Boeing Drone Frame

Final Proposal

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DISCLAIMER

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EXECUTIVE SUMMARY

The Boeing Drone Project was created by The Boeing Company to design a drone frame for the quadcopter surveillance drone. The clients of the project are The Boeing Company, Amanda Nemec, Michael Vogelsang, Reed Esper, and other employees of The Boeing Company. This project is still in the early stage and has been made to target the frame weight and flight time. The main customer requirements for the project are reducing the weight to under 3lbs and increasing the thrust-to-weight ratio above 1.81 along with the component FOV, ease of manufacturing, frame strength, cost, and minimal hardware in the frame. 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 will be placed on top of the first disk, between the discs, and below the third disk, and the legs and motors are attached to the arms. The material used for the initial prototype was 100% PLA plastic with 10% fillings. The first prototype the team created was with 3D printing and did not go as planned because of the material selection. The PLA plastic used in the 3D printing came out fragile and flimsy. Also, the measurements the team took for the drone did not come out perfect and the team had to drill extra holes or widen the holes to connect all the parts. The team now is performing different tests on the material to decide on what material to use. The first is dog bone testing which is currently in process. The team has selected 4 varied materials: non-reinforced ONYX, Kevlar-reinforced ONYX, Carbon fiber-reinforced ONYX, and Fiberglass reinforced ONYX. All materials selected are now 50% fillings unlike 10% for the first prototype. Once the tests are done the team will finalize the material and will proceed with the 3D printing. Other bunch of tests will be done in ANSYS for stress and fatigue. The team will be using ANSYS for high wind test, and a hard landing test, as well as a maximum throttle flight test. The second prototype is a little different than the first one as the team improved the design of the drone legs and made it more stable at the arm-leg connection. The team designed the legs much closer to the main body and designed the connector of the legs such as the top part of the connector is attached to the spacers and the lower part of the connector is attached to the legs. Also, the angle between the legs and the disk has been increased to more than 90 degrees (previously 90 degrees) which covers more surface area on the ground, provides more stability, and will be able to handle the weight of the entire drone. Talking about the results, in the first prototype the team achieved mostly all the customer requirements, the total weight of the drone was around 0.96lbs (excluding legs) which was well under the requirements which also increased the thrust-to-weight ratio, also it was easy to manufacture, the component FOV was good, and had minimal hardware and cost. The only customer requirement that did not fulfill was strength. Therefore, the goal for changing the design and materials of the second prototype will be to increase the strength of the drone along with reducing weight, increasing thrust-to-weight ratio and other customer requirements.

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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.

2.2 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. The weights of all these requirements are important when coming up with usable requirements within the decision matrix shown below [table 1].

Table 1: Customer Requirements and Weights

Criteria	**Weight (%)**
Lightweight	25
Component FOV	20
Ease of Manufacturing	15
Frame Strength	20
Cost	10
Minimized Hardware	10
Total	100

2.1 Engineering Requirements (ERs)

To make the customer requirements more useful in the design stage of the project, it is important to dimensionalize the requirements to have a way to understand what exactly needs to be accomplished. These dimensionalize engineering requirements 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 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.

2.2 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.

2.2.1 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.

2.2.2 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.

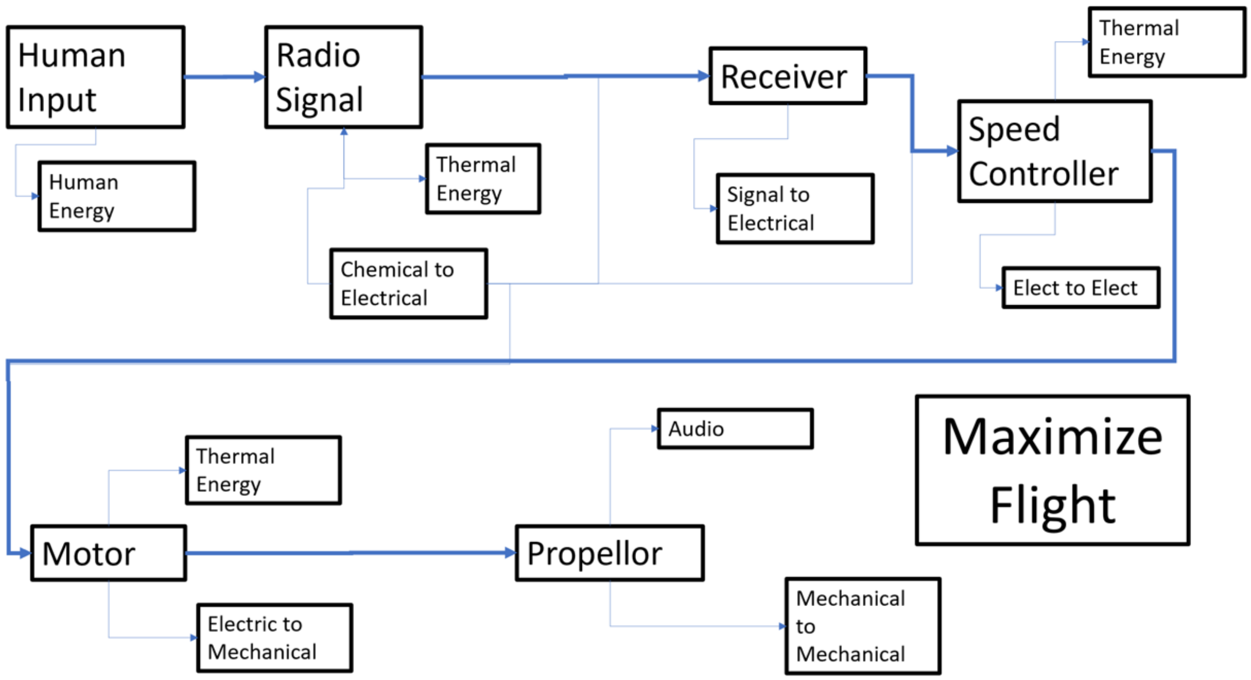

Figure 2: Drone Functional Decomposition

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.

2.3 House of Quality (HoQ)

The purpose of the Quality Function Deployment (QFD) model, located in appendix A, 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 Need 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

2.4 Standards, Codes, and Regulations

Based on requests from the client, ASTM D638 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 2, there are two standards that Team Hi-Jacks will be using in the preliminary testing stages of this drone.

Table 2: 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 Testing Procedures (TPs)

The engineering requirements that need to be analyzed for the drone body are the overall weight and the durability of the materials used. Both requirements will contribute to our thrust in weight ratio and overall strength of the frame. To test the durability of different 3D printed materials, the team printed multiple ASTM-D638 Type 1 dog bones made of different materials that will be strength tested in a universal tensile tester. There are five samples printed for each material selected which includes onyx with no reinforcement, onyx reinforced with Kevlar, onyx with carbon fiber, and onyx with fiberglass. This means 20 total dog bone samples are put through durability testing for analyzation. This tensile testing machine will output a variety of data that will be used in the material decision process for the drone. Using estimated weight and load forces should be a main contributor to choosing a material with certain properties.

3.1 Testing Procedure 1: Material Durability Testing

The material durability testing of the Boeing drone will be satisfied by a dog bone tensile stress test. This test is used in the industry to find durability data of different plastic materials. The team was recommended this test from a material and processes technologies employee at Boeing. The dog bone samples that were printed will be put into a universal stress testing machine. The exact data that will result from this test is still unclear, but the clients tell the team that it will display all information needed for the material selection process.

3.1.1 Testing Procedure 1: Objective

This test will be run to discover the capabilities of a variety of printed plastic materials. This is crucial to the success of the drone frame because failure of any type will not be tolerated. Cracking, snapping or any other types of failure will cause the drone's weight and stability to be compromised which results in the failure of the drone frame. This tensile test in the NAU engineering building will consist of stretching all the dog bones samples until failure. After 5 tests per material, there will be sufficient data to observe trends and accurate material properties.

3.1.2 Testing Procedure 1: Resources Required

20 total onyx, ASTM-D638 Type 1, dog bones with 50% infill are needed for testing: five Kevlar reinforced, five fiberglass reinforced, five carbon fiber reinforced, and five non-reinforced onyx dog bones are needed for this experiment. A universal tensile tester is used to analyze the durability of the 4 different materials.

3.1.3 Testing Procedure 1: Schedule

All dog bones were submitted to the Idea 3D Printing Lab in the NAU Engineering building on the 16th of November. These samples are expected to be finished on the 21st of November so testing can be completed on the 23rd. This will be the first material test for Team Hi-Jacks with many others to come. The team plans to have one more prototype made out of the selected material before the end of the semester which leaves plentiful time next semester for full drone body testing.

3.2 Testing Procedure 2: ANSYS Stress Testing

3.2.1 Testing Procedure 2: Objective

Ansys Software will be utilized to test various stress against the full drone body. This will include a high wind test, and a hard landing test, as well as a maximum throttle flight test. These tests are all important to the flight of the drone and crucial to the failure modes. High winds, hard landings and high thrust from the propellors are all common when flying a drone with this much power and it is important to simulate them on Ansys before risking thousands of dollars’ worth of parts.

3.2.2 Testing Procedure 2: Resources Required

The only required resources to test a drone frame on Ansys is a 3D model of the drone frame itself and a software license for the program itself. These are both free resources as university students and can be modified throughout testing as needed.

3.2.3 Testing Procedure 2: Schedule

As the CAD model of the drone body is being updated weekly, Ansys testing is scheduled to begin testing in early December and will stretch well into next year as the team edits the drone body and materials used. Proper Ansys testing cannot be done until the team has delivered all components of the drone like the motors and propellors to see what type of thrust numbers are present on each end of the drone as well as an official weight.

4 Risk Analysis and Mitigation

Analysis was done of potential failures, also known as FMEA. 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 the failure is. 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.

4.1 Critical Failures

4.1.1 Potential Critical Failure 1: Plate Impact Fracture

[Provide a brief description of the potential failure here, how that failure could be caused, the effect of the failure, and then discuss how the failure can be mitigated.]

This failure concerns itself with the plates that make up the core of the drone's body. The concern is that the drone falls out of the sky or impacts an object while in flight. This would impart impact stress to the discs and cause them to fracture. The effect of this failure would be catastrophic, as the discs serve as an attachment point for nearly every other component. There is potential for components to fall out of the sky harming human operators below. Mitigation efforts could be centered around thickening the plates so that they are more resistant to impact.

4.1.2 Potential Critical Failure 2: Plate Key Warping

On the plates there is a key-slot where the key from the spacers and arms attaches. These keys prevent the arm and spacer from rotating, but due to the nature of the design, are very fragile. Failure of the key holes could cause the arms to rotate, decreasing performance and leading to uncontrollable flight. Although this failure was one of the less critical ones, it has a high potential for occurrence and therefore was important to consider. Potential mitigation efforts could be focused on making the keys larger or designing another way to prevent the arms from rotating.

4.1.3 Potential Critical Failure 3: Arm Key Break

In conjunction with the plate key holes, the keys that are attached to the arms are another critical point in the system. These keys attach to the top of the arm spacer and prevent the system from rotating. These could break by impact on the arm causing a moment force. This would cause the arms to rotate freely and could bend other components such as the plate and bolt. Increasing the size of the key or improving how it attaches to the rest of the arm could mitigate this danger.

4.1.4 Potential Critical Failure 4: Arm Impact Failure

Failure of the arms is another concern for the team. Like the plates, should the drone crash during flight, the arms are susceptible to breaking from the impact. Effects of this failure would be the drone falling out of the sky, potentially harming operators below. Erratic flight could also be caused by a broken arm, which would result in further damage to the drone. Failure mitigation could be created by thickening the arms or adding a truss that extends from the arm to the spacers above.

4.1.5 Potential Critical Failure 5: Arm Fatigue Failure

Like the impact fracture of the arm, fatigue failure was another concern. This method of failure derives from the propellers activating and deactivating. This causes an action that when repeated many times, will weaken the structure of the arm through fatigue. Like arm impact failure, this could cause the arm to break off, and the drone to fall out of the sky. Should the arm partially detach, this would cause erratic flight and damage to other drone components or human operators. This could be mitigated by increasing the strength near the base where moments from the propeller action are the greatest.

4.1.6 Potential Critical Failure 6: Arm Propellor Stress

The propellors and motors on the drone body are the components that were recommended to the team from Boeing. These same components were used on a drone much heavier than the one the team currently has. The thrust alone from the motors and the propellors could easily create an upward force moment and snap the arms right off from the body. It is important that when testing the drone, maximum throttle is not used until calculations are made, or the team is prepared for the possible failure.

4.1.7 Potential Critical Failure 7: Leg Impact Failure

In the new and improved drone body design, the team prioritized getting the legs attached and properly supported. There is no plan of the drone crashing to the ground too hard but for such an important client, the team cannot afford the legs to snap off after a tiny fall. There are now force moment supports connected to the body of the drone that were designed to lower the force taken by the legs and distribute it. Testing will soon prove the capabilities of this leg design.

4.1.8 Potential Critical Failure 8: Spacer Impact Failure

On the drone, there are spacers that separate the top and middle disc. Upon an impact to the top or bottom of the drone, these spacers could compress or fracture. Due to the nature of the cause, where failure requires an impact from the top or bottom, there is no risk to operators on the ground. Other components could be damaged, and repairs would have to be made on the drone before the next attempt at flight.

4.1.9 Potential Critical Failure 9: Bolt Impact Failure

Failure of the bolt that connects all the components together had the highest RPN. This failure could happen by impacting any part of the drone that travels to the bolt and causes it to break. This failure would cause the drone to shatter, and potentially ever component could come loose during flight and fall to the ground. This would cause substantial damage to the components, and any operators below the drone.

4.1.10 Potential Critical Failure 10: Washer Bending

One of the most likely failures to occur was the bending of the washers during installation. Although this failure would be unlikely to harm other subsystems or the rest of the drone, it would still cause problems. Namely, the plate could be attached at an incorrect angle, causing improper flight characteristics. This could potentially harm operators, but the risk is relatively low. Increasing the size of the washer would mitigate this, and the area of contact would increase leading to more stability.

4.2 Risks and Trade-offs Analysis

When comparing different modes of failure, it is important to analyze whether mitigating one failure will increase the likelihood of another. For this project, all failures are linked to either fatigue or impact. Due to this, if one part is strengthened, it is possible that by strengthening one part, it could lead to an early failure in another part because of brittle failure. Some parts could be helped by slightly giving way to a large force or pressure. For the most part, however, this is unlikely. By strengthening one part it will mitigate and force transferred though it to another part. For example, in the event of a hard landing, most of the force will be in the legs. If this part were weaker, the force could transfer up through the truss and break it off from the spacer unnecessarily. If the parts are strong, they will be able to absorb more or the force.

One specific example of this is increasing the key size. By doing this, the keyhole in the plate would be increased as well. This would increase the size of the weak point in the plate and make the system less resistant to fracture. Mitigating these effects will come once an understanding of the material strengths are gained through testing and computer simulation.

5 DESIGN SELECTED – First Semester

The final design for this semester is a slightly modified version of the original model. Based on research and hands-on-time with the prototype it has been decided that the overall design is sound and is a great starting point that doesn't need to be drastically altered. The only changes required are small and simple and are detailed in this chapter.

5.1 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.

5.1.1 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 7 and part number 3 in table 3. 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 place underneath another new feature that prevents a bending moment in the arms during flight and landings (table 3 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 3: Printed 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			

5.2 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 4. Table 3 above shows the bill of materials for 3D printed and purchased body hardware. Figure 6 shows the completed assembly to be 3D printed. Figure 7 shows this same model in an exploded view.

Table 4: 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 6: 3D model to be printed.

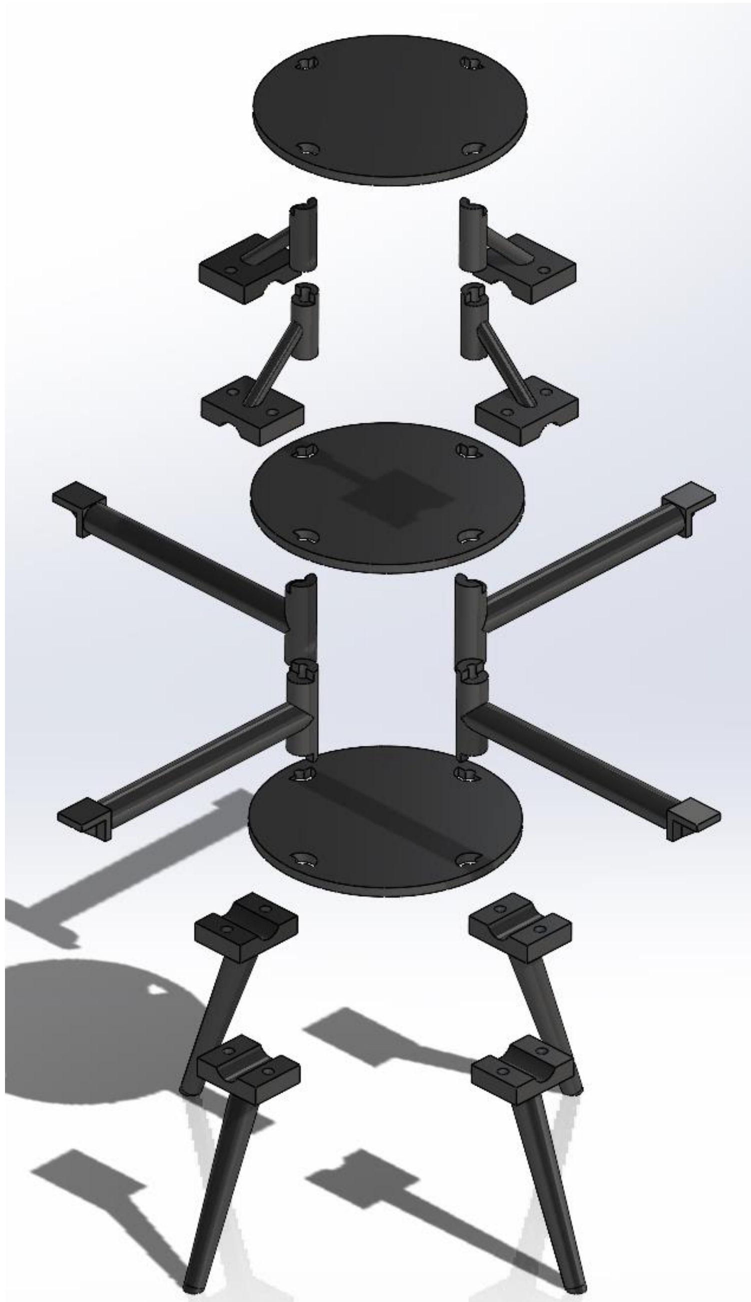

Figure 7: Exploded view of 3D design.

For the next semester, there are several further activities required for implementation. This includes, but is not limited to, further hardware acquisition, building and iteration, testing, and demonstrations. The details of these events are not currently defined, and knowledge of required resources is very limited. As the Fall semester progresses, the team will gain an understanding of the scope of work required for the following Spring semester. Table 5 shows the current proposed schedule for the upcoming semester.

Table 5: Tentative schedule for second semester implementation efforts.

Week (of Spring semester) - Date	Action Item
2 - 17 Jan	All required parts acquired
5 - 7 Feb	33% completed build/testing
8 - 28 Feb	67% completed build/testing
10 - 21 Mar	100% completed build/testing
15 - 25 Apr	Demonstration and testing results

6 CONCLUSIONS

The requirements of the project set forth by the client Boeing included the design of a lightweight (under three pounds) drone that utilizes pre-selected components. Flight time was to be maximized and thrust-to-weight ratio was to improve over the previous 1.81 value. Over the course of the semester, Team Hi-Jacks has worked to fulfill the requirements of the project. Specifically, this semester’s focus was on the initial design phase, including prototyping. The team has been able to generate concepts, initialize prototyping, refine, and test to work towards the completion of the project. The final design features discs for components to be housed, circular arms that maximize strength and minimize weight, and extra trusses to further improve rigidity. The current prototype also fits all components without wasting any extra space to further minimize weight. Overall, the proposed design achieves the current goals of the project. Future work will include testing and simulation of the prototype, and further building and iteration.

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8 APPENDICES

8.1 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
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

	Customer Needs	Customer 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	Customer Opinion Survey: 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					

8.2 Appendix B: FEA of 3D Printed materials via Compression test

Figure 1: FEA of 3D Printed materials via Compression test

	Thermoplastic Polyurethane (TPU)	Acrylonitrile Butadiene Styrene (ABS)	Polyethylene Terephthalate glycol-modified (PETG)	High Impact Polystyrene (HIPS)	Polylactic Acid (PLA)	Onyx
Impact Strength	High	High		High	High	High
Durability	High	High	High	High		High
Flexibility	Very High	Low	Low	Low	Low	-
Chemical Resistance	Medium-high	High	High	High	Low	High
Water Resistance	Medium	Medium	High	Medium	Medium	High
Nozzle Extruder Temperature(°C)	220-250	230-260	210-250	230-260	190-210	230-260
Closed Chamber	Not necessary	Recommended	Not necessary	Recommended	Not necessary	Recommended

Figure 2: FEA of 3D Printed materials via Compression test part 2

4.1 Model Testing

Table 2 presents the results obtained from the compression test of the test specimens. It also presents the load at which these test specimens experienced failure and on what axes the load was applied according to the axes on which the test specimen was printed.

Table 2: Practical Test Results

Material	% Infill	Shape	Dimensions (mm)	Direction of force	Colour	Fn (KN) Failure
TPU	25%	Cube	25mm	Horizontal	White	1.5
TPU	25%	Cube	25mm	Horizontal	White	0.88
TPU	25%	Cube	25mm	Parallel (Vertical)	White	0.59
TPU	25%	Cube	25mm	Parallel (Vertical)	White	0.48
TPU	50%	Cube	25mm	Parallel (Vertical)	White	5.18
TPU	50%	Cube	25mm	Horizontal	White	9.78
PETG	25%	Cube	25mm	Parallel (Vertical)	White	0
PETG	25%	Cube	25mm	Horizontal	White	4.63
PETG	50%	Cube	25mm	Parallel (Vertical)	White	0
PETG	50%	Cube	25mm	Horizontal	White	6.4
PLA	25%	Cube	25mm	Parallel (Vertical)	Black	7.42
PLA	25%	Cube	25mm	Horizontal	Black	11.44
PLA	50%	Cube	25mm	Horizontal	Black	16.09
PLA	50%	Cube	25mm	Parallel (Vertical)	Black	10.22
ABS	15%	Cube	60mm	Parallel (Vertical)	White	8.01
ABS	50%	Cube	50mm	Horizontal	White	12.2
Onyx	50%	Cube	50mm	Horizontal	Black	21
HIPS	50%	Cube	50mm	Horizontal	White	25.05

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