Boeing 3D-Printed Drone Frame Design and Optimization

Final Report

Team Hi-Jacks

Damien Brothers

Dante Faria

Jay Khunt

Colby Murphy

Thomas Schreiber

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NORTHERN ARIZONA UNIVERSITY

College of Engineering, Informatics, and Applied Sciences

Project Sponsor: Boeing

Sponsor Mentor: Michael Vogelsang, Amanda Nemec, Reed Esper

Instructor: Armin Eilaghi

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EXECUTIVE SUMMARY

The Boeing Company created the Boeing Drone Project to design and manufacture a drone frame for a quadcopter land surveying drone. The clients of the project are Boeing, Amanda Nemec, Michael Vogelsang, Reed Esper, and other employees of Boeing. The focus of this project was to target the frame weight and flight time. The main customer requirements for the project were reducing the weight to under 3lbs and increasing the thrust-to-weight ratio above 1.81. In addition, good component FOV, ease of manufacturing, frame strength, cost, and minimal hardware in the frame were also customer requirements.

In the first prototype, the team created a drone frame that consists of 3 circular discs, 4 spacers, 4 arms, and 4 legs. The 3 discs are placed parallel on top of each other and were separated by spacers (first and second discs) and arms (second and third). All the pre-purchased components would be placed on top of the first disk, between the discs, and below the third disk. The legs and motors were attached to the arms. The material used for the initial prototype was 100% PLA plastic with 50% infill. The first prototype the team created was with 3D printing and did not go as planned because of the weak material. The PLA plastic used in the 3D printing produced a fragile and ductile result.

The second prototype consisted of a stronger material, Onyx, and yielded much better results. Legs were added to this print, which were connected by a truss added to the spacers between the first two plates. The print was outsourced, which increased the quality, and no major adjustments were needed to manufacture the drone. On this prototype, all the components required for manual flight were added, and flight was achieved. After crashing a few times and breaking components, the team made several design iterations to arrive at the final prototype.

This prototype was printed during the second semester, and manufacturing also went smoothly. This prototype was used for testing, which was done to validate the given customer and engineering requirements. The drone succeeded in meeting all requirements, and the client was satisfied with the final product. In the future, the project could be expanded to work on the autonomy of the drone, or further reduce its weight.

ACKNOWLEDGEMENTS

Team Hi-Jacks gives a very special thank you to Amanda Nemec, Michael Vogelsang, Reed Esper, and all other employees from Boeing for being our clients and supporting the team every step of the way. The feedback and support given from these three clients throughout the last two semesters was nothing short of amazing. The organized visit to the Apache Helicopter plant in Mesa, AZ was above and beyond while the team cannot thank you enough for the generosity.

The whole team would also like to give a special thank you to Armin Eilaghi, David Willy, and Constantin Ciocanel for the time they committed outside of class time to help this team succeed. This includes material testing with special equipment such as an Instron machine, answering the teams' questions around the clock, and committing a Friday of their busy weeks to visit Boeing.

TABLE OF CONTENTS

Contents

1 BACKGROUND

1.1 Introduction

The Boeing Drone Project was created to analyze and optimize a surveying drone that is still in its early stages of design. This project was specifically created to enhance the current weight and flight time of the existing drone from Boeing. The sponsors of this project can benefit from this project by furthering their drone's ability to survey large plots of land without a worry of losing the contraption to battery depletion. Thrust to weight ratio is one of the main focuses of this project as the components in the body of the drone will be the only weight carried in flight. Stress tests will be excessively used on protypes of the drone body to ensure durability of the landing components as well as the safety of other components.

1.2 Project Description

This team was formed with the purpose of assisting the Boeing team in Mesa, AZ to create a fully functional, 3D printed body for a quad copter drone. The clients for this project would be The Boeing Company, Amanda Nemec, Michael Vogelsang, Reed Esper, as well as many other employees of Boing from around the country. They expect the team to create and test a functional drone body that is lightweight and can travel long distances for multiple purposes. They also expect the team to simulate multiple forms of drag and lift that are associated with the drone body.

The original project description was described by the sponsor as follows:

> Students will design, analyze, and manufacture a 3D printed drone frame that minimizes weight and maximizes flight time using a set commercially available motors, battery, rotor blades, and hardware suite. The design should be analyzed for adequate strength, lift performance, and flight duration while maintaining adequate space provisions for the mounting of a representative set of equipment (e.g., Jetson Nano GPU, Pixhawk PX4 flight controller, LiDAR, PM07 power management board, Arducam IMX477 PTZ camera and gimbal). Equipment not required and can be derived from available models or specification data. Stress and aerodynamic analysis can be performed using ANSYS or similar software. Load cases should include, but are not limited to, static, dynamic, and fatigue loads. Flight duration and power draw should be performed using both hand calculations and open-source analysis tools such as eCalc multi-copter. Other tools available and/or used by students are acceptable. Any recommendations for equipment or provisions are also acceptable. The focus is the design methodology and process to evaluate designs and take to prototype. The project supports tailoring and collaboration to ensure success for both students and Boeing.

2 REQUIREMENTS

To complete the objectives of the Senior Capstone project, every team is required to work on a given project that is assigned to the team. For Team Hi-Jacks, the project that was assigned was to work with Boeing and create a lightweight and sturdy drone frame. To better understand the assignment, a client meeting was held to get a grasp of all of the objectives that needed to be completed in order to make that goal achievable. The client for this project is the Boeing employees that are working to help the team create the lightweight drone frame with certain requirements that were given to the team. These requirements are a vital part of how to go about building the frame and doing so with the ideas to make it better than the original.

2.1 Customer Requirements (CRs)

The set of requirements that were given from the Boeing employees include: the drone frame to be lightweight, an optimized thrust to weight ratio, an optimized component location, a 3-dimensional (3D) material process, a manufactured prototype airframe, a flying prototype, less than $5000, and minimal hardware included with the airframe. These specifications on the airframe were given straight from Boeing and must be followed to make the clients happy. Each of the requirements have a weight of how important the requirements are to the overall project and from what the client has said, the lightweight aspects of the drone frame are the most important to the project while cost and projected flight are at the bottom of what is important. In addition to the customer requirements, there are a set of requirements that apply to every single project given to the teams by the instructor. These requirements include: the cost of the designs is within budget, durable and robust designs, reliable designs, and that the designs are safe to operate (Table 1). The weights of all these requirements are important when coming up with usable requirements within the decision matrix shown below (Figure 3).

Table 1: All customer requirements

REQUIREMENT NUMBER	CUSTOMER REQUIREMENT
CR1	Lightweight
CR2	High thrust to weight ratio
CR3	High frame strength
CR4	Long flight time
CR5	Ease of manufacturing
CR6	Inexpensive
CR7	Optimized component locations
CR8	Minimal hardware
CR9	Flyable

2.2 Engineering Requirements (ERs)

To make the customer requirements more useful in the design stage of the project, it is important to give dimensions to the requirements to have a better way to understand what exactly needs to be accomplished. Requirements that have received dimensions are called engineering requirements and let the team rank against the customer requirements. After receiving the customer requirements and adding dimensions to these requirements, it was made possible to come up with a set of the engineering requirements (Table 2) including: the weight reduction to be 3lbs or less, adequate thrust to weight ratio greater than 1.81, field of view for the lidar to be 180 degrees, the camera field of view of 360 degrees, centered mass, material stress and cost analysis, long flight time, less than $5000, and minimal hardware pieces. The current drone frame that Boeing has designed is 4.02lbs and that is where the requirement comes from in the fact that the frame should have considerable weight reduction to where it will be 3lbs or less. The current drone frame also has a thrust to weight ratio of 1.81 and all components remain the same for flight, so the only way to increase the ratio would be to decrease the weight of the frame. As for the lidar and camera field of views, the current model has the same angles as what is expected. The next requirement was to ensure that most of the mass is centralized on the frame and to make sure that all the weights are evenly distributed elsewhere. To ensure that material stress and material cost are at a minimum, it is important that many tests are run through simulations before manufacturing begins and when the weight is reduced as much as possible, the cost will also greatly reduce. A big factor in flight time will also be the overall weight of the frame and this will also ensure that the model will be less than $5000. Hardware pieces can be reduced in the design stage of the frame by designing the frame to have pieces that can be attached via other methods of security.

Table 2: Engineering requirements

REQUIREMENT NUMBER	ENGINEERING REQUIREMENT
ER1	Weigh less than 3 pounds
ER2	Thrust to weight ratio greater than 1.81
ER3	Able to withstand impacts and forces of flight
ER4	Flight time around 10 minutes
ER5	Simple to produce
ER6	Total project less than $5000
ER7	Central COG and good FOV
ER8	Few parts
ER9	Ability to takeoff, maneuver, and land

2.3 Functional Decomposition

To aid with concept generation and evaluation, the team broke the design down into a Black Box Model and functional decomposition. The Black Box Model helped to visualize energy, material, and signal

inputs/outputs within the system. This helped to idea what sections of drone would be required to provide the inputs and outputs. Functional decomposition developed this idea further by linking the inputs and outputs together through their respective energies. This assisted the team by providing an outline for which components are needed, and how they connect to other components.
Functional decomposition was important to the drone's design specifically because of the breadth of components involved. There are several pieces of the drone, either electrical or frame-based, that are required to achieve the team's goal of lightweight and extended flight. By breaking the drone down into these respective systems, the team can better visualize what needs to be designed, and how it fits into the system. It also helps identify which components interact with each other directly, and the team can use this information to maximize compatibility and function.

2.3.1 Black Box Model

The Black Box Model identifies the function the team is trying to achieve – maximized flight time for the drone. It then identifies the inputs and outputs to a control volume surrounding the theoretical drone. For material, air is input, and wind thrust is an output from each blade. Energy is input as both electrical from the controller and drone batteries, and human from the human-controller input. This is output in the form of kinetic energy through blade rotation and drone movement. Thermal and acoustic energies are output as waste of the system. Finally, radio signal is input via the controller. Signal outputs consist of position, audio, and visual signals sent to the human pilot. Figure 1 below shows the final Black Box Model used by the team.

Figure 1: Black box model

The Black Box Model assisted the team by breaking the drone into a control volume and identifying the inputs and outputs in the needed forms as discussed above. By understanding these flows, components can be selected to fulfill each need. The functional model takes this further by looking at what happens within the control volume and identifying flows from an inside perspective.

2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional model takes the drone and breaks it into individual steps. Starting from the input by the human controller… intermediate steps are identified through to a final output by the propellers as thrust. The functional model then identifies any energy involved with a respective step. The final functional model can be seen in Figure 2.

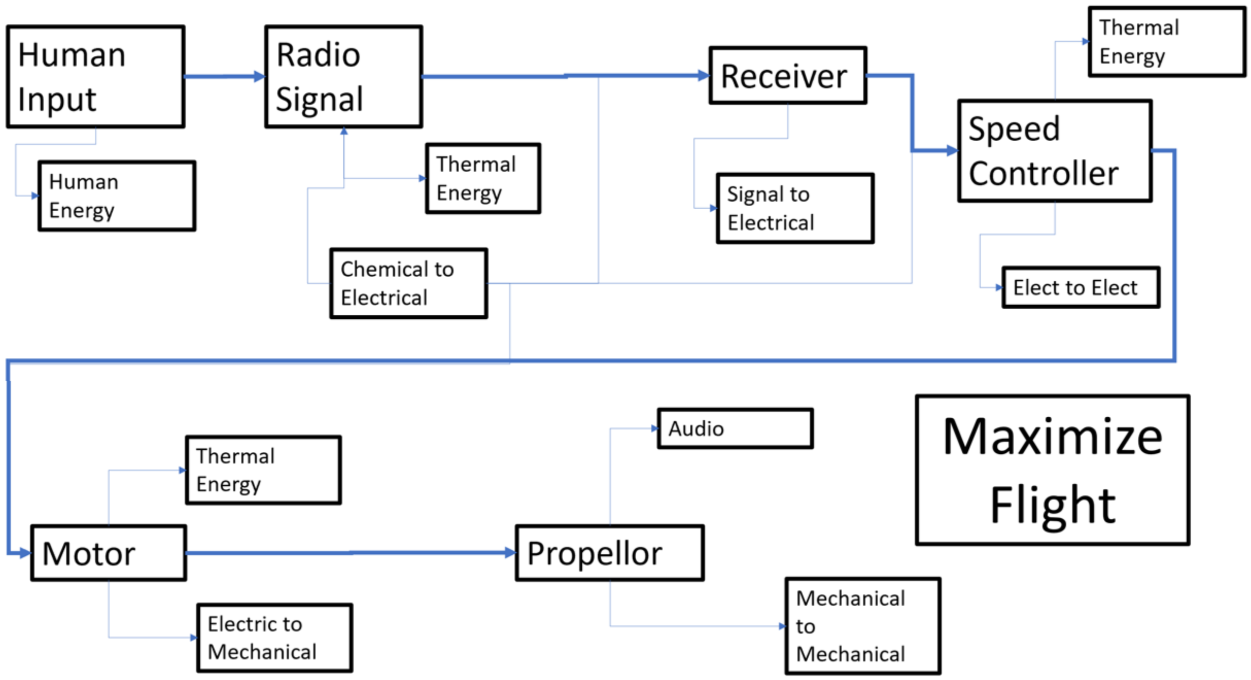

Figure 2: Drone functional decomposition

The functional model helped the team identify components associated with each step as required for flight. It then provided the energy associated with each of these steps. For concept generation, this was useful as it provided topics that would need to be designed for… such as the arm and body configuration. Because the team is focusing on the body of the drone and components were pre-selected by Boeing, the functional decomposition was used less for the selection of individual components. It was instead used as a template for how the components connect and gave a deeper understanding into how drones function. After understanding these concepts, the team used the Black Box Model and functional decomposition to begin concept generation.

2.4 House of Quality (HoQ)

The purpose of the Quality Function Deployment (QFD) model, located in Appendix A: Table 1, is to accurately rank the customer requirements against the engineering requirements. This is a great way to figure out the important aspects of the project while also ranking which requirements are related in order to optimize the design process. The best way to set up the QFD is to have the customer needs weighed with their importance in Figure 3 ranked against the engineering requirements in Figure 4. This was a great way to compare the two together to figure out whether or not they are related to other requirements.

Customer Needs	Customer Weights
LIGHTWEIGHT	5
OPTIMIZED THRUST TO WEIGHT RATIO	4.5
OPTIMIZED COMPONENT LOCATION	3.5
3D MATERIAL PROCESS	4
MANUFACTURED PROTOTYPE AIRFRAME	5
FLYING PROTOTYPE	2
LOW COST	1.5
MINIMAL HARDWARE	3

Figure 3: Customer needs with their weights

Technical Requirements									
WEIGHT REDUCTION < 3LBS	THRUST TO WEIGHT RATIO > 1.81	LIDAR FIELD OF VIEW	CAMERA FIELD OF VIEW	CENTER OF GRAVITY	MATERIAL STRESS ANALYSIS	MATERIAL COST ANALYSIS	TIME OF FLIGHT	LESS THAN $5,000	MINIMIZE HARDWARE PIECES

Figure 4: Engineering requirements

As shown below (Figure 5), the engineering requirements must have units and target goals so that a good comparison can be made to find out the importance of each requirement technically to the overall project. As shown below, the weight reduction of the engineering requirement will be measured in pounds (lbs.) whereas the thrust to weight ratio is dimensionless and does not need any units. The lidar and camera field of views are measured in degrees and the center of gravity will be measured using inches or feet depending on where the center is located. The center should be at zero inches if the origin point is going to be the geometric center of the drone. Material stress analysis will be measured in pounds per square inch (psi) and the cost analysis in a dollar amount. Time of flight will be measured in minutes because the flight time will not be expected to be hours long but more around 30 minutes. The cost is very similar to the cost analysis and will be measured in a dollar amount while the number of hardware pieces is just a number.

Technical Requirement Units	LBS	N/A	DEGREES	DEGREES	INCHES	PSI	$	MINUTES	$$	#
Technical Requirement Targets	2.8	2	180	360	0	2000	150	30	1500	24
Absolute Technical Importance	225	154.5	94.5	94.5	95	110	118.5	106.5	114.5	69
Relative Technical Importance	1	2	7	7	7	5	3	6	4	10

Figure 5: Units and targets for engineering requirements

2.5 Standards, Codes, and Regulations

Based on requests from the client, ASTM D638 Type 1 will be the standard used for durability testing of plastic materials. The dog bone testing of these materials applies to these standards as all samples are created the same exact way, are tested in the same exact conditions, and are compared to each other in such manner. It can also be known that this standard is applicable to reinforced plastics being tested under a variety of temperatures, humidity, and testing machine speeds. Finite Element Analysis standards are needed when Ansys software is used because the software cannot run properly without following this standard. Shown in Table 3, there are two standards that Team Hi-Jacks will be using in the preliminary testing stages of this drone.

Table 3: Standards of practice as applied to this project

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASTM D638	Standard Test Method for Tensile Properties of Plastics	The dog bone testing method is being used for material durability on the drone frame. Multiple materials will be used.
FEA	Finite Element Analysis- Code and Standards Compliance	Ansys software is used to numerically analyze the structural durability and heat transfer of the drone frame produced.

3 DESIGN SPACE RESEARCH

Design space review concerns itself first with literature review. This goes over research done by each team member that adds to the current understanding of the group. Benchmarking is then discussed. Benchmarking was done on two levels. First, system level benchmarks are reviewed to give the team an understanding of drones that have already been designed, and to provide a template to work off. Then, subsystem benchmarks are done for different systems within the drone, such as the arms and legs. Following the benchmarking, functional decomposition occurs where the drone system is broken down into its material or energy parts to further help the team understand the system at a deeper level.

3.1 Literature Review

To begin the design space research, each team member focused on their own section of literature review. The focus of each member is dependent on their role within the group. Members set out to gather state-of-the-art information on their respective topics to bring to the group to be used as references for concept generation and selection. Each individual group member, their respective role, and five of their sources are discussed below.

For benchmarking, sources found were primarily the manufacturer websites for consumer drones. These sources provided information on pricing, weight, and technological capabilities of current market drones. This provided the team with expectations of the final price and ability of the drone. Literature review sources consisted of manufacturing information on different 3D printing techniques, software simulation, costing, and examples of other drones. Several of these sources served as training guides for the work to be completed later in the project. Other sources provided insight into the current state of the drone field. These sources helped the team better understand the scope of the project, as well as any issues that may occur and how to fix them. These sources were primarily found through internet searches and examining similar systems.

3.2 Benchmarking

To provide a framework for the team to work off, drone concepts developed by other companies were studied. This facilitated an understanding from two perspectives. First, system level benchmarking was done to gain an understanding of how drones work from a higher level. Subsystem benchmarking was then done to look at each individual component of a drone, and to help the team understand what systems would need to be designed for.

3.2.1 System Level Benchmarking

Three different drones were looked at for the purpose of system level benchmarking. Each one is available to consumers and was created by different companies. Benchmarking these drones helped provide an understanding of what components are required to create a fully functional drone. It also provided a template for how the components connect. Each drone design studied is discussed in further detail below.

3.2.1.1 Existing Design #1: DJI Phantom 4 RTK Drone [1]

This DJI drone was selected as a representation of a typical consumer drone. It consists of a single plastic frame and legs. The camera is mounted on the bottom and has four individual propellers. This was selected as it represents a very basic, yet easy to manufacture design. It is available for a price of $6000 and contains most of the features the team is designing for, including a top-mounted electronics hub. The drone can be seen in Figure 6 below.

Figure 6: DJI Phantom 4 RTK drone

3.2.1.2 Existing Design #2: Yuneec Typhoon H Plus [2]

The Yuneec drone was selected as a benchmark for its robust and simple design. It features six arms and propellers instead of the usual four. The arms and legs are also detachable from the frame, leading to better repairability and less weight. This drone is also the cheapest coming in at $2000. This design showed the team that a modular and plain design would work and can be seen in Figure 7.

Figure 7: Yuneec Typhoon H Plus

3.2.1.3 Existing Design #3: Parrot ANAFI USA Drone [3]

The Parrot ANAFI Drone as shown in Figure 8 represents a more unique selection of components. The drone is very compact, which would help to reduce weight and cost. The legs are also directly attached to the arms, leading to easier manufacturing. The drone's simplest configuration comes at a price of $4000. Although this drone provides ideas for compactness and simplicity, the team doesn't plan on creating a drone with its form factor or component configuration.

Figure 8: Parrot ANAFI USA drone

3.2.2 Subsystem Level Benchmarking

3.2.2.1 Subsystem #1: Arm Style

Because the team is focusing on the construction of the drone's frame, arm design was selected as an important concept. It consists of the form-factor of the arms, as well as how they connect to the rest of the drone. Key concepts such as strength and wiring were kept in mind as benchmarking was done. Three different possibilities were investigated as discussed below.

3.2.2.1.1 Existing Design #1: Carbon Fiber

The first arm style looked at was the carbon fiber arms from the Mark 4 HD5 DJI drone. The drone is meant for racing, so the arms needed to be lightweight and strong. They also feature a flat design, which the team had not thought of before. Although they might be a bit more expensive, the strength and weight metrics could outweigh the price. This style drone arm can be seen below in Figure 9.

Figure 9: Carbon fiber drone arm

3.2.2.1.2 Existing Design #2: Tube Arm

The arm being a tube would have a couple of advantages. First, it has a decent amount of strength coupled with weight reduction from the removed core material. Second, it allows for wiring to be routed through the center of the arm, increasing aesthetic appeal and potential snags with obstructions. This style of arm can be seen in Figure 10. These arms also come in carbon fiber options, increasing strength even more.

Figure 10: Tube drone arm

3.2.2.1.3 Existing Design #3: Solid Rectangular Arm

This style of arm as shown in Figure 11, in addition to being heavier, has more strength and rigidity. Although the drone being lightweight is the team's highest priority, structural strength also ranks highly. This style also allows for easier mounting, as its simple geometry makes attaching different components relatively easy.

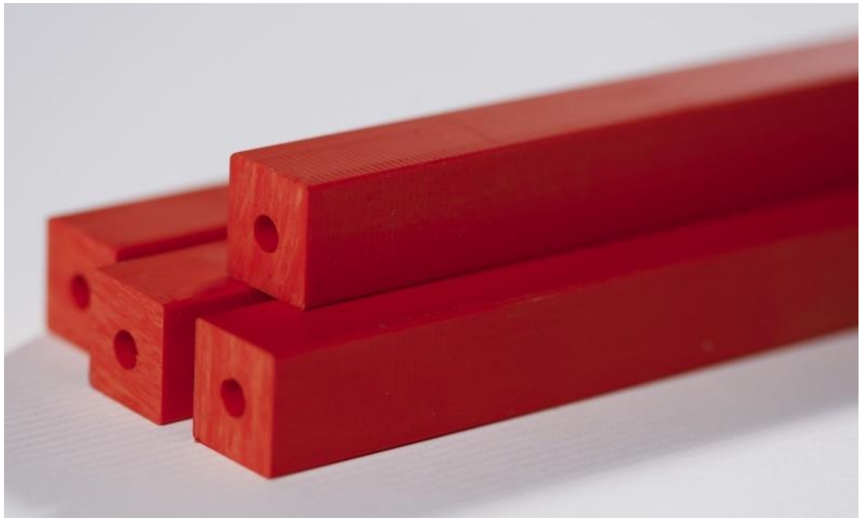

Figure 11: Solid rectangular arm style

3.2.2.2 Subsystem #2: Body Configuration

Body configuration concerns itself with the construction and shape of the drone. This is where most components will be attached, so it is important to think about both space and strength. Different shapes and ways to space the components are discussed below.

3.2.2.2.1 Existing Design #1: Stacked Discs

Stacked discs have a couple of advantages. First, they are relatively simple and would require minimal 3D printing effort. They also provide a somewhat modular body, allowing components to be switched around as needed. Although they could prove heavy, their strength would offset this downside. An example of this can be seen below in Figure 12.

Figure 12: Example of a stacked drone frame

3.2.2.2.2 Existing Design #2: Solid Body

The second frame style benchmarked was the solid body. This consists of a single 3D printed or machined drone body as shown in Figure 13. Although strong, this style has several drawbacks. First, if any part of the body were to break, the entire frame would have to be remanufactured. It is also the most difficult to fit components into, as once the location of components is decided, it is difficult to move things around without doing a redesign.

Figure 13: Solid plastic drone frame

3.2.2.2.3 Existing Design #3: Modular Body

Creating a drone with a modular body has several advantages. First, it allows components to be swapped in and out extremely easily, lessening the losses caused by broken components. It also lessens weight as the frame would be mostly negative space as shown in Figure 14. The greatest downside is the difficulty involved with manufacturing such a frame and designing it in a way that is efficient.

Figure 14: Example of a modular drone frame with modular components

3.2.2.3 Subsystem #3: Leg Configuration

Leg configuration is important as it affects the stability and strength of the entire drone. It is what contacts the ground, and a stable foundation is required to have a strong system. Three different methods were looked at and benchmarked below.

3.2.2.3.1 Existing Design #1: Body-Attached Legs

The first style of leg benchmarked was also the most common. These consist of legs attached directly to the frame as shown in Figure 15. These provide a good amount of stability, while also being quite strong. One downside is the attachment to the body, which could reduce space for components.

Figure 15: Drone legs attached to the body

3.2.2.3.2 Existing Design #2: Truss Style Legs

The second style adds on the previous body-attached legs by adding trusses. This increases the strength by a considerable amount and negates any concerns of breakage but comes at the cost of increased weight. Should there be an area where the team can add more weight, this would be one of the top candidates. An example of this can be seen in Figure 16.

Figure 16: Example of trusses between sets of legs

3.2.2.3.3 Existing Design #3: Wing-Attached Legs

The final style of legs benchmarked was also the second most popular. Wing-attached legs consists of pegs attached directly to the "wings" or arms of the drone. Although this design is the lightest as it requires the least amount of material, it also concentrates stress on the arms, which isn't ideal. The location axially along the arm could be adjusted however, allowing the stressed to be concentrated to different areas as needed. This style can be seen in Figure 17.

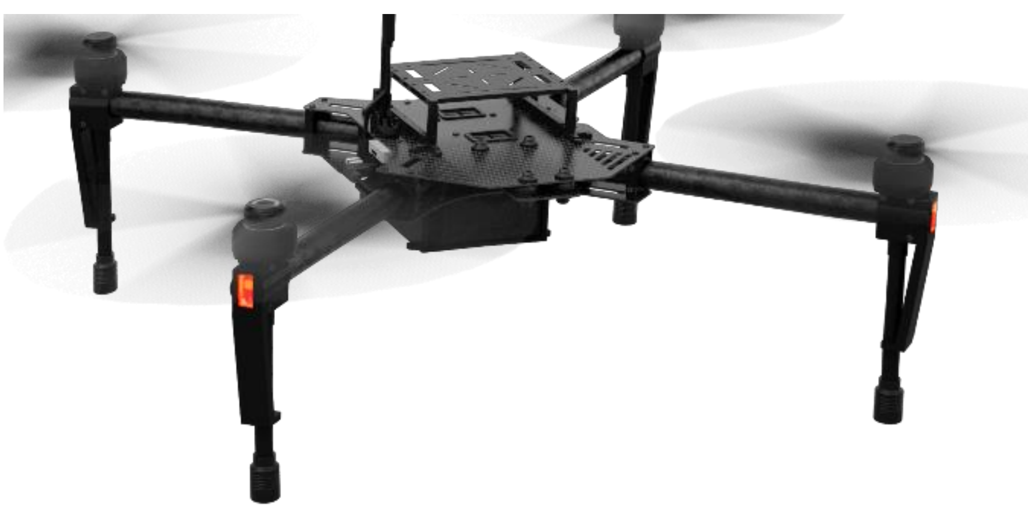

Figure 17: Drone landing legs attached directly to propeller arm

4 CONCEPT GENERATION

To brainstorm potential concepts, the team used the morph matrix method (Appendix B: Table 1). This consists of deciding on the general, yet most important, subsystems of the design. For the drone they are the arm connection style, material, body configuration, leg style, component configuration, and arm style. Each team member was tasked with generating one idea for each subsystem and making a detailed sketch of it. The ideas are then put into a morph matrix where each design can be compared.

4.1 Full System Concepts

Using the morph matrix, each team member takes one design idea from each subsystem and combines them in a final sketch of a full drone to be used as a potential prototype. The 5 full designs are compared to the original system given by Boeing in the Pugh chart (Appendix B: Table 2) as the datum. Then three designs are selected and are compared to each other using a decision matrix (Appendix B: Table 3) and a final design is found.

4.1.1 Full System Design #1: Truss System

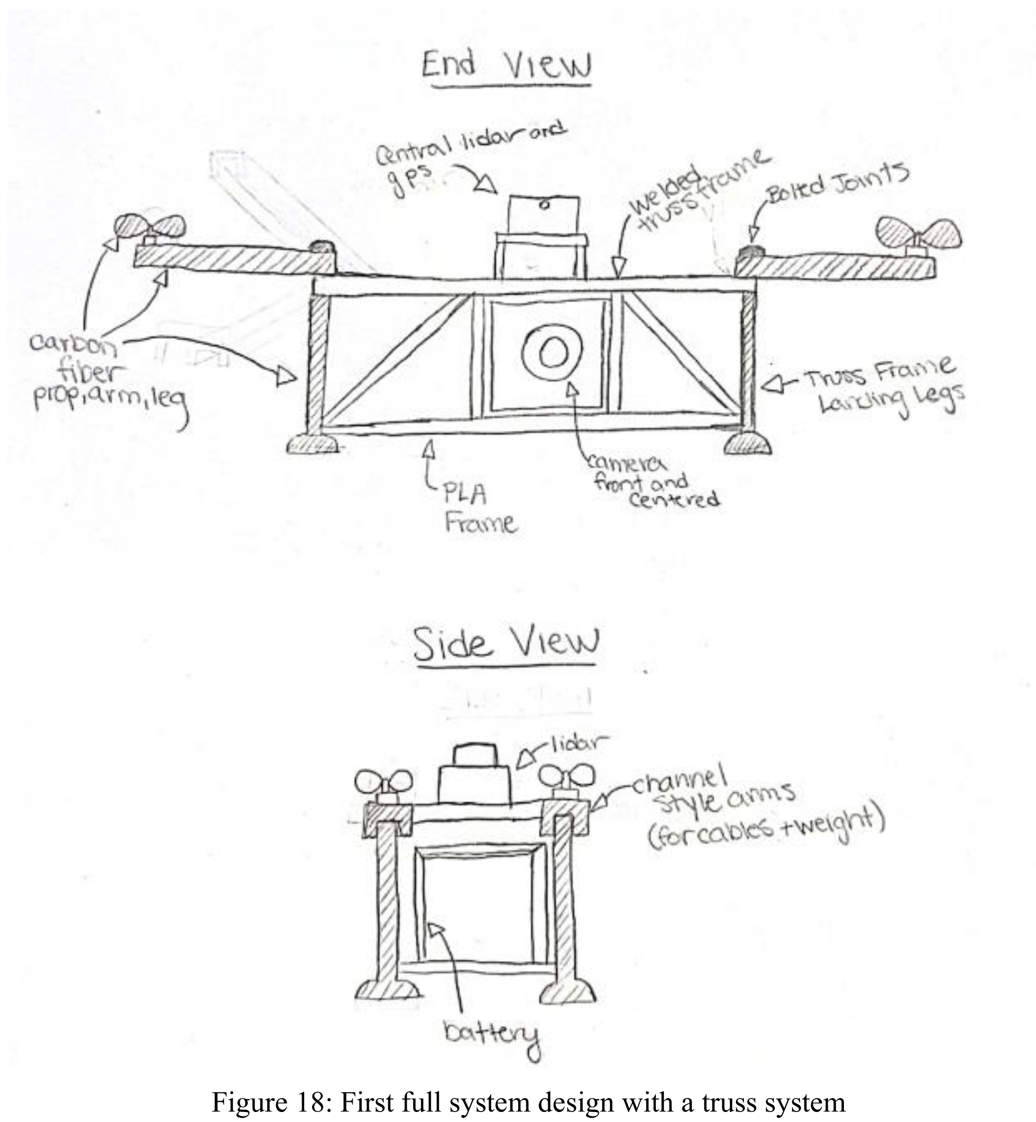

Figure 18: First full system design with a truss system

The truss system (Figure 18) is designed to be sturdy over anything else. It would likely be the strongest design but also the heaviest. It focuses on strength and survivability especially in the case of a crash or hard landing. The rectangular shape would make it difficult to fly but it would have a good layout for each component, allowing a wide field of view for each.

4.1.2 Full System Design #2: Folding Arms

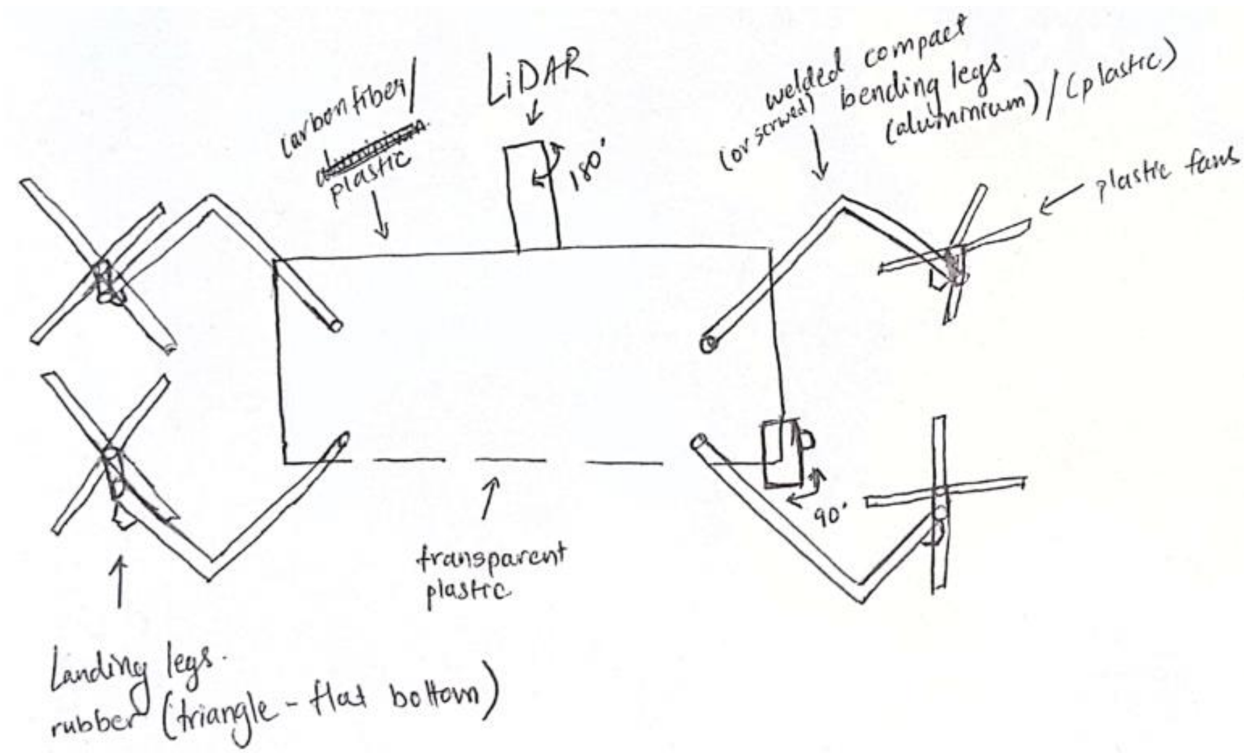

Figure 19: Second full system design featuring folding arms

This design is built for ease of storage (Figure 19). The arms fold in and out so it can be carried in smaller spaces. This would likely increase the weight and difficulty of manufacturing compared to others due to the extra hardware and complexity. The parts would be fitted inside a hollow cube with the parts that need to be seen on the outside. This would be simple to design but would likely not meet all the customer's requirements.

4.1.3 Full System Design #3: Stacked Discs

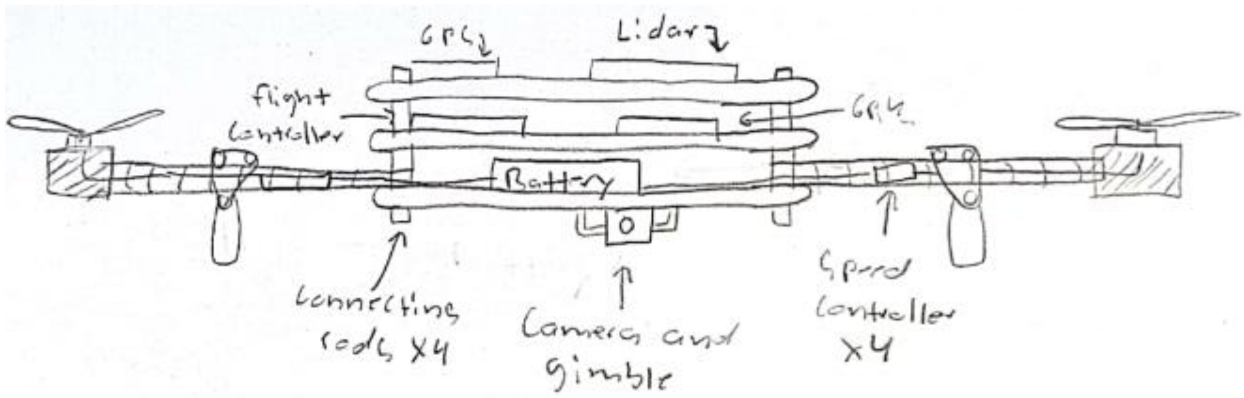

Figure 20: Third full system design with stacked discs

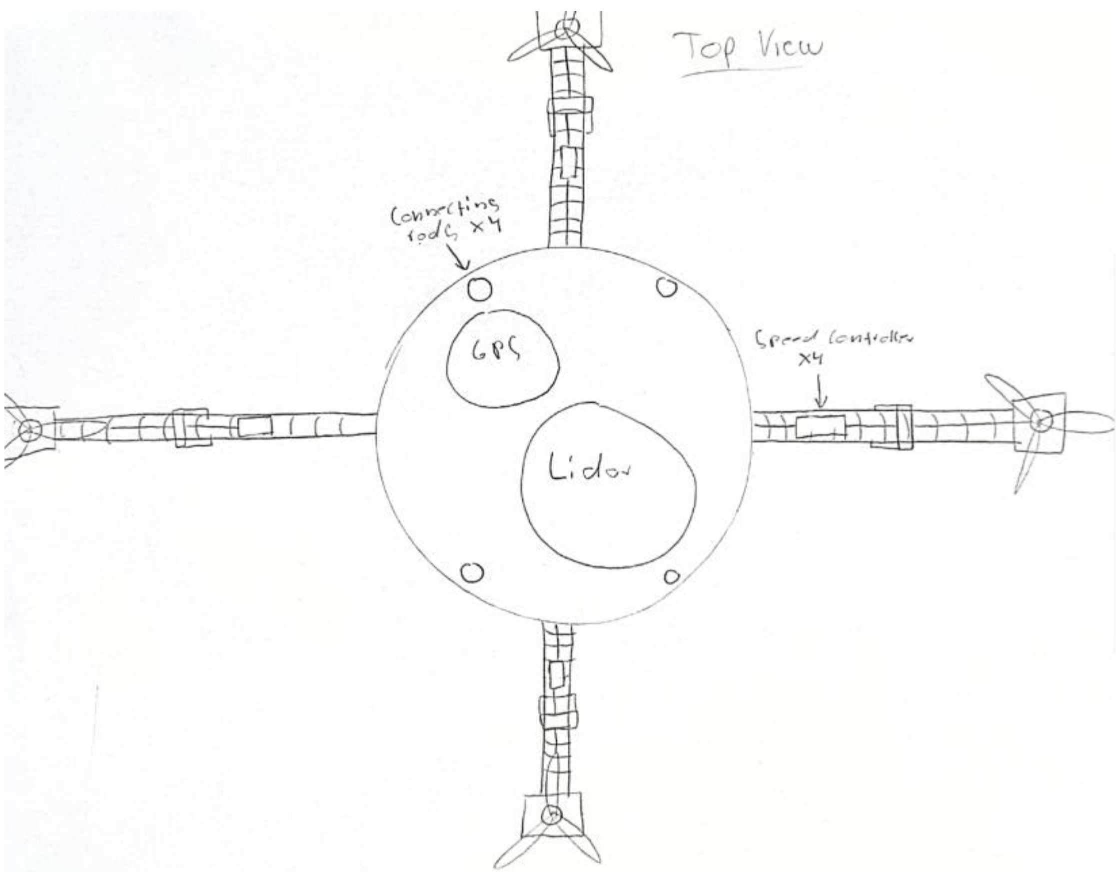

Figure 21: Third full system top view

This design (Figure 20 and 21) is the one that was ultimately decided on for the first prototype. The disc design allows for ease of manufacturing and utilizes as much space as possible while keeping the center of gravity as close to the center as possible. The downside is that with the tubular arms, the speed controllers will need to be crudely connected in the first version. Testing is required to find the optimal location because too much weight above the arms will cause flight instability. It is designed with 3 discs with spaces in between, connected by 4 bolts. The arms connect to the bolts as well, making it easy to assemble and disassemble whenever needed.

4.2 Subsystem Concepts

The following subsystems are the 3 most important for the drone. The arm style, body configuration, and leg style had the most thought put into their design as they decide the size and shape of the body. Much thought was needed to optimize flight performance, size, component compatibility, and ease of manufacturing.

4.2.1 Subsystem #1: Arm Style

The arms of the drone need to be able to withstand the forces of landing as most of the designs have legs connected to the arms. They also need to be correctly sized, so they don't get in the way of any components like the camera and lidar. Since all the motors are connected at the tips of the arms, they need to have a strong resistance to bending as well.

4.2.1.1 Design #1: Tubular Carbon Fiber

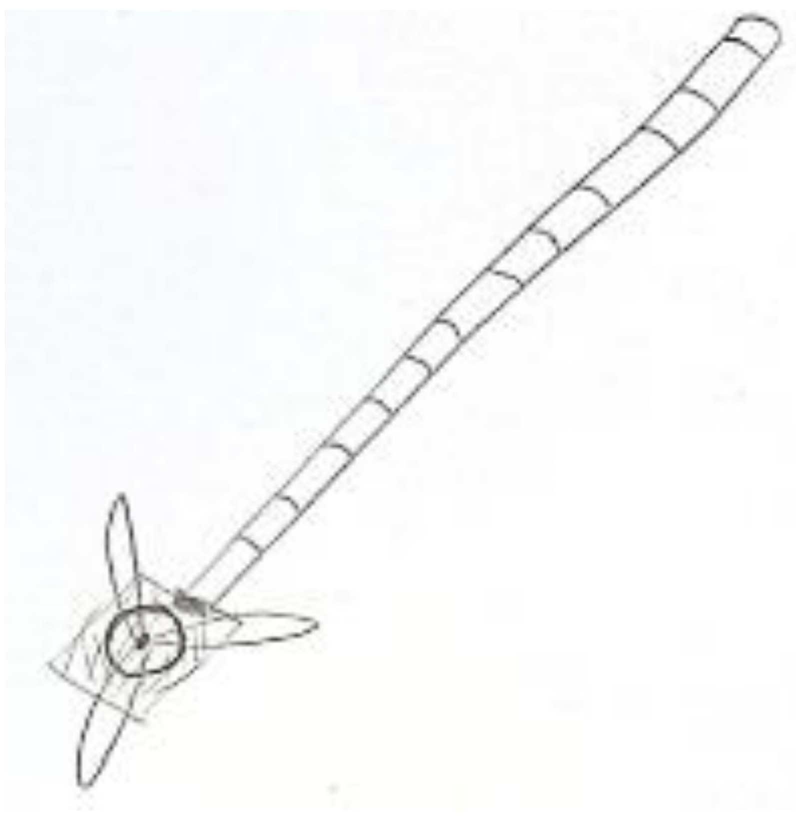

Figure 22: Tubular carbon fiber arm with 3D printed end cap

Carbon fiber arms would help decrease weight but is much more difficult to work with (Figure 22). Parts would need to be outsourced rather than 3D printed. Increases strength but may not be necessary. A 3D printed end cap would be made to mount the motor to the end of the rod.

4.2.1.2 Design #2: U-Channel

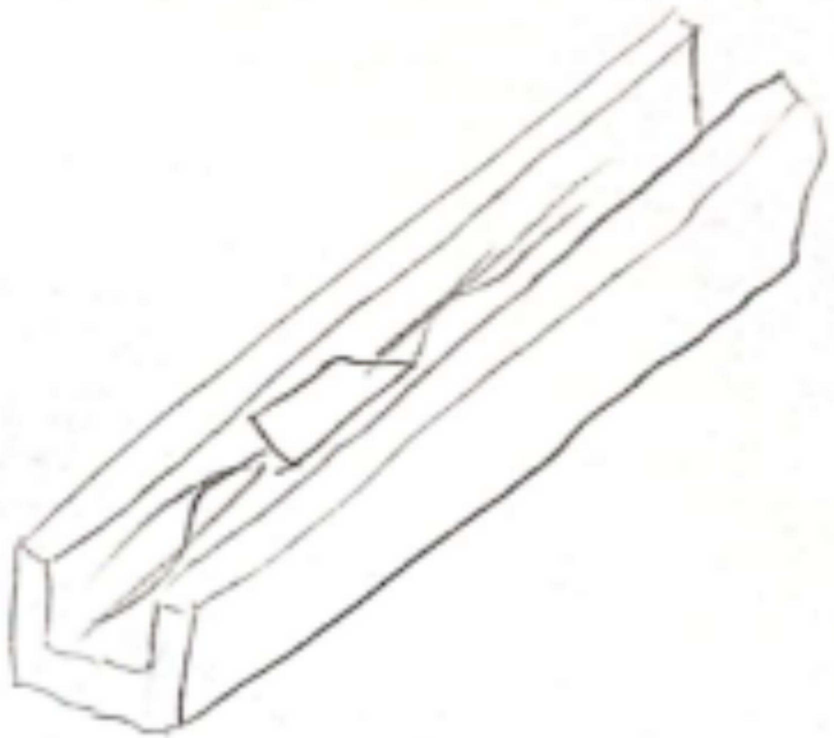

Figure 23: U-channel arm design

Having a U-channel arm design (Figure 23) would easily hide any cables or speed controllers. It would be placed in any orientation that the team believes would work best. It would be very light and improve the look of the design, but it could harm the structural rigidity of the arm. It would be the most likely to break in the event of a hard impact.

4.2.1.3 Design #3: Hollow Cube

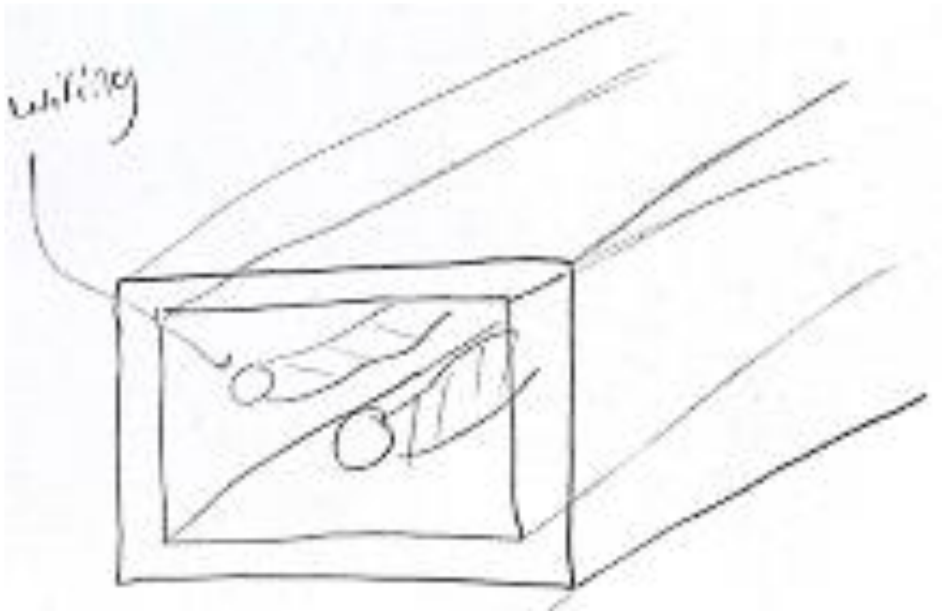

Figure 24: Hollow cubic arm design

The hollow cube improves the design of the U-channel (Figure 24). It is stronger and hides the components more efficiently but would make servicing the drone difficult if a wire disconnects inside the tube. Additionally, it may be wider than the other arms to accommodate the speed controllers inside rather than on the outside.

4.2.2 Subsystem #2: Body Configuration

Body Configuration decides the shape of the drone more than any other subsystem. The goal is to keep the center of gravity as close to the center as possible and to efficiently use space. This will help the stability, reduce weight, and improve the flight performance.

4.2.2.1 Design #1: Stacked Discs

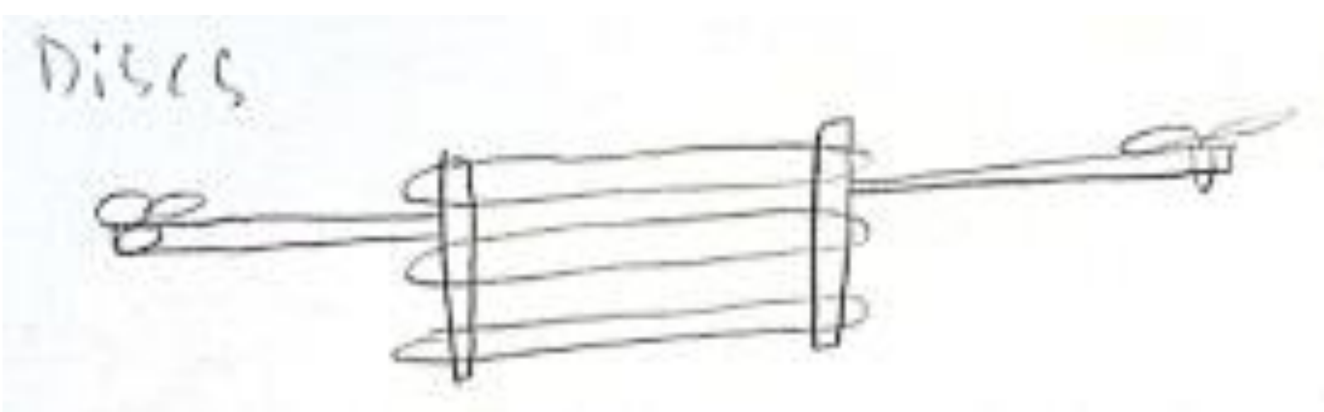

Figure 25: Stacked discs body design

The disc design (Figure 25) is made to reduce weight and manufacturing time and centralize the center of gravity. It will be more stable than the original system and will weigh much less. Fine tuning the design will be much more complicated than the others because the arm length and location will need to be optimized as well as the placement of each component. Drag may be increased due to parts and wires being placed on the arms.

4.2.2.2 Design #2: Modular Slots

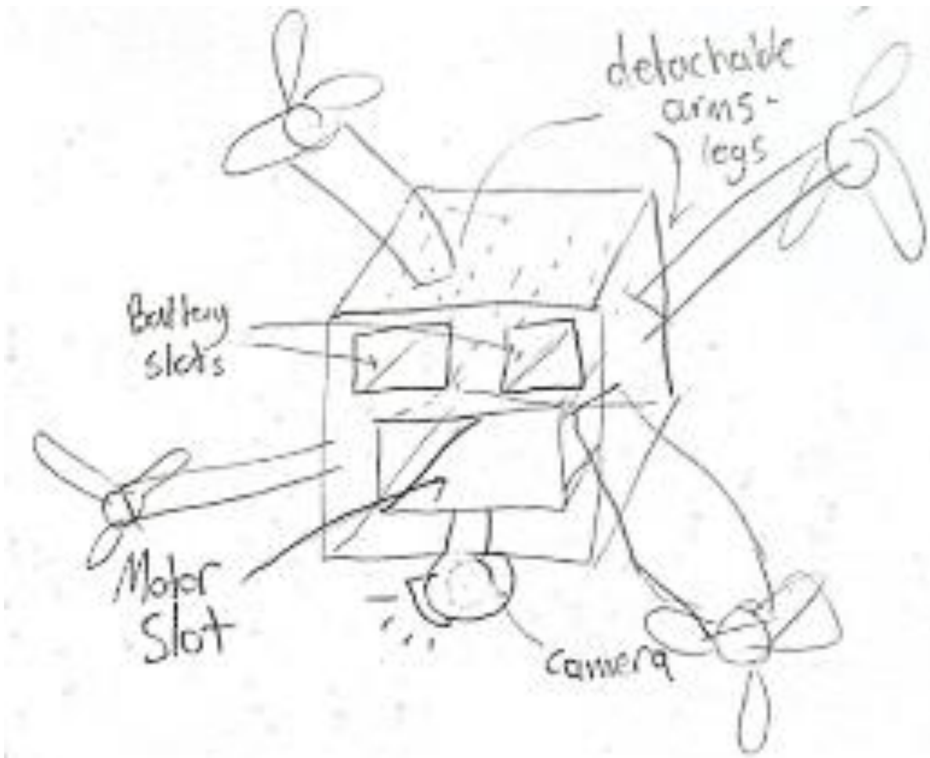

Figure 26: Modular slots body design

This design is made with component compatibility and ease of use in mind (Figure 26). Each one has its own slot in the body so they will not affect the aerodynamics. The aesthetics will improve but it will very likely be heavy with each component being enclosed. The arms are detachable making for easy storage and high portability. The flight performance may be hindered by the body being a cube which will not perform well.

4.2.2.3 Design #3: Solid Body

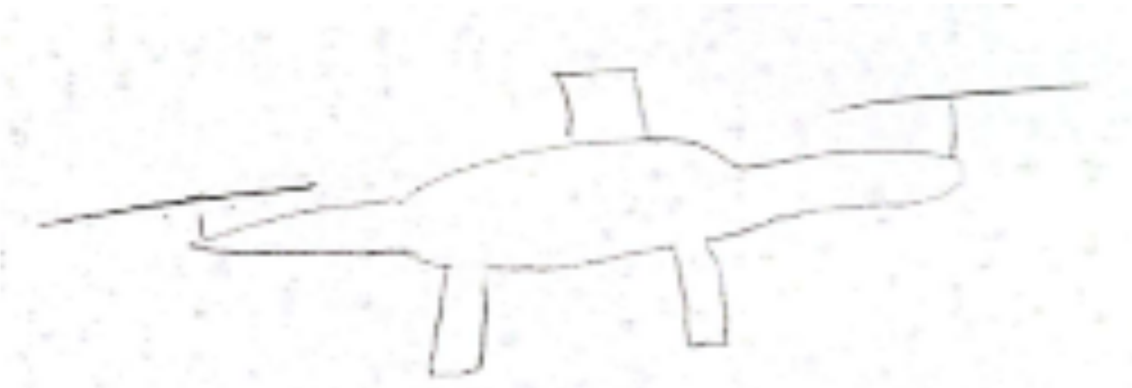

Figure 27: Solid body design

A solid body would make the design process much easier, however it would increase manufacturing time and would likely be overweight (Figure 27). This design would be more like a commercial enthusiast drone with enclosed parts. Aerodynamics would improve since each part can be covered and streamlined but requires much more material.

4.2.3 Subsystem #3: Leg Style

The legs of the drone will be the component that takes most of the force when the drone lands. They need to withstand this as well as any extra force in the event of a crash. Additionally, they need to be long enough to accommodate the camera which will likely be placed on the bottom of the drone.

4.2.3.1 Design #1: Slidable

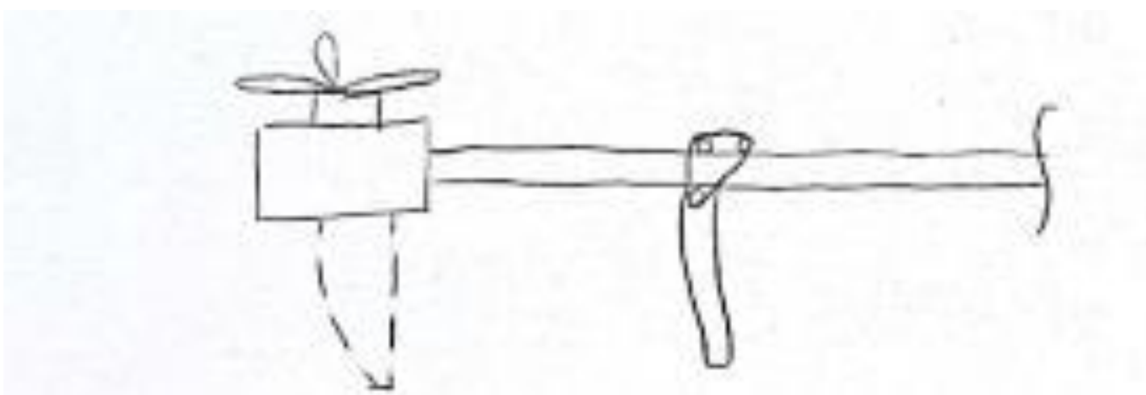

Figure 28: Sliding leg style

These legs are designed to be moveable along the length of the arm (Figure 28). Ideally, the legs would be placed outward to make landings and stability on land much better, but this would increase stresses closer to the body, possibly causing the arms to break off the body. Legs that are close to the center help the stress during hard landings but would make it more difficult to land especially if the landing area is not flat and smooth. This design allows the configuration in any position to be tested to find the optimal location. Depending on the locations of the arms, however, would make the legs very long which could lead to potential issues.

4.2.3.2 Design #2: Truss

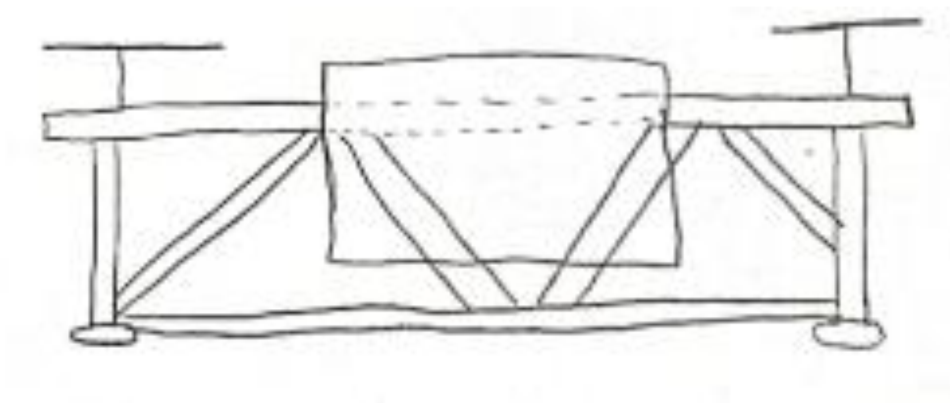

Figure 29: Leg design with truss system

The trusses on the legs are made to increase the strength of the body and the legs themselves (Figure 29). This meets the design requirement of having a sturdy frame, but it comes at the cost of weight. Connected to a central square body, the center of gravity of near the center and each component has a wide field of view. This would be costly and time-consuming to manufacture but would be a good design if these weren't taken into consideration.

4.2.3.3 Design #3: TV Stand

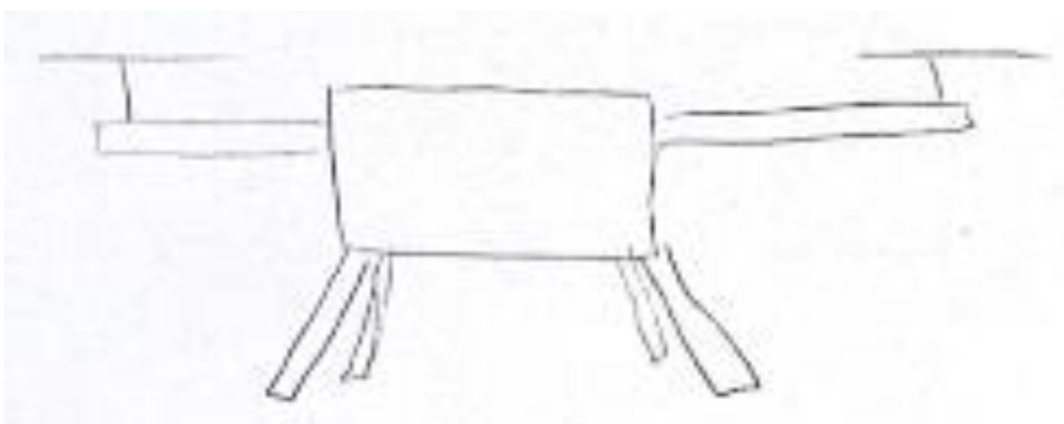

Figure 30: Simple extruded leg design

This design has 4 simple legs either made solid with the body or attached as a separate part (Figure 30). This reduces cost and production time, but points force up into the body where components are place. In the event of a hard landing there is potential for this to damage a part, the square body, or the legs themselves. Additionally, this design improves the field of view for the camera and lidar, if they are mounted to the bottom and top, respectively.

5 DESIGN SELECTED – First Semester

In this chapter, the final design choice that was chosen from concept generation will be dissected and briefly analyzed. This design scored the highest points amongst the team as the most likely to satisfy the customer needs.

5.1 Technical Selection Criteria

Technical criteria that will be used to compare final designs include total weight, materials used, and drag analysis. This is the most important criterion because all three will directly interfere with the customer requirements. To achieve a drone under 3 pounds, the material used will directly affect the total weight of the drone while the drag analysis on Ansys Software will be determined by the shape of the body. Thrust to weight ratio will vary depending on all these technical requirements, which is the team's biggest priority. As seen in Appendix B, frame strength and lightweight were the most heavily weighted criteria used to grade all drone designs. The final designs that scored the most points were the drones that used the strongest materials such as carbon fiber as well as the drones that used the least amount of material. A slim drone body that is made mostly of carbon fiber seemed to be the team's bias.

5.2 Rationale for Design Selection

Full design 1 and 3 were the top drone body choices for Team Hi-Jacks capstone project. These two designs scored well on the Pugh chart (Appendix B: Table 2) where all six designs were ranked against a datum set which happened to be the original drone frame that was built by another team and supplied by Boeing. These designs were then able to move onto the decision matrix where they were compared to the criterion and a third design that passed the Pugh chart phase of design selection. These criteria are like the customer and engineering requirements from the HoQ (Appendix A: Table 1) portion of the design process with minor changes where certain aspects of those requirements could be combined due to the likeness of the requirements. These modified engineering requirements were then weighed on how important they were to fulfill the customer needs and to make the drone as efficient as possible. After the engineering requirements were weighed, it was time to rank each of the three designs that made it to the decision matrix stage of testing and find out which two designs could be found to be most promising in the manufacturing stage of the design project. These two designs happened to be design 1 (Figure 18) and design 3 (Figures 20 and 21) which can be found listed in sections 4.1.1 and 4.1.3. Design 3 happens to have the highest score in the decision matrix so that is the design that is going to be referred to frequently but aspects from design 1 will also impact the final look of the drone frame design. In order to start working with stress analysis, cost analysis, and total frame weights, it was important to start working with SolidWorks to get a rough design sketched together (Figure 31). This design is a good outline of what Team Hi-Jacks will continue with in the future but will be adjusted as needed.

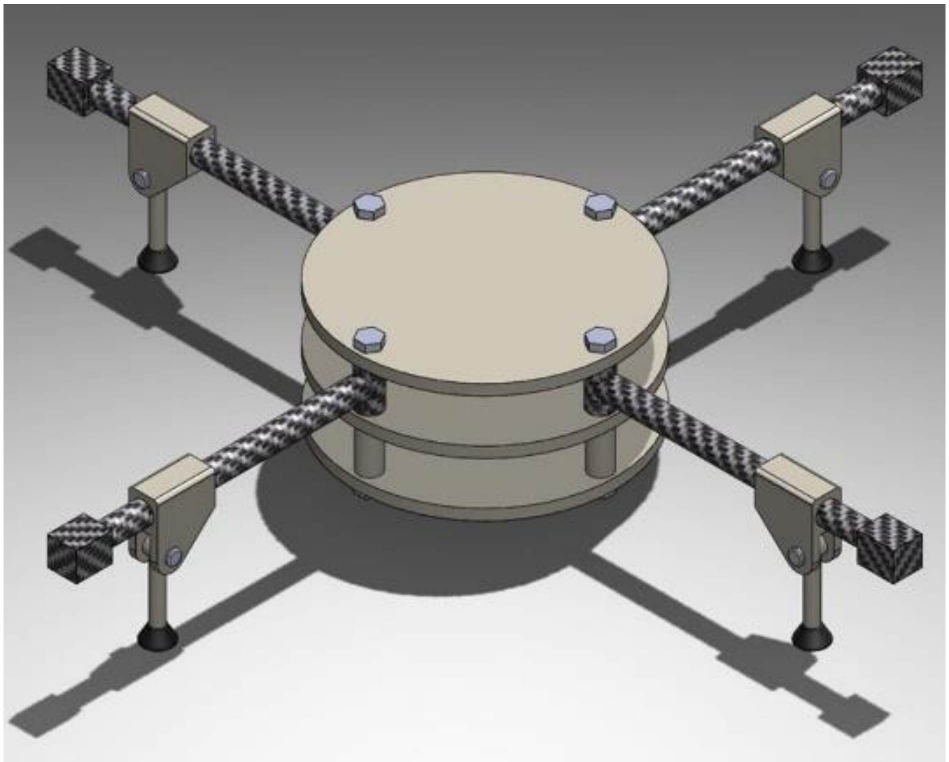

Figure 31: Rough CAD model

5.3 Maker Lab Prototype

Figure 32 below shows the printed prototype from the Maker Lab. This prototype served as a proof of concept for the plate design. It also showed the weaknesses with PLA printing material and highlighted the need for better printing. This prototype failed shortly after printing by being dropped.

Figure 32: Maker Lab prototype

5.4 Design Description

The main design has a main body consisting of 3 circular plates where a majority of the components will be placed. The arms extend out a precise distance from the body to not interfere with each other or any other component. The arms hold the other components not attached to the body, those being the motors, propellers, and speed controllers.

5.4.1 Design Changes

For the next prototype there are many small and large changes made. The most obvious change is the addition of legs shown in Figure 33 and part number 3 in Table 4. Originally, a good design could not be decided on for the initial prototype, so they were left out. They are slanted at an angle to give a wider base which helps with landing and stability on the ground. The legs are intentionally placed underneath another new feature that prevents a bending moment in the arms during flight and landings (Table 4: part 2). This part combines itself with the spacer in the original prototype to reduce manufacturing cost and time.

The minor changes to the current version are additional and larger keys added to each plate. When building the previous version, it was discovered that the keys on the arms that prevent them from swaying left and right were very flimsy. By adding a keyway to each plate and increasing the size, it will be less likely to break when building and especially in the event of a crash or hard landing. The last change is an increase to the diameter of the arms. It was decided that they should be thicker to decrease bending and to give an increase to general rigidity.

Table 4: Drone frame parts bill of materials

PART	PCS.	ITEM NO.	ITEM DESCRIPTION	NOTES	WEIGHT [gm]	PIECE SIZE	U/M	W-C
1	3	22F-001	ONYX 3D PRINTED PLATE W/KEY		183		SQFT	FAB
2	4	22F-002	ONYX 3D PRINTED ARM W/SPACER		108		SQFT	FAB
3	4	22F-003	ONYX 3D PRINTED LEG W/ARM CLAMP		76		SQFT	FAB
4	4	22F-004	ONYX 3D PRINTED SPACER W/ARM CLAMP		60		SQFT	FAB
5	4	22F-005	HEX BOLT ZINC 1/4" X 5-1/2"		112		SQFT	PURCH
6	8	22F-006	HEX BOLT ZINC 1/4" X 1-1/2"		96		SQFT	PURCH
7	4	22F-007	HEX NUT ZINC 2/4"		12		SQFT	PURCH
8	8	22F-008	FLAT WASHER ZINC 1/4"		16		SQFT	PURCH
					663			

5.5 Implementation Plan

The design will be implemented by fabricating a 3D printed prototype. This printing will be done at the NAU IDEA Lab within the engineering building. Design analysis will also be performed in the computer software ANSYS as discussed previously. Resources needed for manufacturing include the IDEA Lab and included 3D printer; chosen printer filament; IDEA Lab facility; and extra components from Home Depot or another hardware store. To implement the design through analytical software, ANSYS and the required knowledge to port the design from SolidWorks and perform analysis will be required. The components that were selected by Boeing and will be required for flights will be purchased at available online stores. Implementation of these components will require the use of electric drills, and components from hardware stores. These attachment components including nuts, bolts, and screws will be determined once the components are purchased and in the possession of the team. The individual flight components and the companies they are available for purchase from are shown in Table 5. Table 4 above shows the bill of materials for 3D printed and purchased body hardware. Figure 33 shows the completed assembly to be 3D printed. Figure 34 shows this same model in an exploded view.

Table 5: Components required for flight, and their respective vendor

Component	Qty.	Company of Purchase

Hobbytown 40A ESC	4	Hobbytown
Gemfan 9045 3-Blade Prop	4	getfpv
Battery Charger	1	Amazon
Battery Connector	1	Amazon
Socokin 6S LiPo Battery	1	Amazon
iFlight XING 2814 880KV Motor	4	PilotHQ
Pixhawk PM07 Power Module	1	getfpv
Flysky FS-i6X 2.4GHz RC Trans/Receiver	1	Amazon

Figure 33: 3D model to be printed

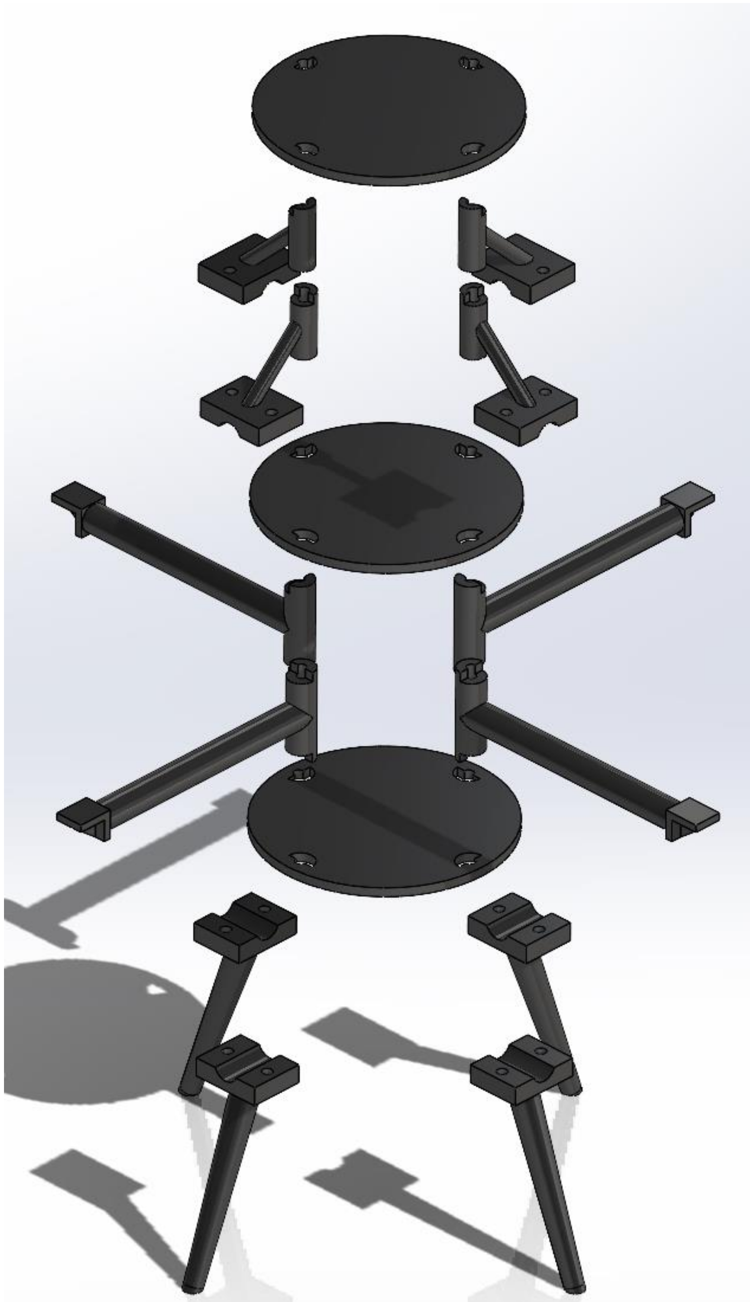

Figure 34: Exploded view of 3D design

6 Project Management – Second Semester

6.1 Gantt Chart

The most current and up to date Gantt Chart can be seen in Appendix C: Figures 1-3 showing all of the work that was done throughout the second semester of the project and what tasks each of the individual team members worked on to complete team assignments. As can be seen in Appendix C: Figure 1 shows the first week up until the end of the fifth week with every single assignment and task assigned to the team. These weeks include the five different timecards in which every member is responsible for keeping track of the hours spent working on the project with a requirement of a minimum of nine hours per week. These timecards were due Monday night for the previous weeks of work. The first big team assignment was the project management assignment in which each team member was required to plan out what needed to be done to finish the project throughout the semester. The next group assignment that is listed is the Engineering Model summary in which the team was required to summarize what the problem the project is trying to answer and how the team planned on solving the problem. Following the Engineering Model Summary, the team was tasked to employ an individual assignment in which each team member was required to research something important to the overall project whether it be learning some new software's needed to test the drone or actual analyzing the drone itself. The final team assignment tasked in the first six weeks was the 33% build checkpoint. For the 33% build, Team Hi-Jacks set a plan to finish up the wiring of the drone and ensure that the wiring was solid enough to run the motors. The team was also tasked with reporting and presenting everything up to this point in front of the professor and the class.

For weeks 6 through 11 (Appendix C: Figure 2), the timecard submissions 6-12 were due similar to weeks 1 through 5. In addition to the timecard submissions, the team was tasked with Undergraduate (U-Grads) Registration, 67% Build Update, Final Testing Plans, and finally the 100% Build Update. For the U-Grads registration, the team was required to finalize a team name, project name, write up an abstract to summarize what the project was trying to accomplish, and submit it to NAU to be included to the U-Grads Symposium taking place on April 28, 2023. For the 67% Build Update, the team wanted to finalize a flying drone, updated CAD model, and a fairly accurate SolidWorks Analysis for the drone frame. To prove that the drone was at this point, the team presented in front of the class with a small demonstration as well. The following team assignment was a finalized testing plan in which the team was required to create a solid plan in which to test the project to ensure that all the customer requirements/engineering requirements were met and/or exceeded. The final assignment on this figure is the 100% Build Update in which the team was required to have their build basically finished up with some initial testing to show that the build works and succeeds in what the team is trying to accomplish. With the 100% Build assignment, the team presented their final product to the class with a short demonstration for everyone.

The final figure shows the finalized Gantt Chart for weeks 11 to 16 up until the final assignment of the Final Report (Appendix C: Figure 3). For these weeks, the team was required to submit the respective week's timecards as well as the Final CAD Package, Initial Testing Results, U-Grads Poster and PowerPoint, Product Demonstration, Final Report, Operation/Assembly Manual, and Client Handoff. The Final CAD Package deliverable required Team Hi-Jacks to submit the entire CAD Model of the drone frame design with drawings, assemblies, and part callouts for every part of the entire project. The Initial Test Results assignment tasked the team to create a presentation to show what types of testing has already been accomplished as well as how the results of the tests were comparing to the customer and engineering requirements set for us by Boeing and our clients. The U-Grads Poster and PowerPoint assignment was to ensure that the team was on track to be able to present at the symposium in April as well as to see a majority of the project and what the team was able to accomplish throughout the past two semesters. The Product Demonstration, Final Report, and Final Testing Results were assigned to the team to be finished in the same week and these assignments are worth a majority of the grade for the semester and will show the success of the work that has been accomplished in the two semesters spent working on the project.

The Product Demonstration is a simple demonstration of the flying drone to show to the professor as well as the rest of the class. The Final Testing Results is a presentation assignment that shows how the testing process has helped in the overall building of the drone frame and the flying that has taken place. The Final Report is a long paper that is meant to report all the work that was done for the semester as well as the work that was done in the previous semester to show the process in which the team completed the goal of a flying drone. The Operation/Assembly Manual is a guide to the client in how to create the drone frame, test, fly, and all other components needed to recreate the drone as well as how to operate the drone and to use in the future without the guidance of the team into a smooth Client Handoff.

In general, the Gantt Chart was a vital piece in order to ensure the smooth process of meeting all requirements for the Mechanical Engineering Senior Design Capstone Class as it laid out all of the deliverables for the semester in a clear, concise manner so each member of the team can keep track of what and when things need to be completed. The major portion of the Gantt Chart that has changed from the beginning of the semester is the design of which tasks were assigned to each member for each deliverable. In the beginning of the semester, it was quite difficult to understand a good way to split up each deliverable in an even manner while following the roles of each team member. This was updated quite often in order to specify which member needed to do to complete all assignments. Tasks were also shared between team members and could not have been predicted due to dynamic assignments in which multiple team members were needed to carry out a task.

6.2 Purchasing Plan

For this project, Boeing granted Team Hi-jacks with $5000 to complete all customer requirements. Along with this budget, the clients provided the team with a list of manual drone parts that were used in previous years at Boeing for similar tasks.

To start the first semester, the team began to create a ‘cheap and dirty’ drone prototype that would symbolize the teams’ ideas of frame shape, frame size, and leg/arm dimensions. This prototype was labeled as ‘Prototype 1’ and was produced using cheap 3D ABS printers at the NAU Maker Lab. This model consisted of only 3 plates, and four arms with no legs (as shown in Table 6). The error on the printers that were used was rather high and caused all parts to be crooked and bent. The total cost of Prototype 1 was $66.49 which is reasonable for the quality and material that was used.

Table 6: Maker lab Prototype 1 BOM

Prototype 1		Print completed October 11, 2022	
ITEM DESCRIPTION	**Qty.**	**ITEM DESCRIPTION**	**Price ($)**
ABS 3D PRINTED PLATE	3	ABS 3D PRINTED PLATE W/KEY	30
ABS 3D PRINTED ARMS	4	ONYX 3D PRINTED ARM W/SPACER	36.49
			Total Price: $66.49

Following the production of the Prototype 1, the team put the budget to use by ordering all the manual flight components that Boeing recommended. This included the battery, motors, flight controller, and a few other components that would be needed to get the drone in the air (as shown in Table 7). These parts were purchased on amazon, various RC websites, as well as websites owned by the manufacturer of the component. The total price of the manual flight components came out to $851.64. While this may sound expensive, these parts are all necessary for flight and will be reused on all remaining variations of the drone.

Table 7: Manual flight components BOM

Manual Components- Purchased	Qty	Cost ($)	Primary Vendor	Manufacturer	Link to Cost estimate
Hobbytown 40A ESC	4	55.99	Hobby Town	Eflite	https://www.hobbytown.com/eflite
Gemfan 9045 3-Blade Prop	4	15.98	GetFPV	Gemfan	https://www.getfpv.com/gemfan-9
Battery Charger	1	52.37	Amazon	HTRC	https://www.amazon.com/Charger-
Battery Connector	1	8.99	Amazon	Elechawk	https://www.amazon.com/Pairs-Fe
Socokin 6S Lipo Battery	1	59	Amazon	Socokin	https://www.amazon.com/Socokin-
iFlight XING 2814 880KV Motor	4	154.4	PilotsHQ	iFlight	https://pilotshq.com/products/xing
Holybro Pixhawk 6C,PM07 Power Module,M8N GPS	1	359.99	GetFPV	Holybro	https://www.getfpv.com/holybro-p
Flysky FS-i6X 2.4GHz RC Trans/Receiver	1	55	Amazon	Flysky	https://www.amazon.com/Flysky-F
Bullet Connectors	1	7.99	Amazon	Bbrand	https://www.amazon.com/LinsyRC-
Male EC5 to Female XT60	1	8.99	Amazon	Fly RC	https://www.amazon.com/RC-Adap
Soldering Iron	1	42.99	Amazon	Guangzhou Yihua Electric Equipement Co.	https://www.amazon.com/YIHUA-A
Solder	1	7.99	Amazon	TOWOT	https://www.amazon.com/TOWOT-
1/2" Rubber Leg Stoppers	2	3.99	Amazon	Waxman	https://www.amazon.com/SoftTouc
EC3 Female Connectors	1	9.99	Amazon	Nuofany	https://www.amazon.com/5Pairs-C
Solder Flux	1	7.98	Amazon	Romeda	https://www.amazon.com/Solder-S
	Total Cost	851.64			

While the manual flight components were being shipped, material testing was a high priority for the team. Heavy research was then put into 3D printed materials and what was available to use. The team came to the decision that the material with the most potential for building a drone was Onyx polymer. To properly test different reinforcement types of Onyx, ASTM D638 Type 1 dog bones. 20 total dog bones were produced, 5 samples of each reinforcement, shown in Table 8. $119.14 was spent on these dog bones and this testing proved to be a huge improvement to the weight to strength ratio of the drone.

Table 8: Dog Bone Testing BOM

Dog Bone Testing		
ITEM DESCRIPTION	**PCS.**	**COST ($)**
ONYX	5	20.91
ONYX W/ CARBON FIBER REINFORCEMENT	5	35.87
ONYX W/ KEVLAR REINFORCEMENT	5	33.46
ONYX W/ FIBERGLASS REINFORCEMENT	5	28.9
	Total Cost	**119.14**

Prototype 2 was then created on December 2nd, 2022, using very similar aspects from Prototype 1 but this time with legs and most parts being made from non-reinforced Onyx. The plates would not fit in the Markforged printer, so the team was forced to try ABS. Bolts, washers and nuts were all required to keep the drone design in one piece, so this added a few dollars to the purchase as well as some weight. In total, this 3D prototype without the manual components attached cost $415.72. This means that Prototype 2 with all components added was around $1200 (Table 9).

Table 9: Hubs.com Prototype 2 BOM

ITEM DESCRIPTION	PCS.	WEIGHT [gm]	Cost ($)
ABS 3D PRINTED PLATE W/KEY	3	183	35
ONYX 3D PRINTED ARM W/SPACER	4	108	178.12
ONYX 3D PRINTED LEG W/ARM CLAMP	4	76	119.08
ONYX 3D PRINTED SPACER W/ARM CLAMP	4	60	76.16
HEX BOLT ZINC 1/4" X 5-1/2"	4	112	2.76
HEX BOLT ZINC 1/4" X 1-1/2"	8	96	2.35
HEX NUT ZINC 2/4"	4	12	1.26
FLAT WASHER ZINC 1/4"	8	16	0.99
		663	**415.72**

This prototype was then put to work with many flight tests which included take-off, landings, and failures. The drone had multiple broken arms, legs, support parts, and a few propellors that would need to be fixed. As shown in Table 10, replacement parts for the entire drone were updated in CAD then sent off to the Idea Lab at NAU. Some of these replacement parts were reinforced with carbon fiber while the plates and legs would remain non-reinforced. These replacement parts cost the team $403.53 which is expensive due to the cost of carbon fiber reinforcement. These parts were printed on March 8, 2023.

Table 10: Prototype 2 replacement part cost

Replacement/reinforced Parts after crash							
Part	**PCS.**	**Item No**	**Item Description**	**Weight [g]**	**What**	**Where**	**Cost ($)**
1	3	22F-001	ABS 3D Printed Plate W/ Key	183	ABS	IDEA Lab	88.8
3	4	22F-003	Carbon Fiber infused ONYX 3D Printed Arm W/Spacer	108	ONYX (carbon infused)	IDEA Lab	146.34
4	4	22F-004	ONYX 3D Printed Leg W/Arm Clamp	76	ONYX	IDEA Lab	119.08
5	4	22F-005	Carbon Fiber infused ONYX 3D Printed Spacer W/Arm Clamp	60	ONYX (carbon infused)	IDEA Lab	49.31

These reinforced and updated drone parts did very well for most of the semester but there were a few CAD model updates that the team wanted to have printed. These updated CAD files were uploaded to Hubs.com and express shipped to the team so they could assemble it and spray paint the body. This is considered the "Final Design" assembly that will be handed off to the clients and shown off at the Ugrads symposium. The parts for the Final Design were $726.95 from Hubs.com and came in just a few days. This was the final purchase made by the team and was completed April 14, 2023. For recap, Table 11 shows that the team spent $2583.44 of the budget in two semesters. This is only half of the total budget which the team is very proud of.

Table 11: Total budget spent BOM

Total Project Budget	Price ($)
Prototype 1	66.49
Manaual Components	851.64
Dog Bone Testing	119.14
Prototype 2	415.72
Replacement Parts	403.5
Final Design	726.95
Total Funds Used	2583.44

Overall, Team Hi-Jacks was fortunate to receive such great funding from Boeing which opened doors such as 2-day shipping on perfectly printed drone parts. Although the team barely scratched half of the budget, the team wouldn't change a thing about the purchases made. Carbon fiber reinforced onyx is one of the strongest 3D printing materials on the market right now and the team used it to its full potential. With a smaller budget, the team likely wouldn't have been able to use these materials and limited themselves to ABS. The team didn't expect to come anywhere close to $5000 and this is exactly what occurred. The team thanks Boeing, once again, for their generosity in funding that allowed the team to approach this project with full potential and zero roadblocks.

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6.3 Manufacturing Plan

For the project, the main goal of the team was to make a design and prototype of the Drone frame. The team started designing last semester by asking each student in the team to make a design of their own and then evaluating using a simple Morphological matrix (Appendix B: Table 1), Pugh Chart (Appendix B: Table 2), and decision matrix (Appendix B: Table 3) to select the best one possible for the project (Refer sec. 4). The design selected consisted of 4 main parts discs, arms, legs and connectors. After the design was selected, the main question was what materials and what infill to use to manufacture the drone frame. The team started thinking about that and decided to make prototype 1 which consisted of plates, arms and connectors using all ABS from NAU MakersLab costing $66.49. After the prototype 1 came in the team realized that the 3D and the material both were below the expectations of the team and will have to find the better way to 3D print with better materials and infill.

The team started searching for new materials and infill to make our drone better and sustainable. The team went to the IDEA Lab and discovered all the materials available. The one material that stuck to the team was Onyx polymer. There were multiple Onyx materials available with different reinforcements such as carbon fiber reinforced Onyx, fiberglass reinforced Onyx, Kevlar reinforced Onyx and non-reinforced Onyx. The team then decided to do a material test before 3D printing the prototype realizing that the team printed prototype 1 without any tests, and it came out the way the team did not want. So, the team printed 4 samples of each Onyx polymer costing $119.14 and performed the Dog-Bone Test (Fig. 42, 43, 44, 45) on all four different varieties of Onyx. The results came out as expected with the highest strength was carbon fiber reinforced Onyx and with the most extension was non-reinforced Onyx. Once the results were in, the team decided to print prototype 2. Prototype 2 consisted of discs, legs, arms and truss (connectors) but with improvements in the trusses (Refer sec. 7). Prototype 2 was made with an ABS disc from IDEA Lab and non-reinforced legs, arms, and trusses from Hubs.com (outsourced). The prototype cost $415.72. Prototypes 1 and 2 were printed in the first semester of Capstone (Fall 2022).

Coming into the second semester (Spring 2023), the team decided to put the drone to real-life test by putting all manual flight components on the drone and flying it. After flying prototype 2 several times indoors and outdoors, an unfortunate thing happens, and the drone crashed on ground from about 20ft in the air. 2 legs, 2 arms and a truss broke at moment and the team decided to reevaluate the materials that needed to be used. The team looked for the most damage and decided to use carbon reinforced Onyx for the arms and truss, an ABS disc, and non-reinforced Onyx for legs from IDEA Lab for the replacement parts costing. $403.53. The discs were kept as ABS because the discs did not fit into Markforged 3D printer. After putting everything together the team wanted to do some more tests on replacement parts by flying it and so decided to print the prototype 3, to be in safer side to have an extra set of parts just in case the team crashed the drone again and needs some replacement before the symposium. Prototype 3 consisted of the same 4 sets of parts but ABS discs and non-reinforced arms, legs, and trusses from Hubs.com (outsourced) because the 3D printer at IDEA Lab broke. Prototype 4 costs around $726.95.

Table 12: Finalized manufacturing BOM

Prototype 1				
Parts	Materials	Manufactured when?	Manufactured where?	Cost
Discs	ABS	10/11/2022	MakersLab	$30
Arms	ABS	10/11/2022	MakersLab	$36.49

Prototype 2				
Discs W/Key	ABS	12/2/2022	IDEA Lab	$35
Arms W/Spacers	Non-reinforced Onyx	12/2/2022	Hubs.com	$178.12
Legs W/Arm Clamps	Non-reinforced Onyx	12/2/2022	Hubs.com	$119.08
Spacers W/Arm Clamps	Non-reinforced Onyx	12/2/2022	Hubs.com	$76.16
Prototype 2 Replacement parts				
Discs W/Key	ABS	3/8/2023	IDEA Lab	$88.8
Arms W/Spacers	Carbon infused Onyx	3/8/2023	IDEA Lab	$146.34
Legs W/Arm Clamps	Non-reinforced Onyx	3/8/2023	IDEA Lab	$119.08
Spacers W/Arm Clamps	Carbon infused Onyx	3/8/2023	IDEA Lab	$49.31
Prototype 3				
Discs W/Key	ABS	4/14/2023	Hubs.com	$214.67
Arms W/Spacers	Non-reinforced Onyx	4/14/2023	Hubs.com	$260.08
Legs W/Arm Clamps	Non-reinforced Onyx	4/14/2023	Hubs.com	$117.52
Spacers W/Arm Clamps	Non-reinforced Onyx	4/14/2023	Hubs.com	$75.68

7 Final Hardware

7.1 Final Hardware Images and Descriptions

The final design is shown below in Figure 35. It is very similar to the design selected at the end of the first semester, shown in Figure 33, with only cosmetic and ease of use changes. The frame is designed for maximum strength, especially in case of a hard landing. The legs are connected to the truss through the arms to distribute forces away from just the legs and arms. Like the original design, the stacked plate idea held out due to a naturally central CG (Center of Gravity) and compact shape. Unlike the original, keyways in the arms and plates and the trusses were added to prevent the arms from rotating, a design idea that proved to be immensely useful when spinning up the motors at takeoff. The final design with all components mounted is shown in Figure 36. It makes use of the mounting holes for the motors and divots for the battery while all other components are taped or secured with Velcro.

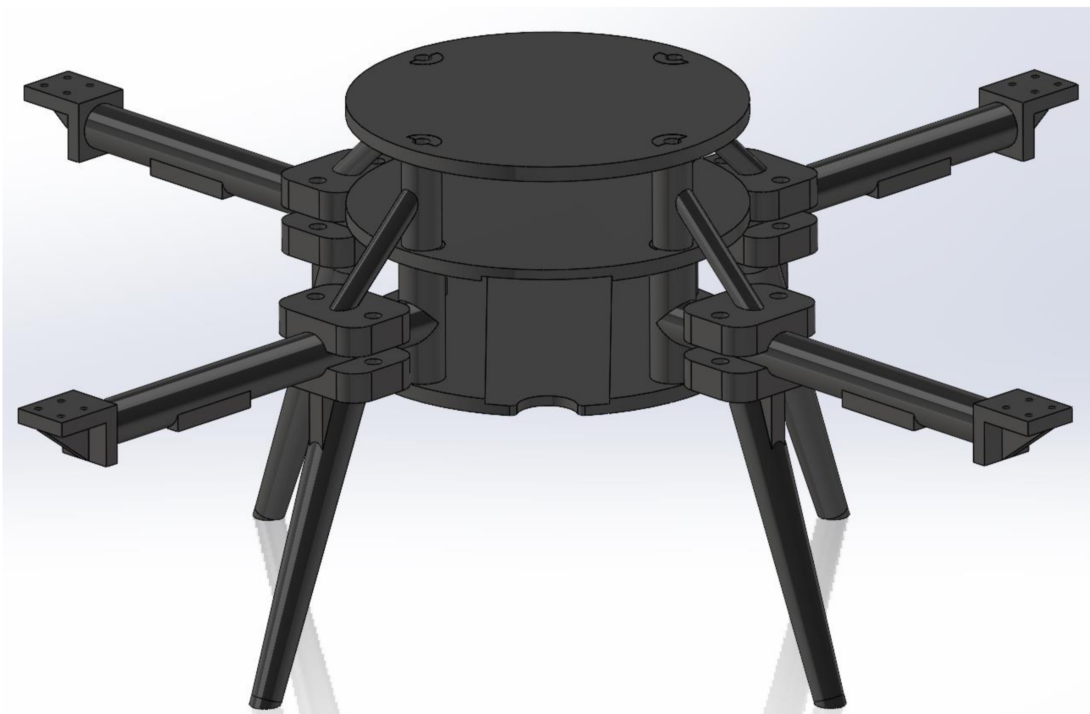

Figure 35: CAD model of final design

Figure 36: Final design with all components mounted

7.2 Design Changes in Second Semester

7.2.1 Design Iteration 1: Change in Arm Discussion

The original arm design in Figure 37 was much simpler and relied on friction from the bolts to prevent it from swiveling. The team concluded that keyways and a truss were needed as it would be lighter than adding a second bolt to each arm. The motor mount changed drastically once the team had motors in hand. It is based on the length of the screws, making them perfectly flush with the screw holes on the motor. Finally, the arms were slightly extended for greater stability in flight and a mount was added on the bottom for the speed controller. The final design is shown in Figure 38.

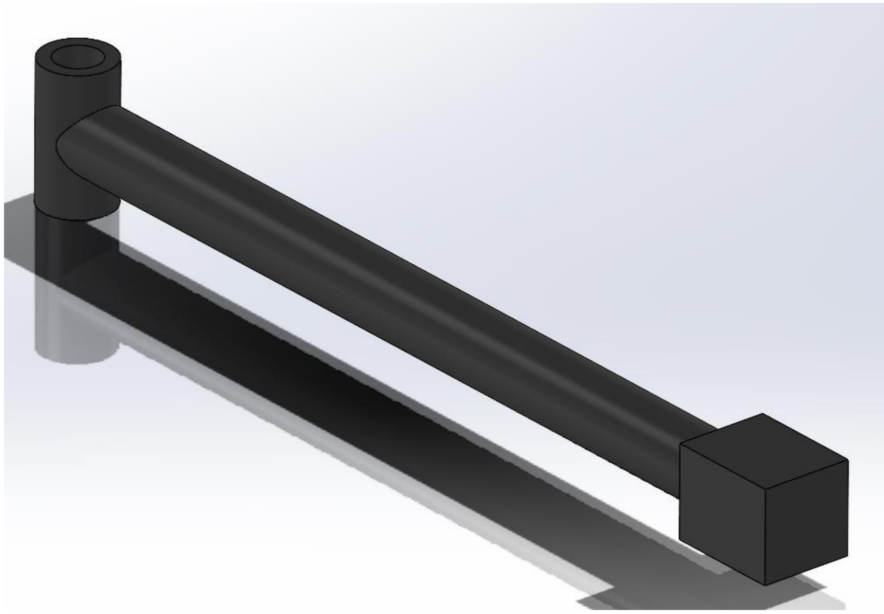

Figure 37: Original arm design

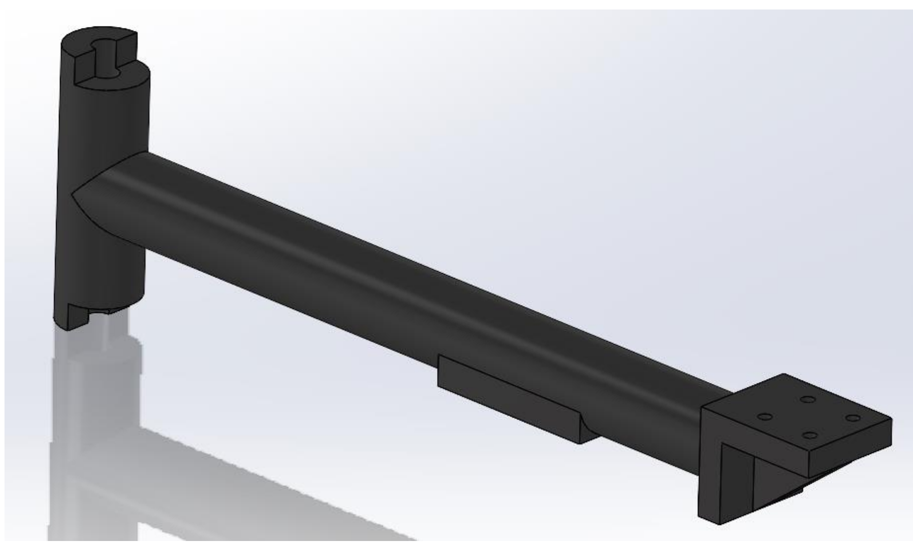

Figure 38: Final arm design

7.2.2 Design Iteration 1: Change in Leg Discussion

The original design for the leg (Figure 39) was just a very rough idea and would not have sufficed. The original design was meant to slide onto the arm, but the team quickly realized this would go against the design idea of having a very modular drone. It also did not take the location of the camera and gimble into account as they are supposed to be mounted to the bottom on the drone. The original leg had no clearance. The final design (Figure 40) solved each of these issues by making a two-part design with the truss. This makes it modular so it can be replaced easily in the event of a crash because it is designed to break rather than transfer load to other components. Since the arm was moved between the bottom two plates rather than the top two, it reduces the required length of the leg, adding strength and overall survivability to the drone.

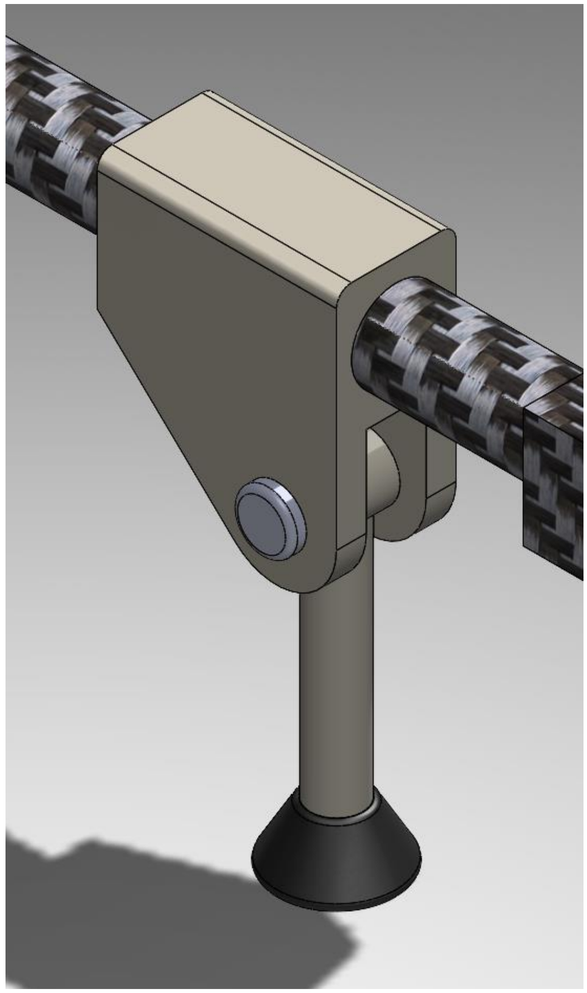
Figure 39: Original leg design

Figure 40: Final leg design

7.2.3 Design Iteration 1: Change in Truss Discussion

The truss system in Figure 41 was not included in the original design and was only present in the previous two prototypes. Its goal is to prevent the arms from swiveling and to transfer force from the legs and arms. It also acts as a spacer for the top two plates. The only major change is the fillet to the sharp edges to reduce weight and make it look more pleasing.

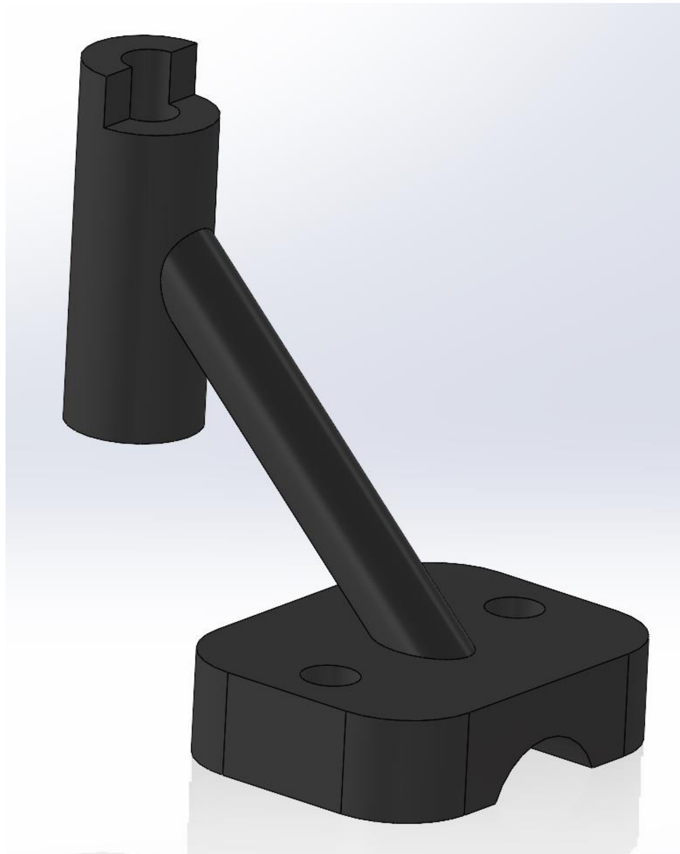

Figure 41: Final truss design

7.3 Challenges Bested

Getting to 100% hardware was an overall smooth process. The only issue the team faced was working with the IDEA Lab. Their short hours every day, occasional broken printers, and competition for those machines with other projects made it difficult to have parts ready in a timely manner. Many days were lost waiting for parts and final testing values could have been reached much sooner. Otherwise, the team worked hard to ensure that every deliverable was ready on time, and the final build was how we and the client wanted it without overrunning the budget or deadlines.

8 Testing

8.1 Testing Plan

To meet all the customer requirements (Table 1) and the subsequent engineering requirements (Table 2), it is important that the team runs a series of testing procedures to gain insight into the outcomes of the project. These customer/engineering requirements were put into the QFD (Appendix A: Table 1) to better understand which requirements were related to the next. Using these similarities, a finalized testing plan could be developed to test to make sure that each of the needs and requirements were met (Table 13). This testing plan explains what will be tested, how each of these tests will occur, where the testing will take place, and which design requirements and questions will be answered. Table 13 is all the testing that will occur to ensure safe and stable flight.

Table 13: Finalized testing plan

TEST	WHAT	HOW	WHERE	RELEVANT DESIGN REQUIREMENTS
TAKEOFF	PERCENT THROTTLE NEDDED FOR AIRBORNE	THROTTLE WILL BE INCREASED BY 5% FOR EVERY TRIAL	INDOORS/OUTDOORS OR QGroundControl	CR1, CR2, CR9, ER2, ER9
MANEUVERING	STABILITY, MANEUVERING, SAFETY WHILE AIRBORNE	SLECTION OF SETTINGS OF MANUAL CONTROLS	QGroundControl	CR1, CR2, CR3, CR9, ER1, ER9
FLIGHT STABILITY	STABILITY, MANEUVERING, SAFETY WHILE TAKEOFF/ LANDING	SELECTION OF DIFFERENT MODES FROM QGroundControl	QGroundControl	CR3, CR7, ER3, ER7
FLIGHT CHARACTERISTICS	PROPERRTY OF THE BODY AND ACCESSORIES OF DRONE. FOR EX. THURST-TO-WEIGHT RATIO, FLIGHT TIME, LOAD CAPACIITY, MAX. SPEED, ETC.	BY COMPUTING ALL THE COMPONENTS IN eClac	eClac	CR2, CR4, ER2, ER4
LANDING	STABILITY, MANEUVERING, SAFETY WHILE LANDING	LANDING DRONE IN DIFFERENT TERRAINS/HEIGHTS	OUTDOORS	CR1, CR2, CR9, ER2, ER9
DROP TEST SIMULATION	MATERIAL TESTING AND IMPACTS	DROP TEST SIMULATION	SolidWorks	CR3, CR5, CR6, CR8, ER3, ER8
THRUST TO WEIGHT RATIO	PERFORMANCE OF MOTORS	BY COMPUTING ALL THE COMPONENTS IN eClac	eClac	CR2, ER2
WEIGHT	WEIGHT REDUCTION FROM ORIGINAL DESIGN	PUTTING ALL THE PARTS TOGETHER AND WEIGHING	WEIGING SCALE	CR1, ER1

To meet every single customer/engineering requirement, material testing is required to better understand what properties the 3D-printed material will have in a real-world sense. Table 14 shows all the required materials needed to run the material testing procedure accurately and efficiently.

Table 14**:** Material test BOM

Bill of Materials							
Team				Boeing Drone Capstone			
Part #	**Part Name**	**Qty**	**Description**	**Functions**	**Material**	**Dimensions**	**Cost**
1	Dog Bone 1	5	No reinforcement	control test	ONYX	115mm x 6mm x 3mm	10
2	Dog Bone 2	5	carbon fiber	test	ONYX	115mm x 6mm x 3mm	40
3	Dog Bone 3	5	Kevlar	test	ONYX	115mm x 6mm x 3mm	35
4	Dog Bone 4	5	fiberglass	test	ONYX	115mm x 6mm x 3mm	35

5	Instron Device	1	NAU Supplied	Tester	n/a	n/a	0
6	Ruler	1	student supplied	measurement	n/a	n/a	0
7	Digital Caliper	1	lab supplied	measurement	n/a	n/a	0
8	scale	1	student supplied	measurement	n/a	n/a	0
Total Cost Estimate:							120

8.2 Testing Results

To meet customer requirement number three (Table 1), high frame strength, Team Hi-Jacks ran a series of material testing on Onyx polymer with different types of fiber reinforcements to find a more accurate measurement of the material strength due to limited research on this polymer. The different types of fiber reinforced parts tested include non-reinforced (Figure 42), carbon fiber reinforced (Figure 43), Kevlar reinforced (Figure 44), and High Strength, High Temperature (HSHT) fiberglass reinforced (Figure 45). The raw data results can be found in Appendix D: Table 1

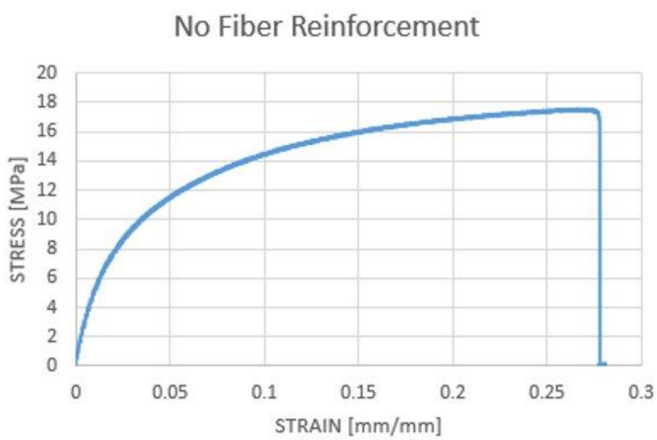

Figure 42: Load data for non-reinforced Onyx polymer

Figure 42 (above) shows the Stress versus strain curve of the plain based Onyx polymer for reference to compare to for the other reinforced parts. This material was the weakest by far but also had the highest strain value and was a great reference for the rest of the data. In addition, the fact that this material had such a high strain value was a contributing factor in choosing which material should be used for the legs of the drone as the legs of the drone experience high factors of strain and less forces compared to the rest of the parts on the drone such as the arms.

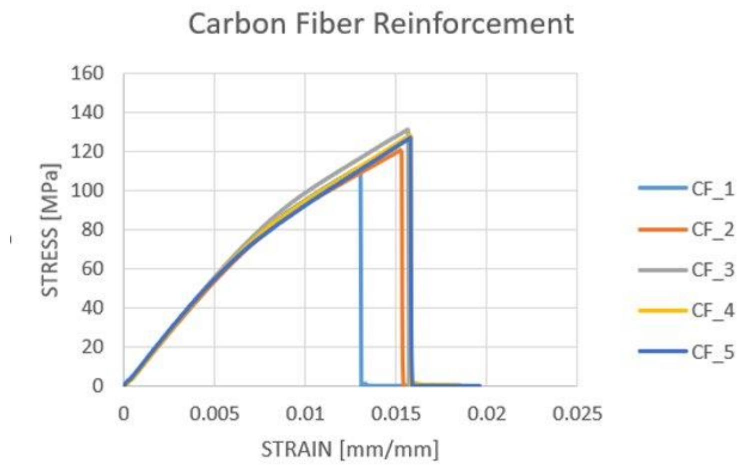

Figure 43: Load data for carbon fiber reinforced Onyx polymer

The figure above (Figure 43) shows the carbon fiber reinforced polymer and shows that this material is the strongest out of all the other reinforced parts. The fact that this reinforced part can experience much higher stresses compared to the others really stood out to the team and was the driving factor in why this material was chosen for a majority of the drone frame. Figure 44 and 45 (below) show the stress versus strain curves of the Kevlar reinforced Onyx and HSHT fiberglass reinforced Onyx, respectively, and were not chosen as the final materials for the drone frame because these sample were not as strong as the carbon fiber reinforced Onyx.

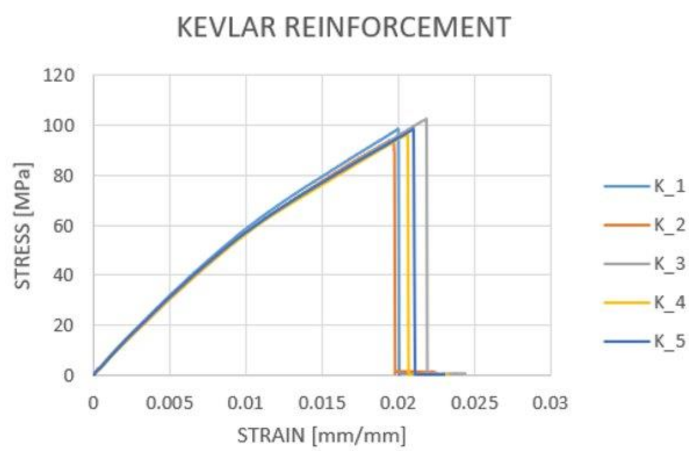

Figure 44: Load data for Kevlar reinforced Onyx polymer

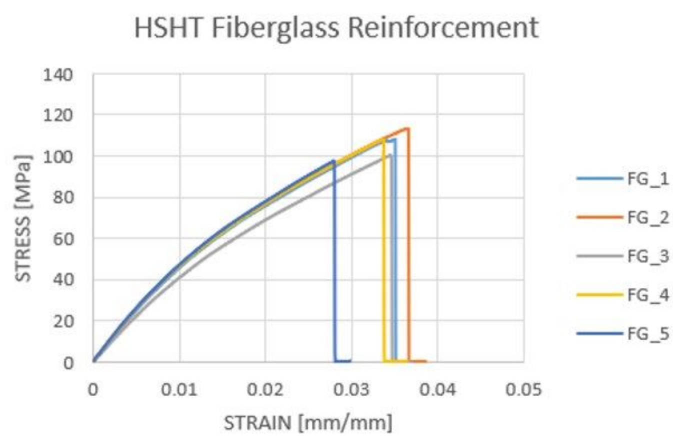

Figure 45: Load data for HSHT fiberglass reinforced carbon fiber

Customer requirement two (High thrust to weight ratio), four (Long flight time), and nine (flyable), which can be found in Table 1, all have to do with the flight characteristics of the drone and the best way to test these is with eCalc, an online resource that will give you these results with a +/- 15% accuracy (Figure 46).

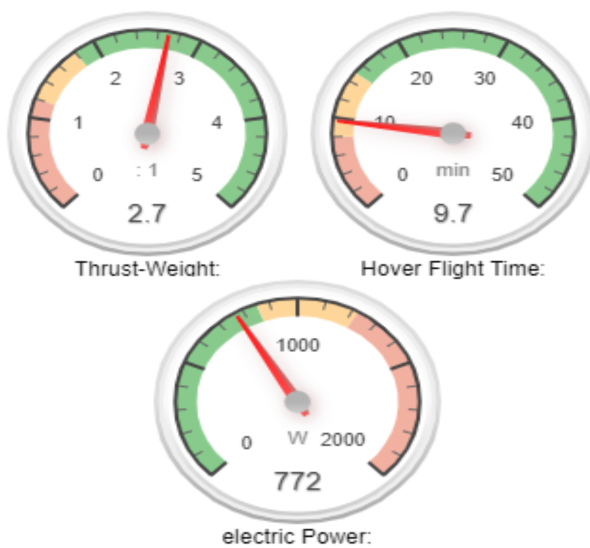

Figure 46: eCalc results

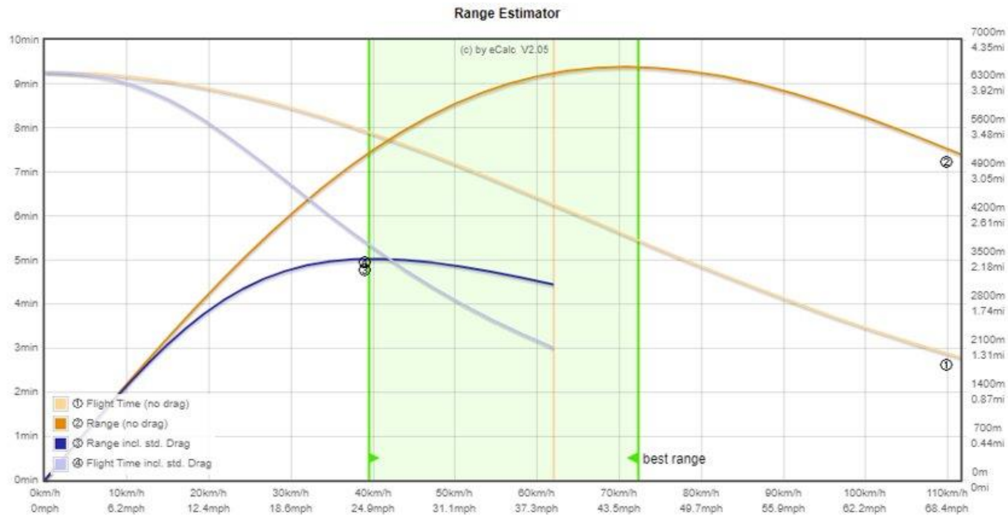

Figure 47: eCalc range, speed, time estimations

A more detailed graph of what results can be expected from drone flight through the eCalc can be seen in the figure above (Figure 47). This graph shows an estimated range of flights with different speeds and assumptions for flight quality. In this graph, the team is assuming flight in Flagstaff in March where the weather is lower than normal. From the results given to the team from the eCalc approximation, the flight time of the drone did not quite meet the engineering requirement of 10 minutes but because of the error in eCalc, a real-world battery test was required to find the actual results of how long the drone would be able to fly.

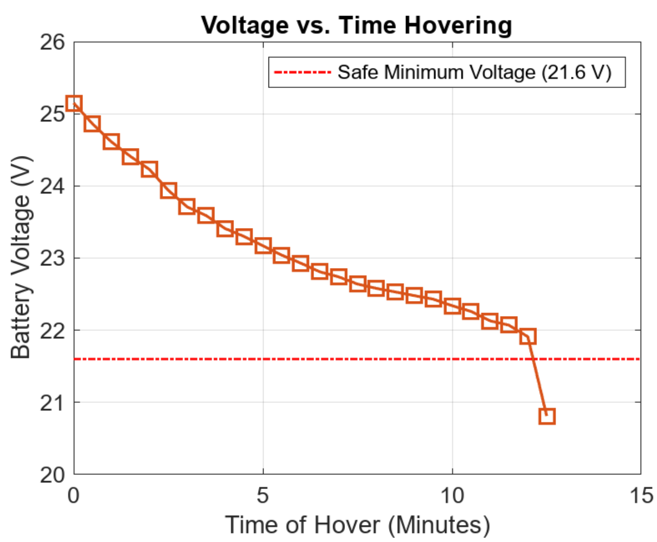

Figure 48: Real world battery voltage testing results

After testing the battery in real-world situations with only a hover, the results show that the battery will meet the engineering requirement of 10 minutes and even exceeds this value by 2.5 minutes. The figure above (Figure 48) shows the battery voltage versus time of hover. The figure below (Figure 49) shows the battery percentage versus time for a better reference of how much hover time the battery will be able to supply to the drone.

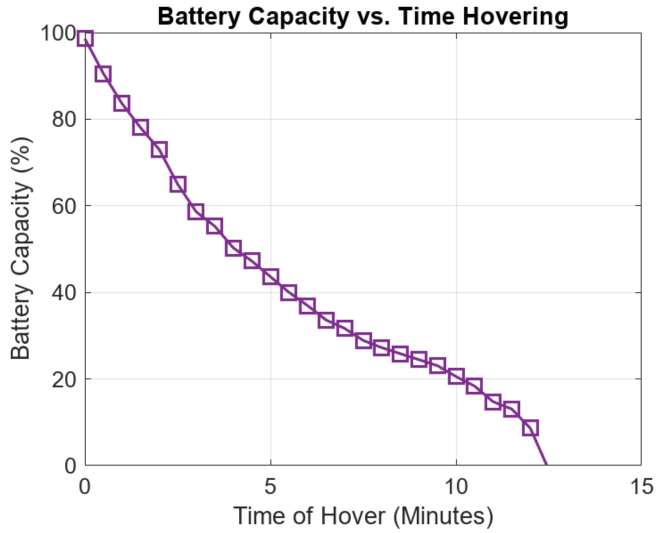

Figure 49: Real world battery percent testing results

To meet customer requirements 1 (Lightweight), 3 (High frame strength), 7 (Optimized component location), and 8 (Minimal hardware) the team designed a drop test simulation to determine and demonstrate the total strength and durability of the drone frame. In this drop test simulation, the frame was dropped from 10 feet in the air at various angles with the weight of each of the components attached to the frame of the drone for more accurate testing results.

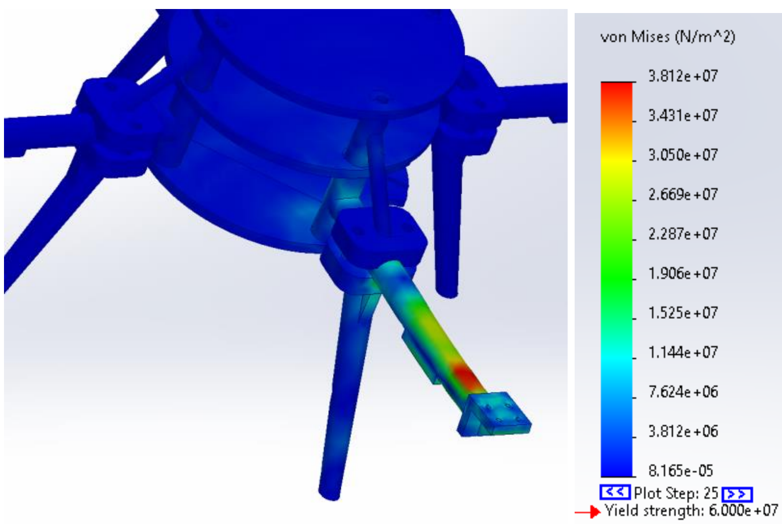

Figure 50: 30° angled 10ft drop testing results

The figure shown above (Figure 50) displays the results of the drop test of the drone at 10 feet in the air and a 30-degree angle on which the drone is falling onto the arm with the weight of all the components added onto the frame. The results shown through the von Mises color chart show that the arm of the drone never experiences enough stress to cause the arm to fracture or even yield.

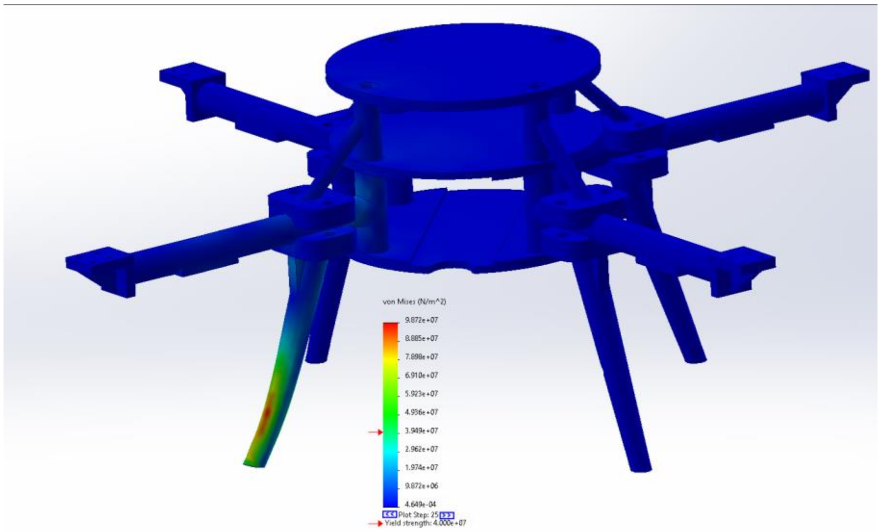

Figure 51: 15° angled 10ft drop test results

In the figure above (Figure 51), the results of a similar drop test can be seen but instead of the 30-degree angle in the previous test, this test shows the results of dropping the drone from 10 feet in the air at a 15-degree angle centered closer to the singular leg. It is important to note that with this test the leg did reach its maximum yield strength, but the leg does not fracture. This is due to the use of the non-reinforced Onyx being used on the legs due to having a lower strength but greater displacement than the rest of the parts. Additionally, it is equally important to note that in both cases of the drop test, the forces do not move inwards on the frame which is due to the way that the drone was designed and will likely ensure that the inner components will stay safe in a crash scenario.

Not shown in any of the figures above are the results of the flight testing. This is because this testing took place using a flight program called QGroundControl (Figure 52) and through slight modifications with controller settings (Figure 53).

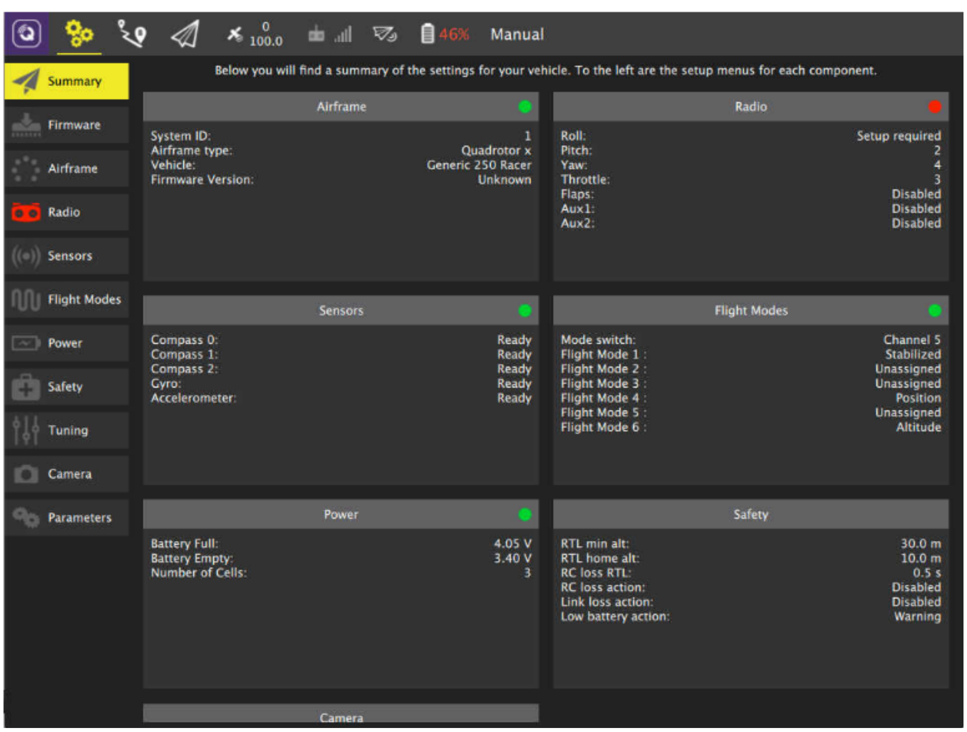

Figure 52: QGroundControl flight summary display screen

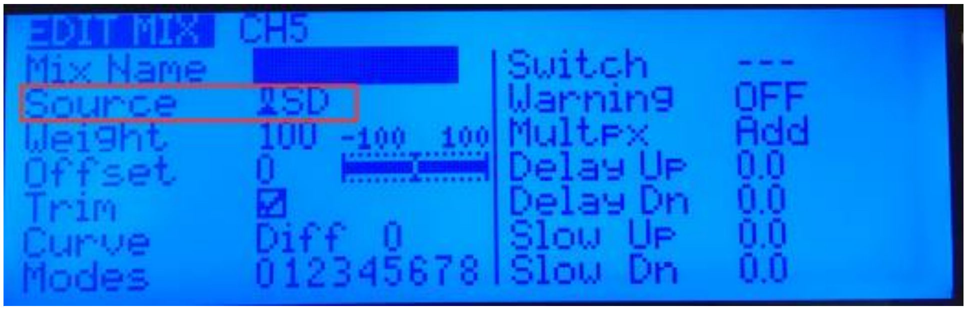

Figure 53: Flight controller settings screen

Using the flight controller settings and QGroundControl, a controlled and iterative flight-testing procedure was introduced. To meet the customer requirements of a flyable and safe drone, the team tested the takeoff, landing, flight stability, and maneuverability of the drone.

Table 15: Customer requirement summary

CUSTOMER REQUIREMENT	CR MET? (✓ OR X)	CLIENT ACCEPTABLE? (✓ OR X)
CR1	✓	✓
CR2	✓	✓
CR3	✓	✓
CR4	✓	✓
CR5	✓	✓
CR6	✓	✓
CR7	✓	✓
CR8	✓	✓
CR9	✓	✓

The table above (Table 15) shows a summary of each of the customer requirements and whether the team was able to meet these requirements after testing was completed. After meeting with the client, the team displayed testing results and if the requirements were met from the team's perspective and the client was able to explain if the results were acceptable in a professional setting. As can be seen in the table, all of the requirements were met, and the client was happy with the results as well.

The Engineering Requirement Summary (Table 16) is a table that displays each individual engineering requirement that the team was tasked to accomplish during the project. These requirements each had a value associated which makes engineering requirements different than customer requirements and each of these values were given directly from the client. The client also gave a tolerance of how close to each requirement the team could get if the exact value was impossible to meet. Through the process of testing, the team was able to measure/calculate the values that the current drone was able to produce. Based on the results calculated/measured, the team was able to conclude that every single engineering requirement was met, and the client was pleased with the work Team Hi-Jacks was able to produce.

Table 16: Engineering requirement summary

ENGINEERING REQUIREMENT	TARGET	TOLERANCE	MEASURED/ CALCULATED VALUE	ER MET? (✓ OR X)	CLIENT ACCEPTABLE? (✓ OR X)
ER1 - WEIGHT	< 3lbs	+0.0 lbs.	2.2lbs	✓	✓
ER2 – THRUST: WEIGHT	>1.81	-0	2.7	✓	✓
ER3 – FORCE	2000 psi	- 500 psi	6000psi	✓	✓
ER4 – FLIGHT	>10 minutes	- 0 seconds	12.5 minutes	✓	✓
ER5 – PRODUCTION	7 days	+/- 3 days	4 days	✓	✓
ER6 – COST	< $5,000	+$0	$2400	✓	✓
ER7 – CG	< ½”	+/- 1/8”	~1/2”	✓	✓
ER8 – # OF PARTS	< 30 parts	+/- 5 parts	27 parts	✓	✓
ER9 – SAFETY	90%	+/- 5%	87%	✓	✓

9 RISK ANALYSIS AND MITIGATION

Analysis was done of potential failures, also known as FMEA (Failure Modes and Effects Analysis). This looks at the design and generates potential points of failure and their causes. It assigns each potential failure a number based on a few different factors. The greater this number, the greater the importance of mitigating failure. This was performed so that the design could be altered to avoid as many of these failures as possible. The top ten most important failure modes are discussed below. Also discussed is how the trade-offs of each design alteration affect other potential failures, and how the risks work together.

9.1 Potential Failures Identified First Semester

Potential failures identified during the first semester can be seen in Table 17 below. The main concerns were the structural stability of various parts, especially the spacer, or part number 4. These failures were identified by analyzing the subsystems of the drone and where their respective weaknesses occurred. These risks were mitigated largely by increasing the size of the 3D printed parts, as well as selecting a stronger material. The full Failure Modes and Effects Analysis can be found in Appendix E: Table 1.

Table 17: Shortened failure modes and effects analysis

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
1	Impact Fracture	Flying debris and inoperative	Impact Loading	56	Increase plate infill
2	Impact Fracture	Flying debris and inoperative	Impact Loading	56	Increase plate infill
3	Impact Fracture and Low-Cycle Fatigue	Flying debris and erratic operation	Impact Loading	63	Increase arm thickness and key size
4	Impact Fracture	Poor appearance	Overstressing	100	Increase spacer thickness
5	Impact Fracture	Flying debris and inoperative	Impact Loading	105	Have spare backup parts
6	Impact Fracture	Erratic operation	Overstressing	72	Have spare backup parts
7	Impact Fracture and Ductile Rupture	Loss of stability	Overstressing	54	Have spare backup parts

9.2 Potential Failures Identified This Semester

There were a couple of new failures identified by the team in the second semester. First, through observation it was noted that the 3D printed parts would have a weak spot at stress concentrations that was magnified by the 3D printing process. The second failure identified was the loosening of various parts from the drone frame. This failure, however, was found to have a low-risk priority number. Other failures were identified concerning the components themselves. These, however, were outside of the design scope of the project and were not investigated further.

The first failure mentioned above was mitigated by adding chamfered sections to stress concentrations, strengthening them. The second failure was mitigated by creating a pre-flight checklist of components to check and tighten before flying the drone. These can both be seen in the full FMEA in Appendix E.

9.3 Risk Mitigation

As mentioned above, most mitigation was done by increasing the size of respective parts. Efforts were also made to ensure the system was safe and ready before each flight. Due to the size of the parts as seen in Figure xxx above, the risk for any given failure is relatively low. Chamfered sections were also added to aid in this. The major tradeoffs of these design decisions were the added weight of increasing part size and adding material. The drone however remained well under the weight requirement, but flight time and maneuverability were decreased. There was no increase in the difficulty of mitigating one risk while mitigating another. No new risks were created during this process either.

10 LOOKING FORWARD

10.1 Future Testing Procedures

The largest obstacle the team is currently facing is the ability to perform flight tests that go higher and farther than has currently been done. None of the team members have flown a drone before and are learning on the go, leading to smaller tests to ensure the safety of the drone and surrounding area. In the future these tests could be done by an experienced drone pilot who can control the drone in case, for example, the wind starts to carry the drone farther away or higher than the team feels comfortable with. Another way to solve this problem would be to set up autonomous flight. The goal of this project was to simply build the frame and perform analyses, but the team wanted to get it in the air. This meant that most of the time was spent getting it to fly manually as well as possible, therefore leaving no time to make it autonomous. This would have likely made it easier to fly higher and farther and gather the data needed to make the drone stable regardless of altitude or speed.

10.2 Future Iterations

Should this project continue with another team, the most important aspect for them would be to implement the rest of the parts given at the start of the project to make the drone autonomous. By adding a LIDAR, GPU, gimble, and camera, a future team could finish off the initial goal of the drone: autonomous land surveying. This could be a very interesting topic as it would likely include programming and some electrical engineering. Since adding these components will add weight and stress to the frame, a secondary goal could be to iterate on the current design by making it stronger and lighter. The current team had many ideas to achieve this but were constrained on time and focused on many other aspects of the requirements than just weight, although the final drone still had much though put into this area.

11 CONCLUSIONS

The Boeing Drone team was tasked with designing, manufacturing, analyzing, and testing a lightweight 3D printed drone frame. Each customer requirement was either met or exceeded, including a lightweight frame, high thrust to weight ratio, sturdy design, long flight time, and manual flight capability, with the latter being an optional requirement the team decided to undertake and expand on. Extensive testing concluded that the three-pound weight requirement was exceeded at 2.2 pounds, the 2.7 thrust to weight exceeded the 1.81 requirement, while surviving 10-foot drop tests met the client needs. Furthermore, the client did not give a minimum flight time but was impressed with 12.5 minutes. Together with the “extra credit” task of getting airborne, the client is very happy with the design, making the project an overall success.

11.1 Reflection

This project is a culmination of many classes taken at NAU. Computer aided design, mechanics of materials, and project design are some of the many skills that were required to complete this project efficiently and effectively. Since a drone as big and heavy as the team’s is so dangerous, these skills were geared towards making safety a top priority. Each part had to be analyzed to ensure it would fit well with the other parts and not break apart under normal, and some extenuating, circumstances. Different tests such as center of gravity and strength were required before the drone flew so the team would be confident that it would be always stable and in control, all requiring knowledge gained from classes at NAU. These tests proved helpful on many occasions when the drone was being tested around people or in smaller spaces. Often the drone would have a hard landing or crash, but it would behave how the team predicted, only breaking where it should, or not breaking at all. Additionally, the team wanted to be frugal with purchasing in terms of cost and material. The design chosen was made to reduce waste and therefore cost, helping the environment and saving a future budget, again thanks to knowledge learned in the last four years.

11.2 Resource Wishlist

If the team were to do the project over again it would be very helpful to have 3D printers that were owned by the team. Many days of work throughout each semester were lost due to printers in the IDEA Lab being used or broken. It would have streamlined the process and being able to change the printer settings would have been very beneficial. For example, the amount of carbon fiber infill in the parts were done without the team by the employee working that day and could have been better optimized for weight and strength through iteration and testing of individual parts. This was not feasible solely due to time constraints in the IDEA Lab. Additionally, ready access to specific tools such as belt sanders, Dremel, and metals saws would have saved time and energy throughout the building process.

11.3 Project Applicability

Damien – The project has helped me prepare for my future career by providing insight into how large-scale projects work and problems that can arise during them. I will be able to look back on the logistical, manufacturing, and implementation problems that occurred and think about how to solve them. Over the course of the project, I also gained a breadth of experience with various software and their applications.

Tommy – This project has given me a much wider view of what I want to do with my future career. I originally thought that I only wanted to focus on the airplane side or aerodynamics but after seeing what Boeing does in Mesa, it has given me a much wider view of interesting fields in the aerospace industry that do not necessarily relate to planes. Working with Boeing has been an honor that I don’t take lightly and I’m hoping I can start my career there with the jumpstart that only this project could have given me.

Dante – Throughout the course of the Northern Arizona University (NAU) Mechanical Engineering Senior Design Capstone, there have been many new concepts that have given me a chance to really apply everything that I have learned in my college career. Our main advisors for this project are the clients we have worked with from Boeing and because of this, we have learned a great deal about how a manufacturing process works in a real-world situation such as Boeing. This has greatly widened my view in the scope of an engineer because I was able to grasp what being an engineer is all about. Additionally, the knowledge I have gained in programs such as ANSYS and SolidWorks has grown exponentially, setting me up for success in future endeavors. In general, this project has made a huge impact on my current knowledge as an engineer and has greatly prepared me for the real world.

Colby – This project was nothing short of amazing in my eyes. We started the project by receiving a client that has goals for the team, just like a professional engineering team would receive a customer. The team is now committed to working with each other to complete this one end goal. Getting to know my teammates, finding their strengths and weaknesses, and seeing them multiple times a week makes me feel a little more prepared for what jobs will ask of me in the future. Boeing was the best client that was offered at our school, and I can say that they just blew my expectations out of the water. Michael and Amanda are the most professional and authentic engineers I have met in my life, and they treated us like we worked at Boeing for two semesters. They were responsive, helpful, and great leaders which shows me how a professional engineer should present themselves. I had a blast every time I worked on this project and feel ready to begin my professional career as an engineer.

Jay – This project has been a really good experience for me especially when you are more inclined to practical hands-on jobs rather than lectures, and you get to do it. The project started from scratch, and the team did an amazing job achieving all the client requirements and engineering requirements. It really taught me how to accept the challenge and move forward without any references. The overall experience of working with all my teammates was fabulous and gave me the experience of working with a team in the future. Constantly being in touch with clients and meetings with clients gave me a professional experience that is usually seen in corporates. The assignments we did throughout capstone, especially the Presentations was gem and made me feel much more comfortable in public speaking than I was ever in my life. I even learned new skills from this project such as Advance SolidWorks, Ansys, and Website building. The best out of all experiences I had in this project was only working on the capstone but also the Boeing Mesa tour that the clients offered us. It was just mind-blowing. There are many experiences that I can list but all in all, I wanted to say this project/Capstone made a huge impact on my life and on my future career by opening my eyes to look at how the product is made from scratch. We started with brainstorming, designing, testing, materials, prototypes, etc. I can say that I have had a whole lot of challenges and tasks that came through this capstone that I am going to see in the future. Overall, it was a really great experience with my teammates, clients, and professors.

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13 APPENDICES

13.1 Appendix A: House of Quality

Table 1: Quality Function Deployment (QFD)

System QFD

Project:	**Boeing Autonomous Drone Weight Reduction Capstone**
Date:	09/18/2022

#	Technical Requirement	1	2	3	4	5	6	7	8	9	10
1	WEIGHT REDUCTION < 3LBS										
2	THRUST TO WEIGHT RATIO > 1.81	9									
3	LIDAR FIELD OF VIEW										
4	CAMERA FIELD OF VIEW			3							
5	CENTER OF GRAVITY	1	1	9	9						
6	MATERIAL STRESS ANALYSIS	3									
7	MATERIAL COST ANALYSIS	9	1				-9				
8	TIME OF FLIGHT	9	9			1		-3			
9	LESS THAN $5,000	3	-3				-9	9	-3		
10	MINIMIZE HARDWARE PIECES	3		1	1		-3			-1	

Legend	
A	DJI PHANTOM 4 RTK DRONE
B	YUNEEC TYPHOON H PLUS
C	PARROT ANAFI USA DRONE

			Technical Requirements										**Customer Opinion Survey**				
#	**Customer Needs**	**Customer Weights**	WEIGHT REDUCTION < 3LBS	THRUST TO WEIGHT RATIO > 1.81	LIDAR FIELD OF VIEW	CAMERA FIELD OF VIEW	CENTER OF GRAVITY	MATERIAL STRESS ANALYSIS	MATERIAL COST ANALYSIS	TIME OF FLIGHT	LESS THAN $5,000	MINIMIZE HARDWARE PIECES	*1 Poor*	2	*3 Acceptable*	4	*5 Excellent*
1	LIGHTWEIGHT	5	9	9			3	3	3	9	1	3		B		A	C
2	OPTIMIZED THRUST TO WEIGHT RATIO	4.5	9	9			1			9					B	AC	
3	OPTIMIZED COMPONENT LOCATION	3.5			9	9	9	1				3		C		AB	
4	3D MATERIAL PROCESS	4	9	9			9	9	9		9	3		B	A	C	
5	MANUFACTURED PROTOTYPE AIRFRAME	5	9	3	9	9	1	9	9	3	9		B		C	A	
6	FLYING PROTOTYPE	2	9	9	9	9				3	3				AC	B	
7	LOW COST	1.5	9					1	9		9	3	A	C	B		
8	MINIMAL HARDWARE	3	9				1	3	3		3	9	B			C	A
	Technical Requirement Units		LBS	N/A	DEGREES	DEGREES	INCHES	PSI	$	MINUTES	$$	#					
	Technical Requirement Targets		2.8	2	180	360	0	2000	150	30	1500	24					
	Absolute Technical Importance		225	154.5	94.5	94.5	95	110	118.5	106.5	114.5	69					
	Relative Technical Importance		1	2	7	7	7	5	3	6	4	10					

13.2 Appendix B: Concept Generation

Table 1: Morph matrix

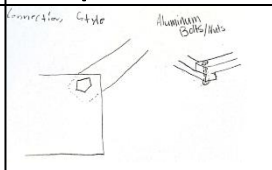
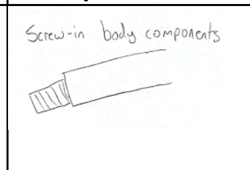
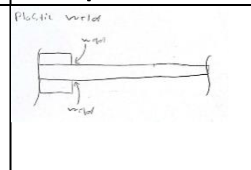
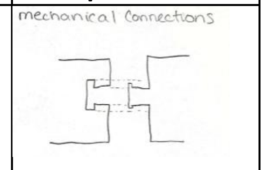
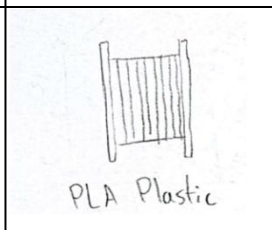
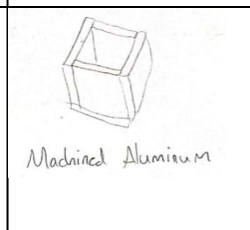
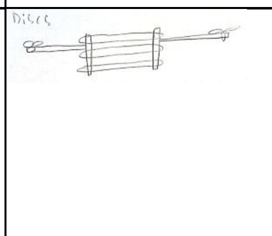
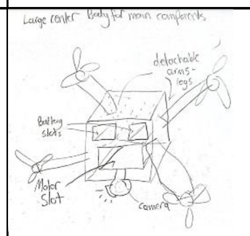
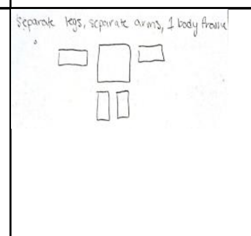
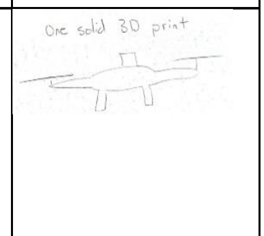
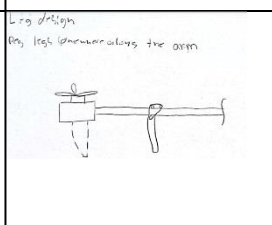
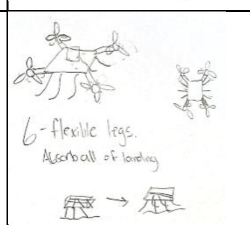
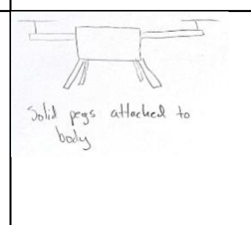
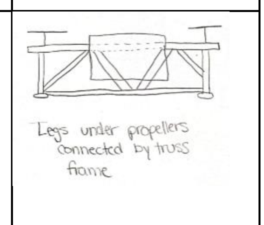
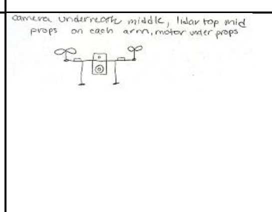
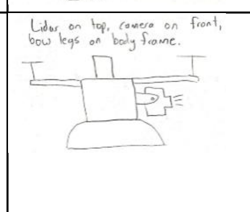
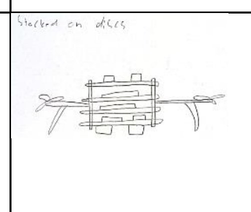
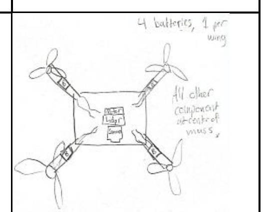
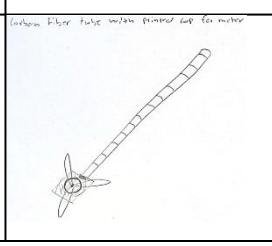
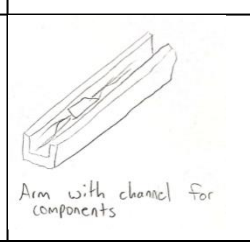
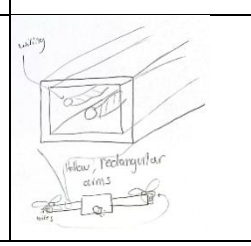
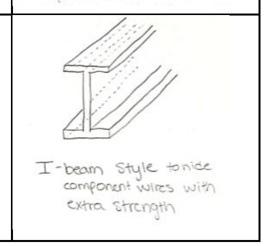
Subcategories	Concept 1	Concept 2	Concept 3	Concept 4
Arm Connection Style				
Material				
Body Configuration				
Leg Style				
Component Configuration				
Arm Style				

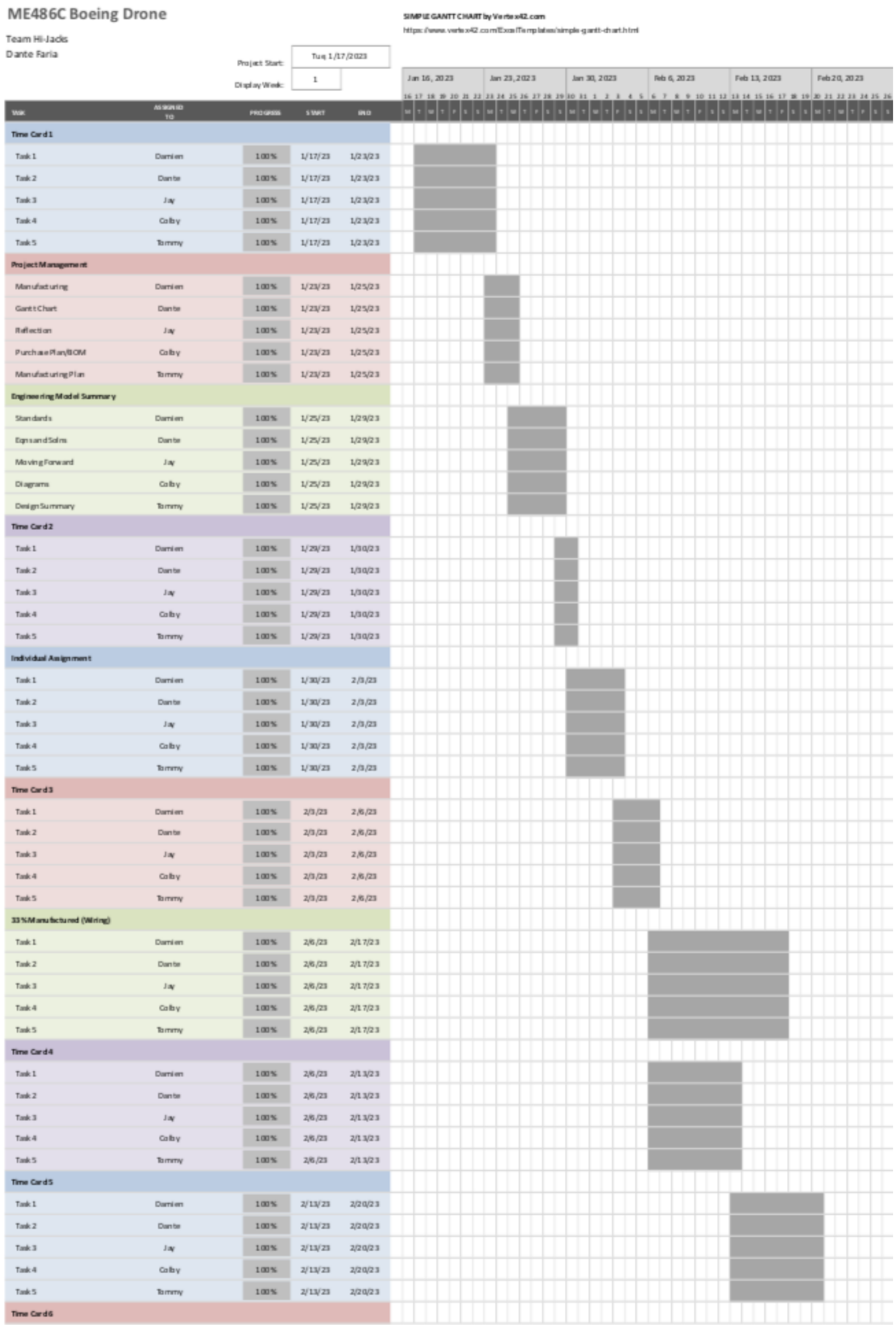
Table 2: Pugh chart

Concept/ Criteria	**Datum – Boeing**	**Design 1**	**Design 2**	**Design 3**	**Design 4**	**Design 5**
Lightweight		+	+	-	+	+
Component FOV		-	S	-	S	S
Ease of Manufacturing		S	+	-	+	+
Frame Strength		+	+	S	+	+
Cost		-	-	-	-	-
Minimized Hardware		S	S	+	-	S
Σ +	N/A	2	3	1	3	3
Σ -	N/A	2	1	4	2	1
Σ S	N/A	0	2	-3	1	2

Table 3: Decision matrix

		Design 2		**Design 4**		**Design 5**	
Criteria	**Weight (%)**	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Lightweight	25	7	1.75	6	1.5	7	1.75
Component FOV	20	8	1.6	7	1.4	7	1.4
Ease of Manufacturing	15	9	1.35	9	1.35	8	1.2
Frame Strength	20	7	1.4	8	1.6	7	1.4
Cost	10	6	.6	5	.5	8	.8
Minimized Hardware	10	5	.5	4	.4	5	.5
Total	100		7.2		6.75		7.05

13.3 Appendix C: Full Gantt Chart



TASK	ASSIGNED TO	PROGRESS	START	END
Time Card 1				
Task 1	Damien	100%	1/17/23	1/23/23
Task 2	Dante	100%	1/17/23	1/23/23
Task 3	Jay	100%	1/17/23	1/23/23
Task 4	Colby	100%	1/17/23	1/23/23
Task 5	Tommy	100%	1/17/23	1/23/23
Project Management				
Manufacturing	Damien	100%	1/23/23	1/25/23
Gantt Chart	Dante	100%	1/23/23	1/25/23
Reflection	Jay	100%	1/23/23	1/25/23
Purchase Plan/BOM	Colby	100%	1/23/23	1/25/23
Manufacturing Plan	Tommy	100%	1/23/23	1/25/23
Engineering Model Summary				
Standards	Damien	100%	1/25/23	1/29/23
Eqns and Solns	Dante	100%	1/25/23	1/29/23
Moving Forward	Jay	100%	1/25/23	1/29/23
Diagrams	Colby	100%	1/25/23	1/29/23
Design Summary	Tommy	100%	1/25/23	1/29/23
Time Card 2				
Task 1	Damien	100%	1/29/23	1/30/23
Task 2	Dante	100%	1/29/23	1/30/23
Task 3	Jay	100%	1/29/23	1/30/23
Task 4	Colby	100%	1/29/23	1/30/23
Task 5	Tommy	100%	1/29/23	1/30/23
Individual Assignment				
Task 1	Damien	100%	1/30/23	2/3/23
Task 2	Dante	100%	1/30/23	2/3/23
Task 3	Jay	100%	1/30/23	2/3/23
Task 4	Colby	100%	1/30/23	2/3/23
Task 5	Tommy	100%	1/30/23	2/3/23
Time Card 3				
Task 1	Damien	100%	2/3/23	2/6/23
Task 2	Dante	100%	2/3/23	2/6/23
Task 3	Jay	100%	2/3/23	2/6/23
Task 4	Colby	100%	2/3/23	2/6/23
Task 5	Tommy	100%	2/3/23	2/6/23
33% Manufactured (Wiring)				
Task 1	Damien	100%	2/6/23	2/17/23
Task 2	Dante	100%	2/6/23	2/17/23
Task 3	Jay	100%	2/6/23	2/17/23
Task 4	Colby	100%	2/6/23	2/17/23
Task 5	Tommy	100%	2/6/23	2/17/23
Time Card 4				
Task 1	Damien	100%	2/6/23	2/13/23
Task 2	Dante	100%	2/6/23	2/13/23
Task 3	Jay	100%	2/6/23	2/13/23
Task 4	Colby	100%	2/6/23	2/13/23
Task 5	Tommy	100%	2/6/23	2/13/23
Time Card 5				
Task 1	Damien	100%	2/13/23	2/20/23
Task 2	Dante	100%	2/13/23	2/20/23
Task 3	Jay	100%	2/13/23	2/20/23
Task 4	Colby	100%	2/13/23	2/20/23
Task 5	Tommy	100%	2/13/23	2/20/23
Time Card 6				

Figure 1: Gantt chart up to week 6

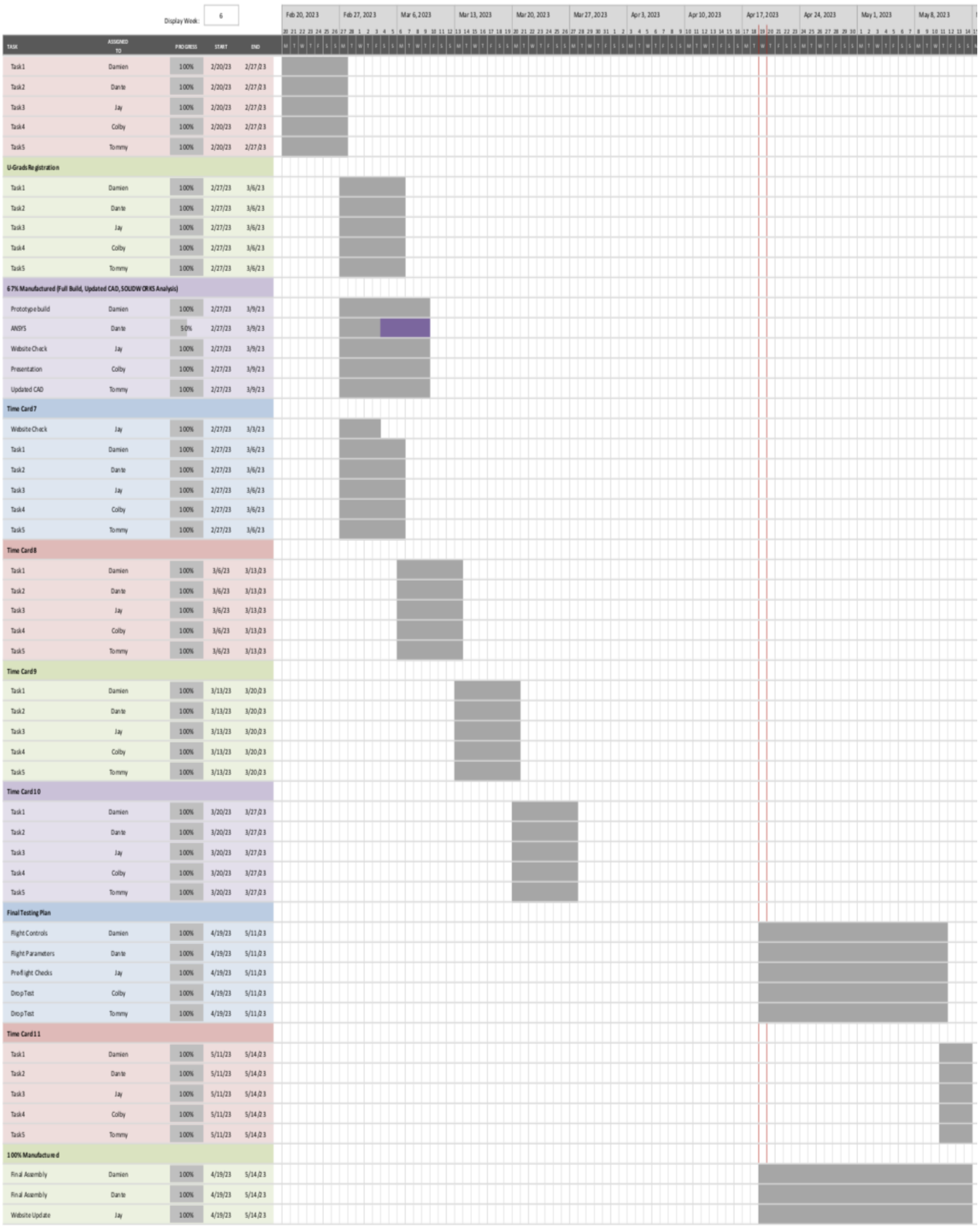


Figure 2: Gantt chart from week 6 to week 11

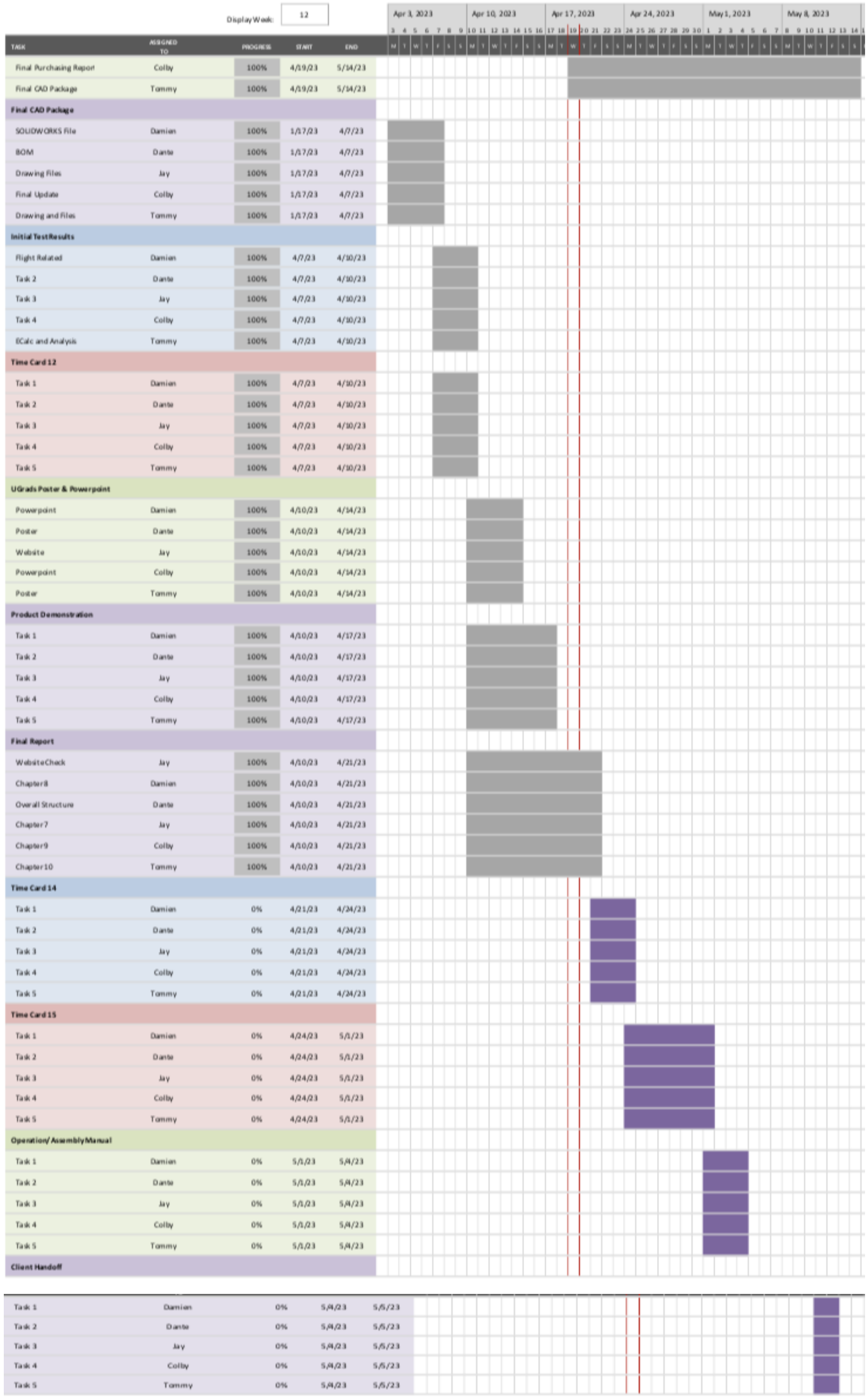


Figure 3: Gantt chart from week 11 to week 16

13.4 Appendix D: Dog Bone Raw Data Testing Results

Table 1: Dog bone testing raw data

	Total			Test Section									
Specimen	Length (mm)	Width (mm)	Weight (g)	Thickness (mm)	Width (mm)	XS Area (mm^2)	Max Force (N)	Elongation (mm)	Strength to weight Ratio	Max Stress [MPa]	Delta L [mm]	Strain [mm/mm]	Modulus [Mpa
NF 1	164.80	18.94	6	3.40	13.05	44.37	814.53	42.69	135.75	18.36	42.69	0.26	384.129
NF 2	164.93	19.01	6	3.41	13.13	44.77	785.29	46.30	130.88	17.54	46.30	0.28	384.129
NF 3	164.95	19.00	6	3.40	13.12	44.61	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NF 4	164.92	19.98	6	3.40	13.08	44.47	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NF 5	164.90	19.00	6	3.39	13.08	44.34	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CF 1	165.02	18.97	10	3.50	13.10	45.85	4935.92	2.69	493.59	107.65	2.69	0.02	11035
CF 2	164.89	18.93	10	3.54	13.06	46.23	5562.44	3.07	556.24	120.31	3.07	0.02	11035
CF 3	164.94	18.88	10	3.51	13.10	45.98	6047.15	2.92	604.71	131.51	2.92	0.02	11035
CF 4	165.01	18.97	10	3.52	13.11	46.15	5919.35	3.06	591.94	128.27	3.06	0.02	11035
CF 5	165.05	19.02	10	3.52	13.17	46.36	5899.35	3.24	589.94	127.26	3.24	0.02	11035
K 1	165.10	18.92	9	3.42	13.07	44.70	4381.55	3.73	486.84	98.02	3.73	0.02	6267.22
K 2	164.97	18.95	9	3.46	13.05	45.15	4243.17	2.74	471.46	93.97	2.74	0.02	6267.22
K 3	164.99	19.02	9	3.41	13.09	44.64	4578.99	3.13	508.78	102.58	3.13	0.02	6267.22
K 4	165.10	18.96	9	3.42	13.03	44.56	4416.02	2.97	490.67	99.10	2.97	0.02	6267.22
K 5	165.15	18.90	9	3.42	13.01	44.49	4509.07	3.12	501.01	101.34	3.12	0.02	6267.22
HSHT 1	164.94	18.95	9	3.41	13.03	44.43	4786.57	3.29	531.84	107.73	3.29	0.02	512.003
HSHT 2	164.89	18.95	9	3.41	13.08	44.60	5052.60	3.78	561.40	113.28	3.78	0.02	512.003
HSHT 3	164.92	18.88	9	3.42	13.06	44.67	4496.79	2.79	499.64	100.68	2.79	0.02	512.003
HSHT 4	164.94	18.91	9	3.43	13.11	44.97	4857.58	3.18	539.73	108.02	3.18	0.02	512.003
HSHT 5	194.95	18.92	9	3.43	13.05	44.76	4369.34	3.02	485.48	97.61	3.02	0.02	512.003

13.5 Appendix E: Full FMEA

Table 1: Full size failure mode and effects analysis

Product Name: **Boeing Drone Capstone**		Development Team: **Project 3 Boeing Drone Frame**					Page No **1** of **1**		
System Name: **Drone Airframe**							FMEA Number		
							Date: **11/08/2022**		
Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 (plate with no key)	Impact Fracture	Flying debris and inoperative	7	Impact Loading	4	Drop Test	2	56	Increase plate infill
2 (plate with key)	Impact Fracture	Flying debris and inoperative	7	Impact Loading	4	Drop Test	2	56	Increase plate infill
3 (arm)	Impact Fracture and Low-Cycle Fatigue	Flying debris and erratic operation	9	Impact Loading	7	Drop Test/Cycle Test	1	63	Increase arm thickness and key size
4 (spacer)	Impact Fracture	Poor appearance	4	Overstressing	5	Drop Test	5	100	Increase spacer thickness
5 (bolt)	Impact Fracture	Flying debris and inoperative	5	Impact Loading	3	Drop Test	7	105	Have spare backup parts
6 (nut)	Impact Fracture	Erratic operation	2	Overstressing	4	Drop Test	9	72	Have spare backup parts
7 (washer)	Impact Fracture and Ductile Rupture	Loss of stability	3	Overstressing	3	Drop Test	6	54	Have spare backup parts
3,4	Impact Fracture/Shear	Flying debris and inoperative	6	Impact Loading	6	Drop Test	2	72	Add chamfered sections
All	Loose parts	Flying debris and inoperative	8	Vibration and Impact Loading	4	Flight Test	2	64	Pre-Flight Checklist