost Summary

Category				Totals
		Materials	$3500	
		Services	$160	
		Non-Labor Subtotal		$3660
Labor Classifications	Loaded Rate	Hours	Cost	
Engineer	$100/hr.	1332	$133,200	
Team Mentor	$175/hr.	60	$10,500	
Engineering Director	$250/hr.	15	$3,750	
Staff	$60/hr.	30	$1,800	
		Labor Subtotal		$149,250
Grand Total				$152,910

The costs shown here reflect the actual costs of materials and services, while labor is based on hypothetical fully loaded rates for the various personnel involved in the project.

6.1) Materials

The main reason for the difference in the cost of the BOM and the total cost is because of the multiple iterations done for this project. The original idea for the frame was to construct it out of carbon fiber but with this came with many manufacturing issues and the adjustability that came with the aluminum made it the better option. There were many ideas that parts were bought for, but they were either not followed through or better solutions were found with other parts. In addition, many additional parts such as motor and tail blades were purchased for spare parts as a precautionary action.

6.2) Services

The only service charges that were incurred were shipping costs.

7.0) Conclusions and Recommendations

In conclusion, the team was able to make significant progress towards accomplishing most of the objectives for this project. The helicopter proved to be reliable throughout the year, except for the Lockheed Martin competition where a bent motor shaft prevented it from taking off. With the package pickup device, good piloting skills, and a fully functioning helicopter, the device was able to successfully pick up and deliver 3 packages, each weighing 5 pounds, to different loading zones.

Throughout this project, many challenges were faced with many learning curves. One of the main struggles that were encountered was selecting the right materials. While extensive testing and calculations were conducted, some materials that were calculated to work well turned out to be unsuitable in practice. Additionally, working with the helicopter was difficult at the beginning as none of our team members had experience with RC helicopters. However, with practice and confidence, our pilot was able to fly the helicopter safely and precisely.

Moving forward, if more time was allowed for this project, the first priority would be to replace the old motor with the new one which was ordered so that the helicopter is fully functional. In addition, there would be a need to upgrade the ESC (Electronic Speed Controller) to allow for a constant 100 amp current, which the new motor requires. Although the package pickup device is reliable and efficient, there is always room for improvement. For example, with some modifications to the chain and sprocket, it could make the mechanism run smoother to prevent squeaks and potential jams.

The project has provided a valuable learning experience for the team, with valuable insights gained into the design and implementation of autonomous delivery systems. The team is excited to apply these lessons to future projects.

8.0) References

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9.0) Appendix

9.1) Engineering Drawings

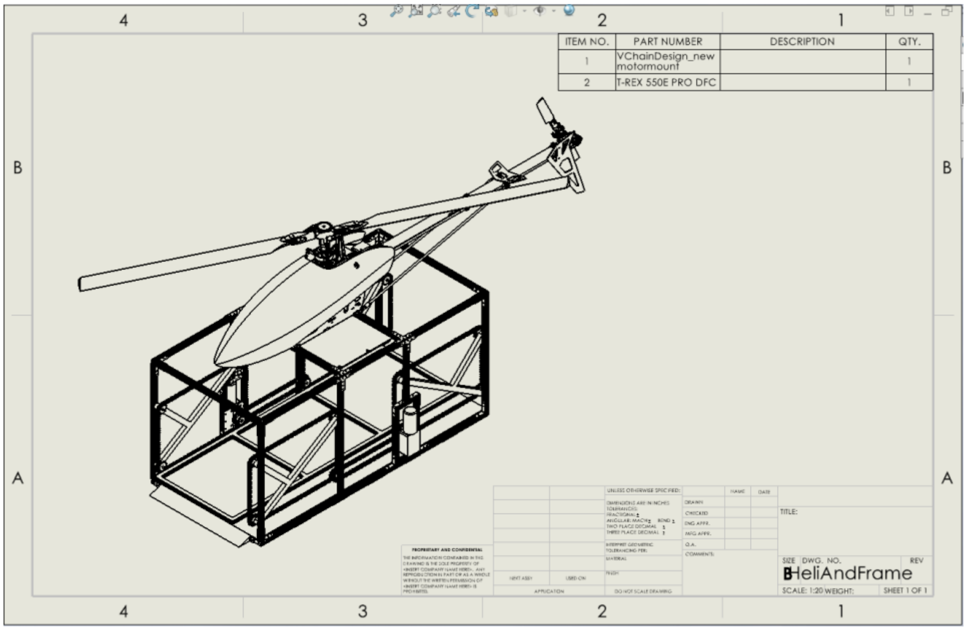

Figure 23) Full assembly drawing

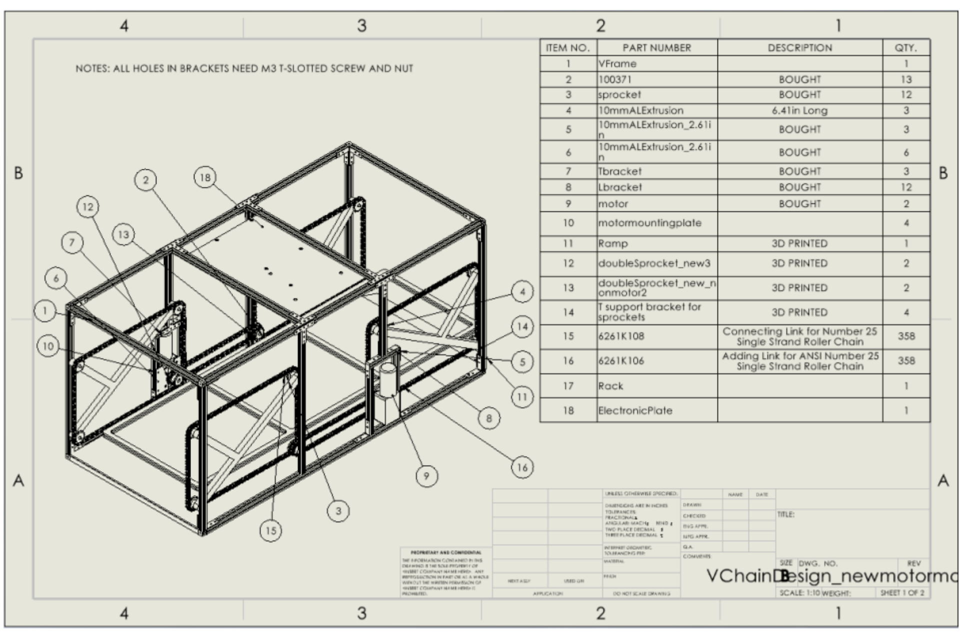

Figure 2424) Package Pickup Device Assembly

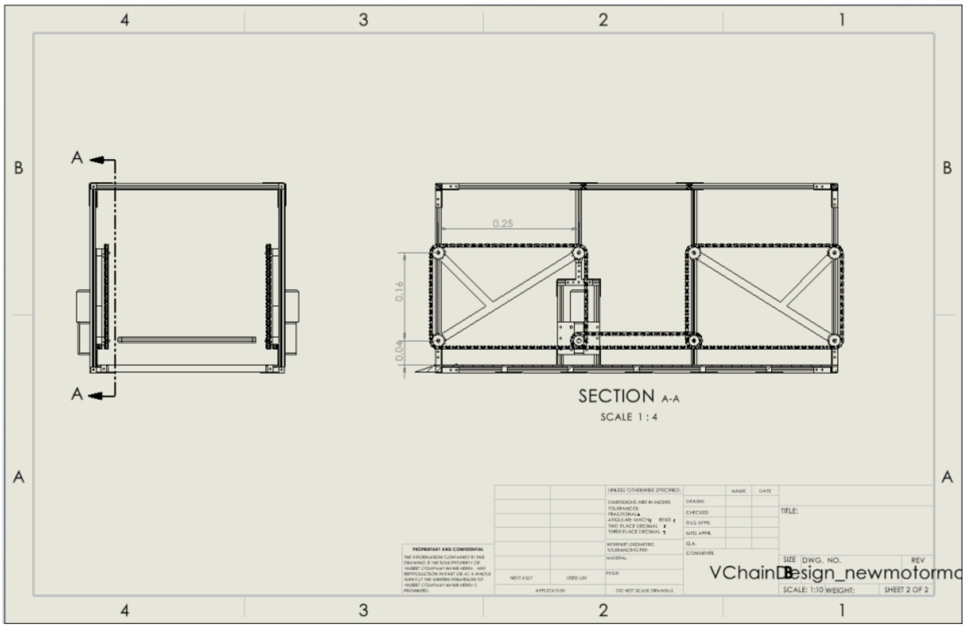

Figure 2525) Motor and Chain System

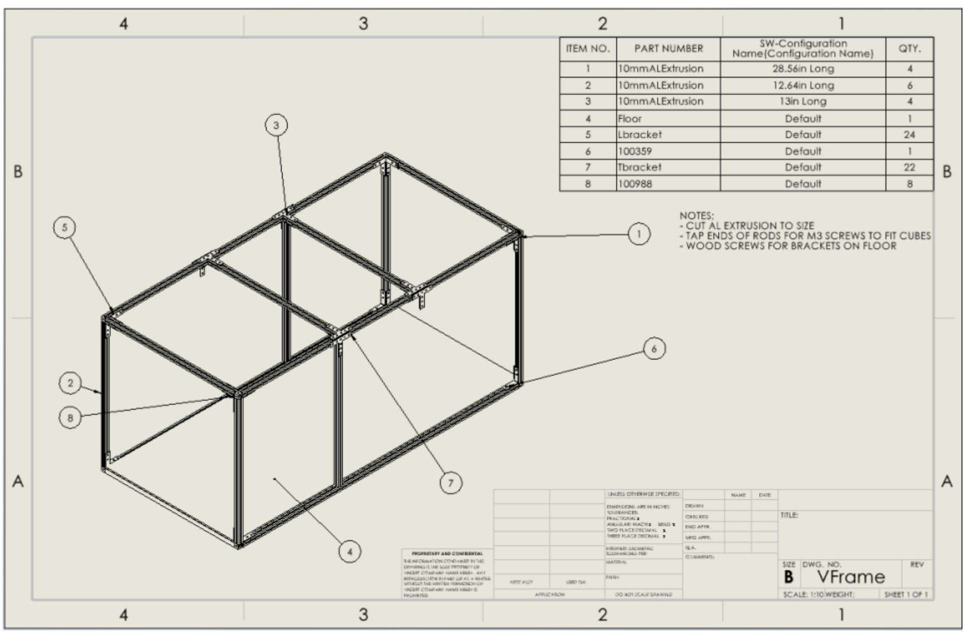

Figure 2626) Frame Subassembly

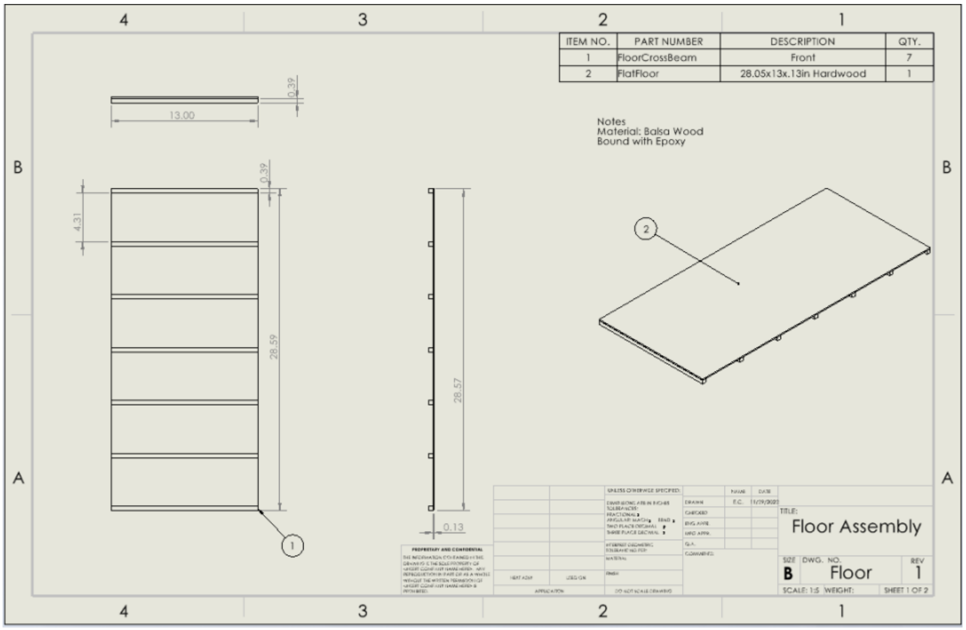

Figure 2727) Floor Subassembly

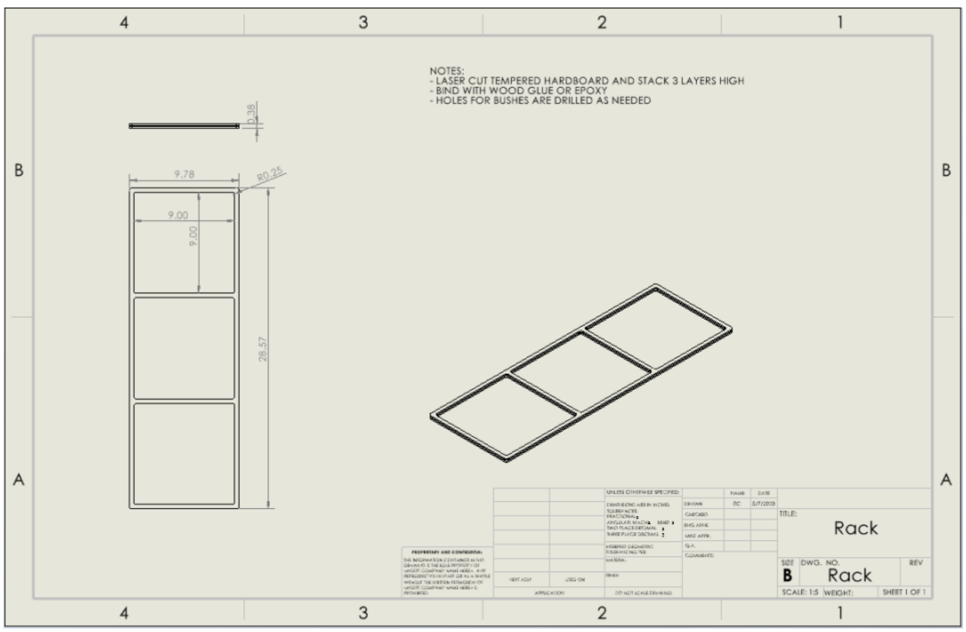

Figure 2828) Rack

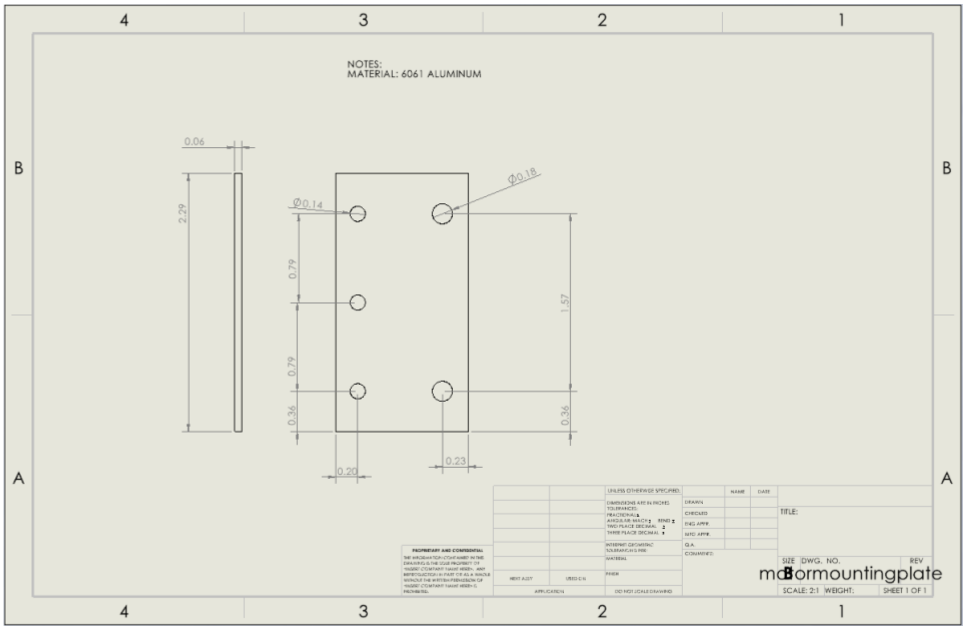

Figure 2929) Motor Mounting Plate

9.2) Motor Control System

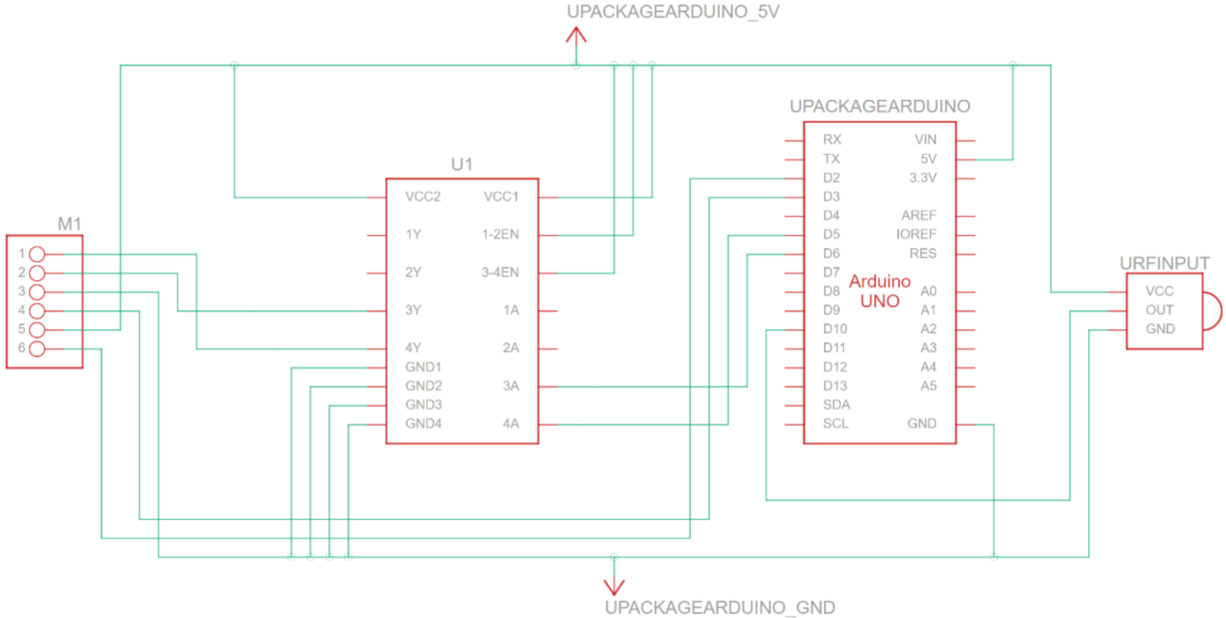

Figure 3030) Wiring Schematic for Package Control System

This schematic shows the wiring connections between the Arduino microcontroller, motor, motor driver, and RF sensor.