Boeing Drone Frame Design

Preliminary Proposal

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DISCLAIMER

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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.

1.3 Original System

Last year, Reed Esper and his team at Boeing began the creation of this drone. They created a heavy but sturdy drone design that is capable of flight with minimal components [Fig 1]. At the beginning of the capstone project, Reed gave the NAU team a summary of what has been created thus far at the beginning of the semester in the first client meeting. This presentation of the original drone came with a set of components used, components to be added, and a few CAD files used by last year's team.

1.3.1 Original System Structure

The structure of the original drone resembles a basic, camera-mounted quadcopter drone [Fig 2]. The camera for surveying is mounted on the underside of the body while a Lidar was attached to the top. With the four blades, there also comes 4 motors at the end of each arm. The landing gears are two ‘D’ shaped legs which can absorb a large impact upon landing but add lots of weight to the drone body. All other components like the battery and transceiver were attached to the front of the body.

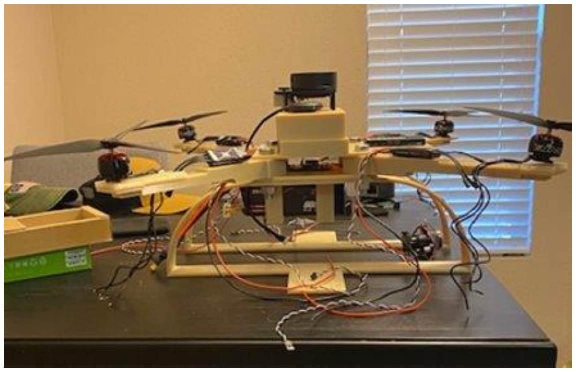


Figure 1: Boeing drone built by Reed Esper and his team

Figure 2: An ordinary camera mounted quad copter

1.3.2 Original System Operation

From the knowledge that team, Hi-Jacks was given, the 2021 drone team used a Flysky FS-i6X Receiver as iFlight XING 880KV Motors [Fig 3]. Not enough data was given to the 2022 team on how the drone operated or where all the parts were connected. The CAD files given to the team did not include the 3D printed body therefore those drawings are not helpful.

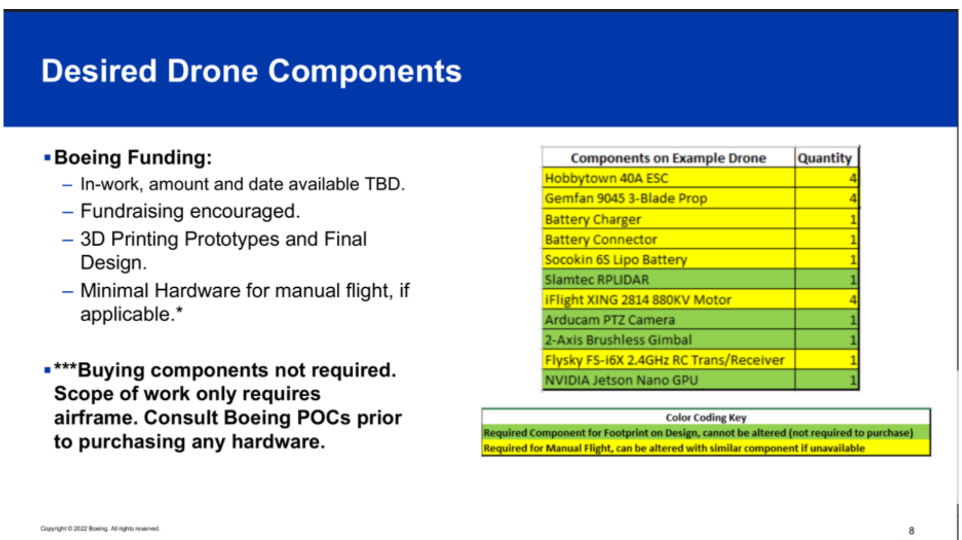


Figure 3: Required and optional components on the original Boeing drone

1.3.3 Original System Performance

The only testing of the previous Boeing drone group that was given to us was a YouTube video of a team member getting the drone off the ground [Fig 4]. Movements of the drone appeared limited as the drone could oscillate up and down but was very touchy when it came to lateral tilting. Landing the drone did not appear to be the most agile landing but the hefty landing gear could absorb the blow. The only quantitative value given by the Boeing team was that this drone weighs 4.02 lbs. and the thrust to weight ratio is 1.81. These values will be easy to improve upon considering the focus of the 2022 team is to reduce weight of the drone which will also higher the thrust to weight ratio.

Figure 4: A team member from the 2021 Boeing drone group testing the flight capabilities

1.3.4 Original System Deficiencies

According to Reed, there were multiple issues with this prototype. First, he said the landing legs were interfering with cameras field of view because they were large and bulky. This meant it would be challenging to use the drone camera for long distance operation and surveying. Another issue to be fixed on the next protype of the drone is reducing the airframe to less than 3 pounds [Fig 5]. Reed's airframe weighed more than 4 pounds which leaves our group the threshold of a 1.02-pound reduction. This goes along with the final goal of achieving higher than a 1.81 thrust to weight ratio. If the weight reduction goal is met, so will our thrust ratio goal.

Fixed Component Weights

- **3D models of fixed components will be provided by email.**
- **Center of gravity shall be assumed if data is not available by supplier.**

Hardware Components			
Part	Quantity	Total Weight (lbs)	Total Weight (g)
Camera	1	0.106	48
Camera Gimble	1	0.073	33
Battery	1	1.881	853
LiDAR	1	0.410	186
Motors	4	0.785	356
ESCs	4	0.406	184
Jetson	1	0.298	135
Pixhawk	1	0.068	31
GPS	1	0.071	32
PM07 Board	1	0.112	51
Propellers	4	0.115	52
Receiver	1	0.033	15
Total Aircraft Hardware		**4.356**	**1976**

9

9/12/2022

Figure 5: Required and optional drone components with their weights

2 REQUIREMENTS

In order 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 (CR)

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 in order 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 of 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

2.2 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 dimensionalized 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 of the 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 the majority of the mass is centralized on the frame and to make sure that all of the weights are evenly distributed elsewhere. In order 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.

2.3 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 (fig. 6) ranked against the engineering requirements (fig. 7). This is 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 6: 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 7: Engineering Requirements

As shown below (fig. 8), 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 8: Units and Targets for Engineering Requirements

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 of. Then, subsystem benchmarks are done for different systems within the drone as a whole, 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.

3.1.1 Damien Brothers

As the team's manufacturing engineer, Damien focused literature review on topics of 3D printing and machining. How to run models on the cost of these methods was also looked at. Five of the sources Damien focused on are detailed below.

3D Printing vs. Machining

First, a resource on 3D printing as compared to machining was evaluated. This resource detailed the differences between the two. It gave insight into the pros and cons of each method, and where the team might be able to integrate either. This helped the team decide on which method to use in different areas and informed why one method would work better than another [1].

Design Guide: CNC Machining

This source provided information on design for manufacturing. It is important to design parts so that they are easily manufactured in order to streamline the process and reduce costs. This source detailed best practices when designing parts intended to be manufactured through CNC machining specifically. The team gained invaluable information on what design choices would and wouldn't work before developing concepts [2].

3D Printing Technology

This resource detailed different 3D printing technologies available for use. Specifically, it discussed their applicability for use in unmanned aerial vehicles, which is relevant to drones. Although this source focused less on design, it gave important information into the various technologies available, and how their use might be beneficial to the drone. It also provided insight into strength of materials, and how to improve the stability of a 3D printed frame [3].

Key Design Elements for 3D Printing

To supplement the previous source, this was used to as insight into how to design for 3D printing. Much like the design guide for CNC machining, this went over the best practices for 3D printing specifically. It went over topics such as overhangs and details. This resource will prove invaluable to the team as the current plan is to use 3D printing for most drone parts [4].

SOLIDWORKS Costing

The final source was used to give the team budgetary insight. SOLIDWORKS has a tool known as costing that allows the designer to implement certain metrics such as cost per weight, and hourly manufacturing rates. This tool will output a total cost per part based on the design in SOLIDWORKS. This source helped the team practice and understood this tool for use in future budgetary planning [5].

3.1.2 Dante Faria

The project manager, Dante Faria, researched many different aspects associated with the Boeing Drone Frame project. To ensure that the project completed the goals set by the client, Boeing, there were certain steps taken to make that happen. Research about the Finite Element Analysis program called ANSYS was conducted to learn the more basic functions of this program and learn how it can be applied to the project at hand. To learn about ANSYS, a tutorial [6] was researched showing all of the different functions in the program along with how the program actually works using stress analysis [7]. To make sure that the team was working well together and that everything was running smoothly, a little research was done on engineering leadership [8] to help Dante understand more about his role as project manager. A clearer understanding of who the client is and what they are known for, some research was set aside on their autonomous drones [9] that are already in use and finally some background research on the drone weight reduction [10] was conducted as well.

ANSYS Tutorial

This tutorial about ANSYS was an intricate introduction to all the various functions associated with the program. It led to a tutorial about creating drawings within the program itself and how exactly these drawings could be analyzed to figure out stresses and other important aspects of a design. The tutorial shows the process of creating a lifting lug that will be connected to a crane and will be used to lift different objects. The lifting lug will be experiencing many kinds of stress and therefore must be strong enough to accommodate them all. It showed how a user can use different functions within the program and how to solve stress using these functions and was a great introduction to the program that is ANSYS [6].

Intro to Stress Analysis – ANSYS Course

This introduction to stress analysis was a course offered by ANSYS and leads the user to a better understanding of what the program can be used for but also how the stresses are solved within the program. There were many definitions that were given throughout this introduction and helped the user to better understand the stress that ANSYS will help you solve in the end. As an engineering student, stresses are a part of the curriculum from an early stage in education in college, so there is a good understanding of what stress is before entering this introduction but the stress that an engineering student is used to solving for is not exactly what the stress is being found through the use of ANSYS. ANSYS gives more of a real-world application to all of the equations that are learned in class and also puts these equations to a real-world application in the objects that are being analyzed [7].

Engineering Leadership 101

Every project has a project leader and a project leader's job is to ensure a smooth and optimized work environment for everyone who is part of the team. This article gives an overview of what it is to be a leader and how to manage a team. There are many aspects of leading a team and it is important to ensure that every team member has good experience. Team meetings, client meetings, project scheduling, and other aspects are important for a good team leader to keep track of in order to ensure things go smoothly [8].

Boeing: Autonomous Systems

To learn more about Boeing and what is expected of the team for the Boeing Drone Frame, it is important to see what Boeing is working on or has worked on in the past. From the Boeing website, there are a multitude of drones with various functions that can be assessed as a working point of view for what the team should view as acceptable data. There are two underwater unmanned drones called the "Wave Glider" and the "Echo Voyager." The Wave glider is a water surface vehicle, and the Echo Voyager is a deep-sea vehicle which is used for further exploration of the Earth's oceans. Boeing also displays six different air drones including: the "ScanEagle," the "Integrator," the "MQ-25," the "Airpower Teaming System (ATS)," the "RQ-21A Blackjack," and finally the "QF-16." Each of these unmanned aircraft serves different purposes where warfare and defense play a big part. There is also a space drone called "X-37B" which functions as a way to explore space without putting lives at risk. All of these drones serve as a way to expand an understanding of what could be expected from the Drone Frame Project and what can be learned. [9]

Drone Weight Reduction

The "Drone Weight Reduction" source can be used to find simple solutions to the big problem that Team Hi-Jacks has been tasked to solve. The whole goal of the project is to reduce the weight of a drone frame while keeping the strength and flight maneuverability at a maximum. This source gives some great ideas on how to reduce the weight of the drone frame and will be used to keep in the reserve. There are more ideas on different components that can be used to keep the power at a maximum while reducing the weight as much as possible. [10]

3.1.3 Jay Khunt

Jay is assigned as both a Test Engineer for this project and a Web Designing. He is focused on testing the prototypes and approving the final model as per the requirements of the client. He is also working on developing a website for the project as required by the rubrics of the Capstone. The five sources of his are as follows:

Client's Requirement List

The main goal of any project is to always achieve or finish the client's requirement list. Therefore, after every prototype, Jay will go through the list of requirements which includes the weight of the frame, stress analysis, airframe, components thrust to weight ratio, optimized component location and more, and check that that design/prototype fulfills every requirement, and if so then it will go through further inspections and testing [11].

User Manuals or Guidebook for pre-purchased parts

For this project our client has a list of pre-purchased parts such as LiDAR, GPS system, camera and mounting gear, batteries, remote control, propellors and other parts. Therefore, to examine all the various parts, select appropriate settings, and learn how to use them or fix them if something goes wrong, the user manuals or guidebooks will be literature to refer to [12].

Adobe Dreamweaver

Along with Test Engineer, Jay is also a Web designer for the project, and he is using Adobe Dreamweaver for it. It has some inbuild tutorials from beginner to expert levels. It provides help from basics such as writing body of HTML code to the level of experts such as including animations, creating responsive menus, responding grid layouts, error checking, shortcut codes, hyperlinks and much more [13].

W3Schools

Along with Dreamweaver tutorials, W3Schools is a very helpful website which gives instant help for minor queries. It is a free live time HTML coding website in which you can select various topics, go into the section, and practice the codes. They give you the dummy code and you can make changes to it according to you and run it at the same time to see the changes your code makes in compared to the dummy code. For example, if Jay wants to search “How to change color of a text?”, then he can go into the “HTML style” menu, select the tutorial and it will show the dummy codes with some color applied to the text besides it and then Jay can make changes to the code to see the respective changes to the text given besides [14].

ANSYS drop test

One of the most important things during prototyping will be the crash/drop test of the drone to test the durability and ductility of the material and design. It prevents the other components from breaking and wasting resources. The ANSYS drop test is performed in two systems: explicit dynamics and transient structure. The main difference between explicit dynamics and transient structure is that explicit dynamics is made for the nonlinear drop test and transient structure which uses implicit solvers is not very efficient with nonlinear drop test, so it is use for linear drop test. Here we will be using explicit dynamics analysis since we have to do it on the drone which can fall from any angle/height and crash on the ground or into trees [15].

3.1.4 Colby Murphy

As the team's financial and logistic manager, Colby was tasked with basing his literature review on the budgeting of different prototyping, the cost of multiple materials, as well as researching if there were lighter options for the main drone components.

Wood Prototyping

In the concept of prototyping, there are many ways to go about it such as material used and how it is manufactured. It was in talks among the team of possibly making the first prototype drone body and arms out wood. Manufactured wood is modified and improved wood that won’t break the bank and still be a good starter material for the team. Walter Parker talks about the pros and cons of different types of manufactured wood. Particle board is lightweight, not easily distorted and can be easily attached to other pieces. This makes particle board a front runner in prototyping materials if we decide to go that route [16].

Costs of 3D Printing- Local

3D printing materials will be present in the team’s final body design but how much will be used is the question. Making the first protype out of 3D printing materials could be in the best interest of the team to become more familiar with this substance. At Northern Arizona University, the only material used in their printing facilities is PLA (Polylactic Acid). This PLA can be infused with other materials such as bronze, copper and steel which could vary the strength of the print along with the selected infill value. Assuming the team uses one of these specialized filaments, it will cost the team 25 cents per gram, which sums to 340 for a full body under 3 pounds [17].

Cost of 3D Printing- Outsourced

If the team decides to send our CAD files to an outsourcing 3D printing lab somewhere in the USA, the material choices would have much more variability. There are no exact price points on most 3D printing sites but using PLA would be the cheap option and while PEI or ASA material would cost much more of our budget. The higher cost materials all have different attributes associated such as fire retardant or high flexibility. After more research we will know what body parts need what type of support so this might be a very good idea for the team’s final prototype [18].

Reducing Component Weights

At the beginning of this project, Boeing did not state that we need to use the same components that the previous drone group used. This leaves room for possible optimization of weight in components on the drone such as different size batteries or propellors. I variation in battery weight could decrease our thrust to weight ratio but can lead to longer flight times to meet our customer requirements. Testing is needed with each changed component to see the direct correlation that part makes on the flight activity. It is worth keeping in mind that the team could make a heavy drone and implement larger batteries and motors [19].

Metal Drone Body

To embark on the idea of making the drone out of metal is an ambitious one but is worth considering. Aluminum would increase the total weight of the drone body by about double while steel would multiply the weight by around 6 times. 3D printing the drone body and arms in metal would be even more costly than high grade polymers and welding the parts within the team is seeming unlikely with everyone's skill set. The increase in weight would also result in component weights and prices going up such as higher power motors and batteries. Overall, a metal drone apparatus is a bad idea for the basics of flight as well as the wallet [20].

3.1.5 Thomas Schreiber

Thomas is focused on computer aided design (CAD) modeling for the project. He works on creating and optimizing the drone before it is ready to be printed. His 5 sources are as follows:

Solidworks tutorials

Solidworks contains many useful tutorials for beginner to expert users. For this project the most helpful was about advanced part making. They focused on making a difficult part quickly, including equations in part sizes to easily scale the part up or down as needed. The other videos presented advanced drawing and assembly techniques, like adding a bill of materials and adding mates to multiple parts [21].

ANSYS tutorials

The ANSYS tutorials are on YouTube and explain the basics of analyzing stresses in objects. They explained how to perform a simple structural analysis of a beam and then how to analyze the results. This project will require a structural analysis of the drone once a final design is decided. Using this software will tell the team how the drone body will react under different loads and how to improve the design for the next prototype [22].

“Optimizing a VTOL” video

This video describes the process of designing, building, and refining a vertical takeoff and landing (VTOL) aircraft. Although it is focused on the design of a tiltrotor aircraft, some of the concepts can be used as potential ideas and inspiration for different parts of a quadcopter [23].

Penn State Aerial Robotics course

This 4-week program from the University of Pennsylvania goes in depth about the basic mechanics and control strategies for a quadcopter. Each week there is a new lesson that is useful for this project. Some of the most important subjects taught are kinematics and how to make a drone more agile. Much of the program, however, focuses on robotics rather than building a drone body [24].

Project introduction presentation and video

When starting the project, the team was given a presentation from Boeing on the expectations for the project as well as where their drone is currently at. This project is tasked with improving upon theirs by reducing weight and increasing thrust to weight. The original design was examined, and some aspects are used in the team's first prototype, while other aspects are changed [25].

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 together. Each drone design studied is discussed in further detail below.

3.2.1.1 Existing Design #1: DJI Phantom 4 RTK Drone [26]

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 9 below.

Figure 9: DJI Phantom 4 RTK Drone

3.2.1.2 Existing Design #2: Yuneec Typhoon H Plus [27]

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 10.

Figure 10: Yuneec Typhoon H Plus

3.2.1.3 Existing Design #3: Parrot ANAFI USA Drone [28]

The Parrot ANAFI Drone as shown in Figure 11 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 11: 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 12.

Figure 12. 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 13. These arms also come in carbon fiber options, increasing strength even more.

Figure 13: Tube drone arm

3.2.2.1.3 Existing Design #3: Solid rectangular arm

This style of arm as shown in Figure 14, 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.

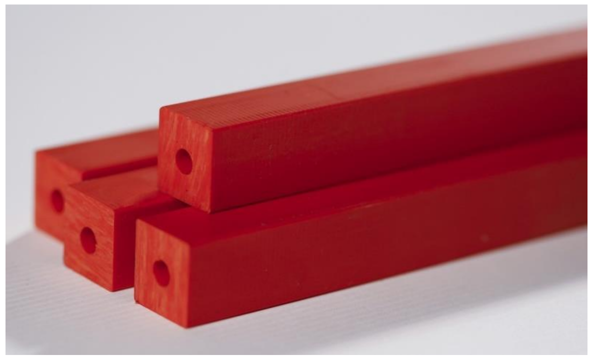


Figure 14: Solid rectangular arm style

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 15.

Figure 15: 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 16. 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 16: 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 17. The greatest downside is the difficulty involved with manufacturing such a frame and designing it in a way that is efficient.

Figure 17: Example of a modular drone frame with swapable 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 18. 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 18: Drone legs attached to the body

3.2.2.3.2 Existing Design #2: Truss Style

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 19.

Figure 19: Example of trusses between sets of legs

3.2.2.3.3 Existing Design #3: Wing-Attached

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 20.

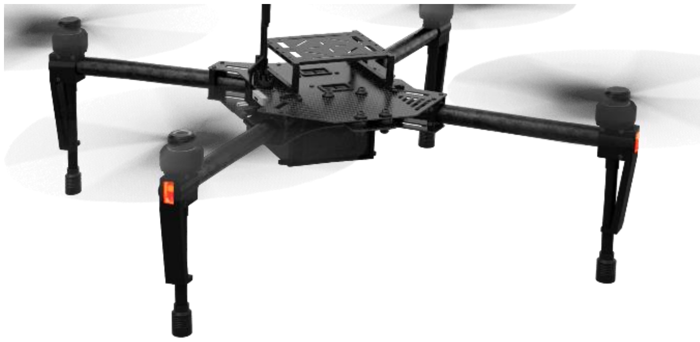


Figure 20: Drone landing legs attached directly to propeller arm

3.3 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 ideate what sections of drone would be required to provide the inputs and outputs. The 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.

3.3.1 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 inputted, and wind in the form of thrust from each of the individual blades. Energy is inputted 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 21 below shows the final Black Box Model used by the team.

Figure 21: 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.

3.3.2 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 22.

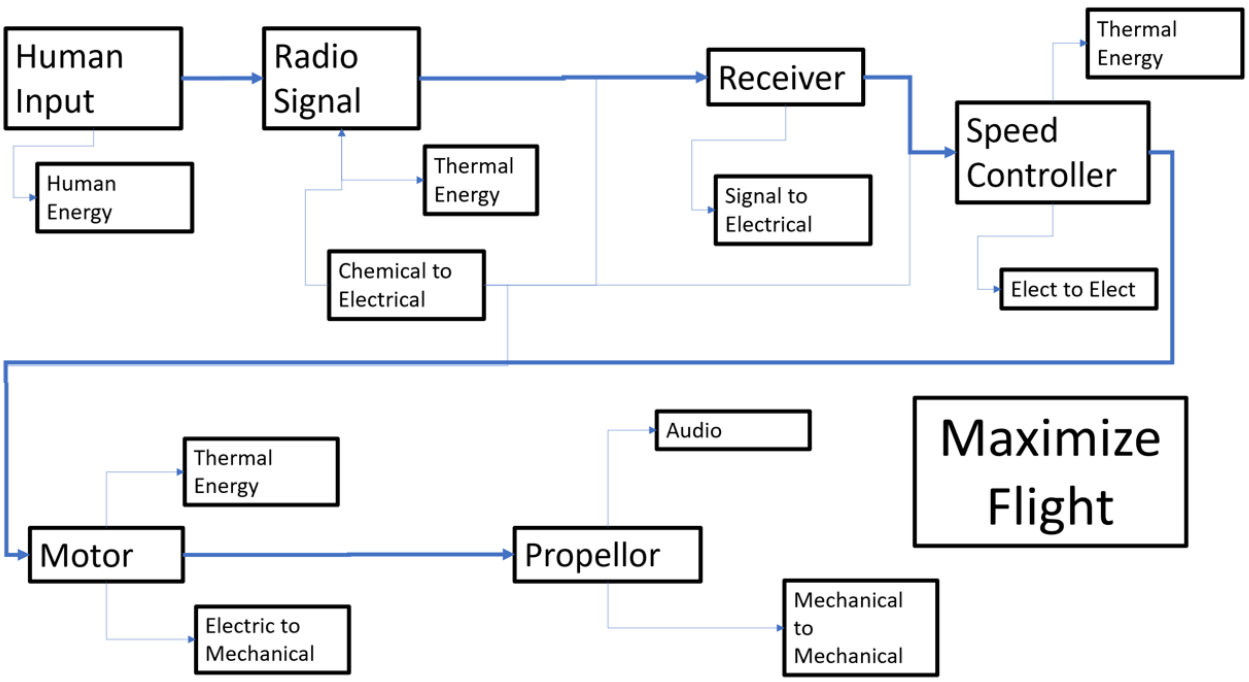


Figure 22: Drone Functional Decomposition

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.

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. 3 designs are selected and then 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

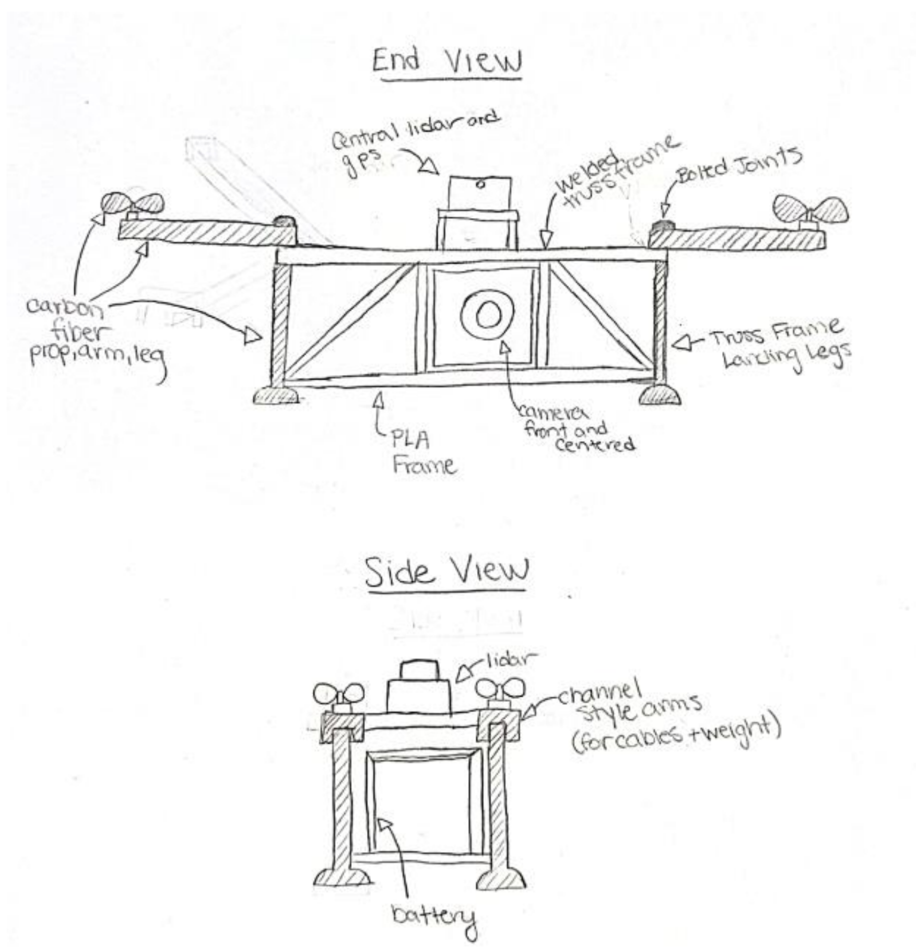


Figure 23: First full system design with a truss system

The truss system 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

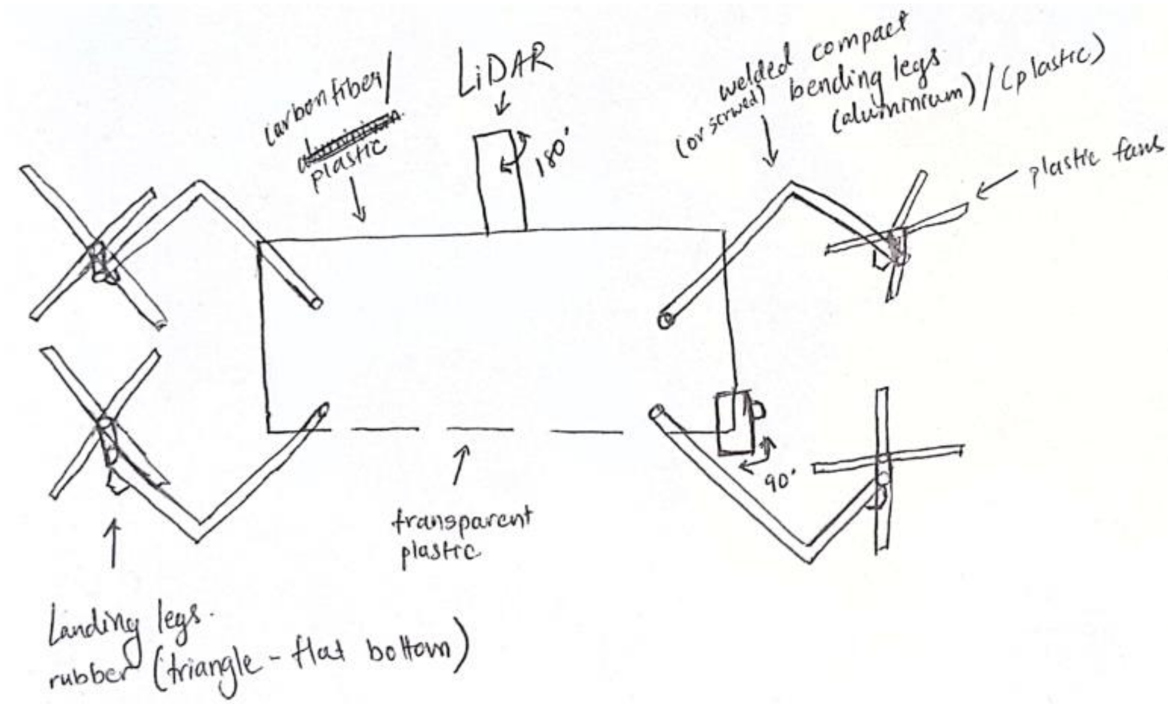


Figure 24: Second full system design featuring folding arms

This design is built for ease of storage. 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 see placed 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

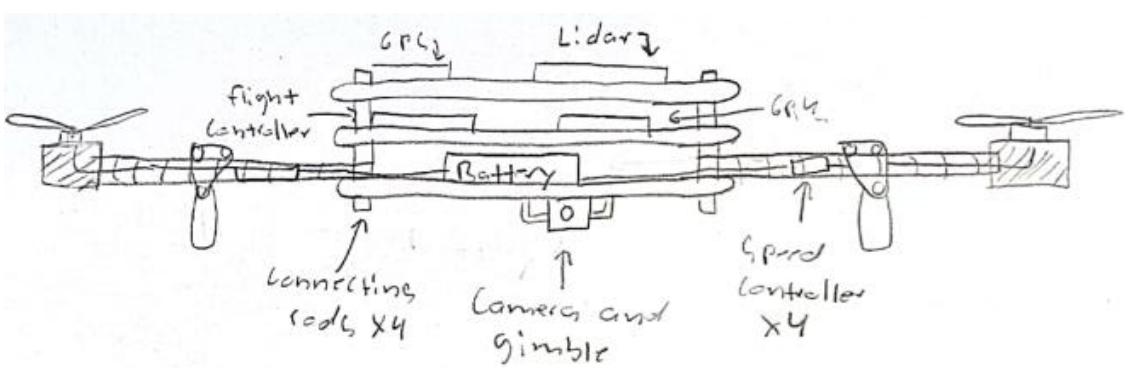


Figure 25: Third full system design with stacked discs

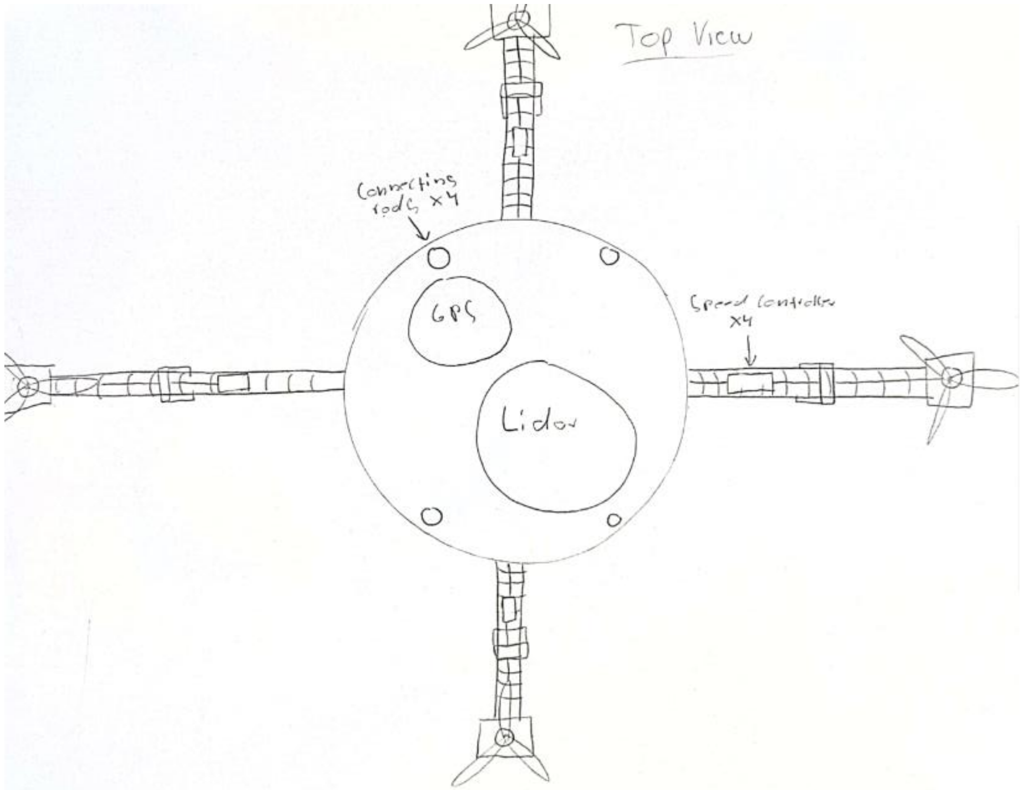


Figure 26: Third full system top view

This design 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

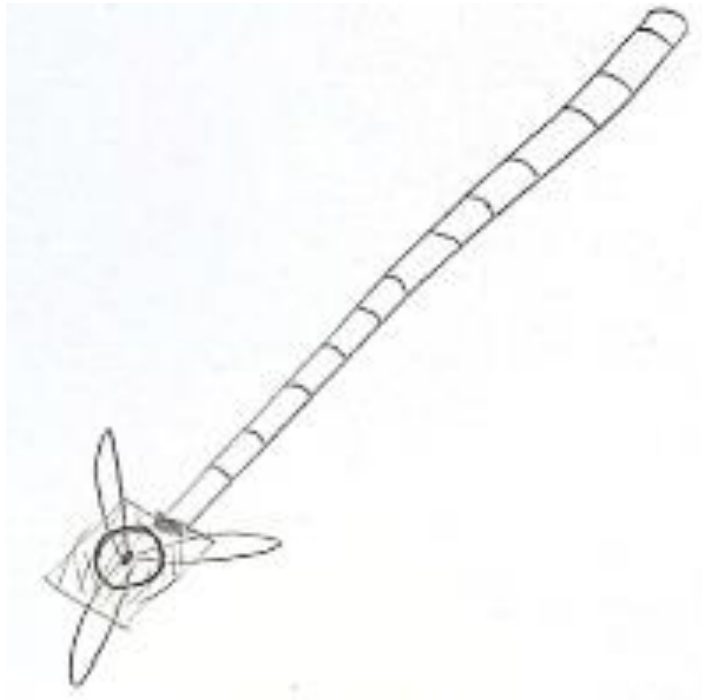


Figure 27: Tubular carbon fiber arm with 3D printed end cap

Carbon fiber arms would help decrease weight but is much more difficult to work with. 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

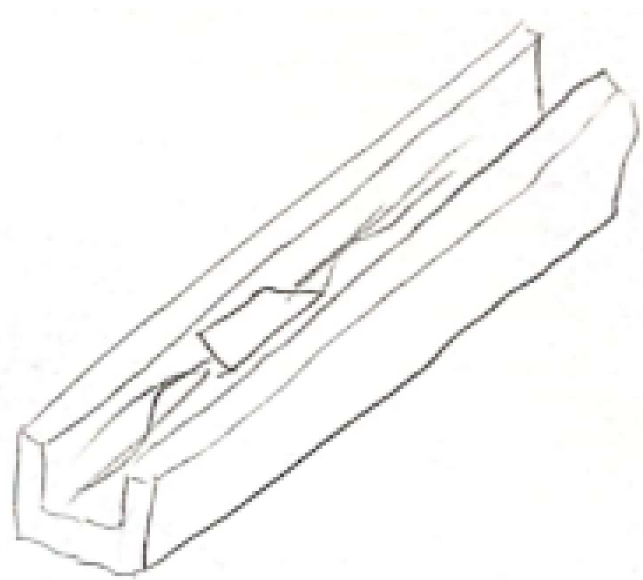


Figure 28: U-channel arm design

Having a U-channel arm design 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

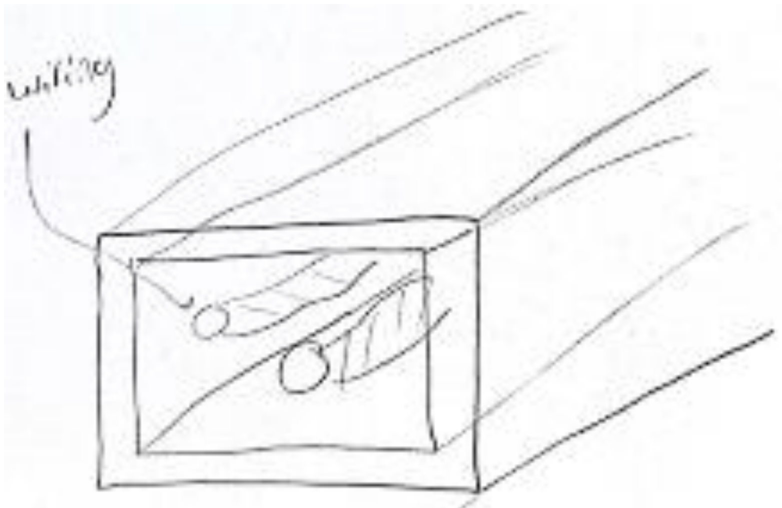


Figure 29: Hollow cubic arm design

The hollow cube improves the design of the U-channel. 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

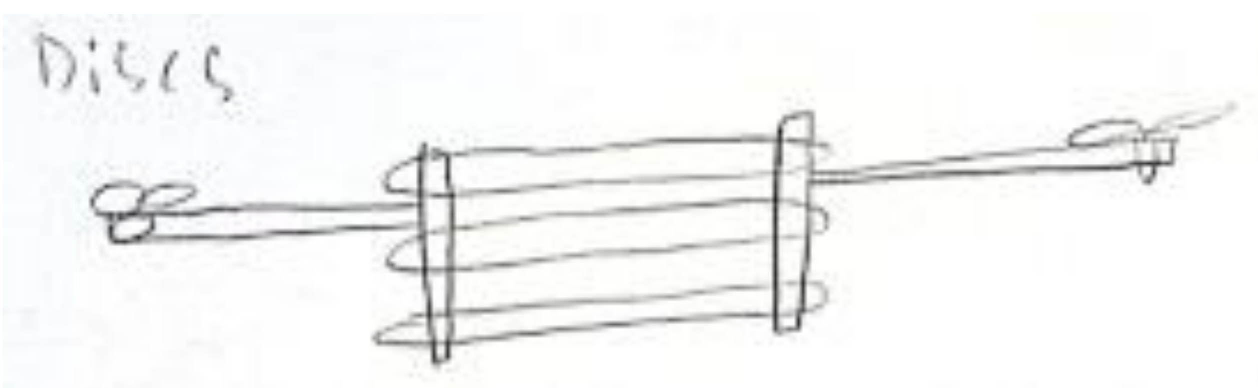


Figure 30: Stacked discs body design

The disc design 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

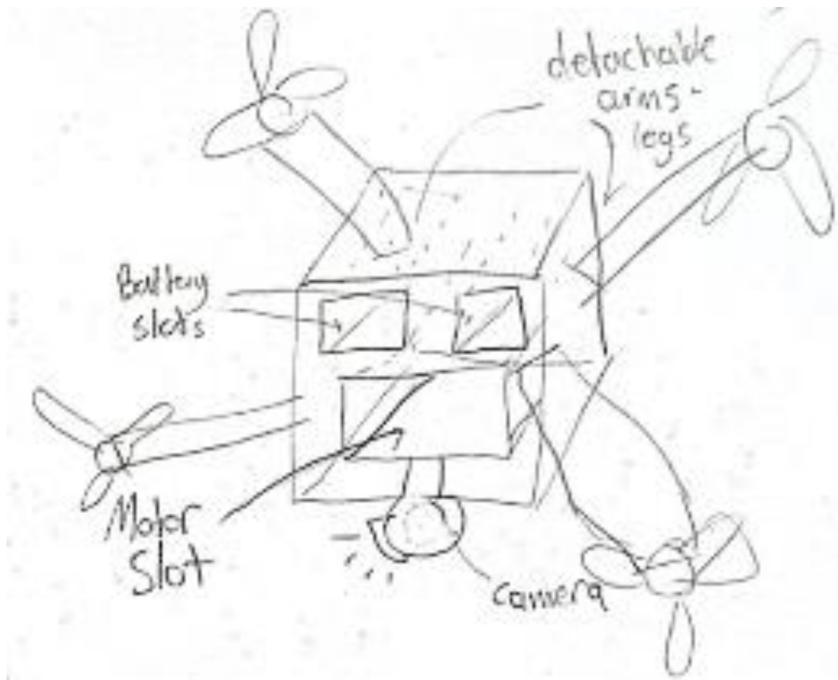


Figure 31: Modular slots body design

This design is made with component compatibility and ease of use in mind. 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

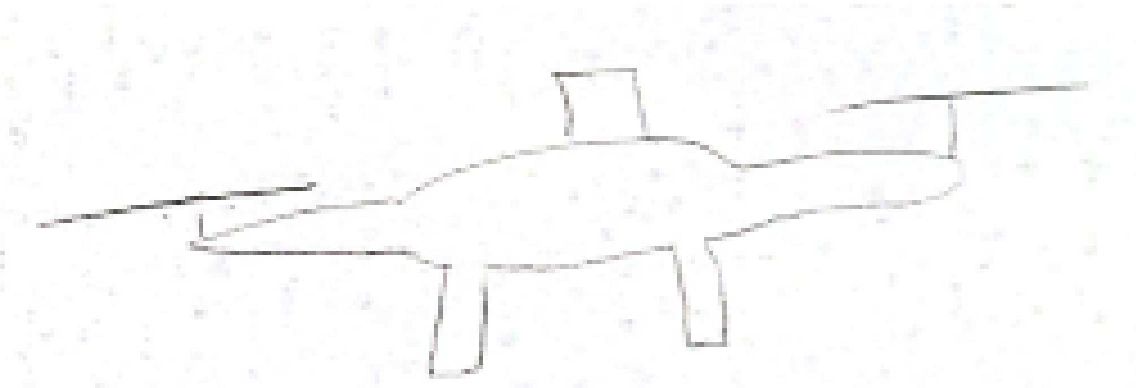


Figure 32: Solid body design

A solid body would make the design process much easier, however it would increase manufacturing time and would likely be overweight. 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

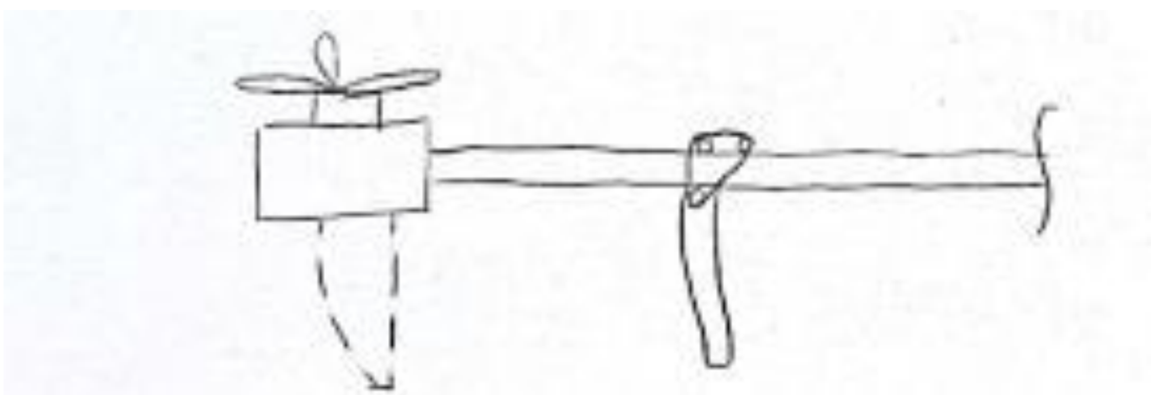


Figure 33: Sliding leg style

These legs are designed to be moveable along the length of the arm. 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

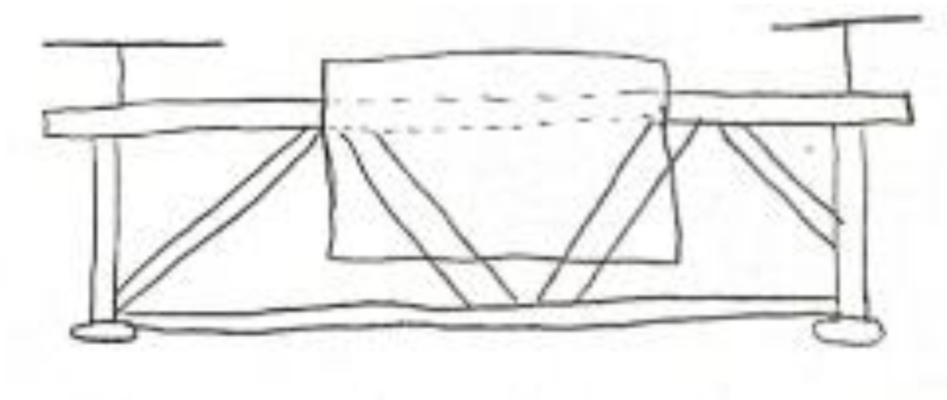


Figure 34: Leg design with truss system

The trusses on the legs are made to increase the strength of the body and the legs themselves. 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

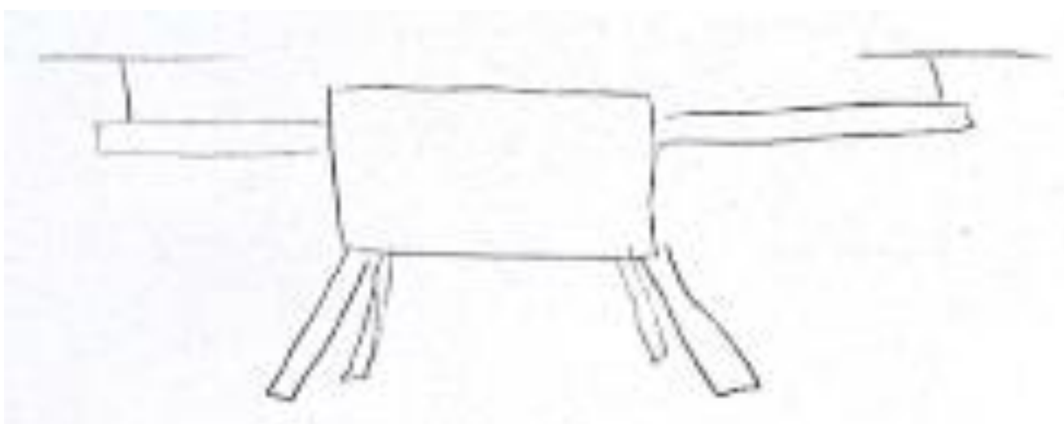


Figure 35: Simple extruded leg design

This design has 4 simple legs either made solid with the body or attached as a separate part. 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 DESIGNS 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 A] 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 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 [fig. 23] and design 3 [fig. 25, 26] 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 [fig. 36]. This design is a good outline of what Team Hi-Jacks will continue with in the future but will be adjusted as needed.

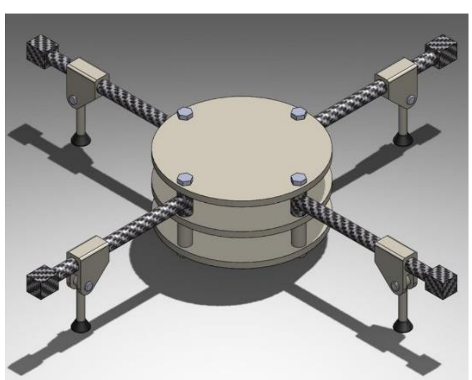


Figure 3: Rough CAD model

6 REFERENCES

[1] S. Ngoh, “On-demand webinar: When to choose 3D printing vs. machining,” *Xometrys RSS*, 09-May-2022. [Online]. Available: https://www.xometry.com/resources/blog/on-demand-webinar-3d-printing-vs-cnc-machining/. [Accessed: 13-Oct-2022].

[2] T. Xometry, “Design guide: CNC Machining,” *Xometrys RSS*, 09-Jul-2021. [Online]. Available: https://www.xometry.com/resources/design-guides/design-guide-cnc-machining/. [Accessed: 09-Oct-2022].

[3] S. K. Moon, Y. E. Tan, J. Hwang, and Y.-J. Yoon, “Application of 3D printing technology for designing light-weight unmanned aerial vehicle wing structures,” *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 1, no. 3, pp. 223–228, 2014.

[4] “What are the key design elements for 3D printing?,” *Hubs*. [Online]. Available: https://www.hubs.com/knowledge-base/key-design-considerations-3d-printing/. [Accessed: 19-Oct-2022].

[5] “Solidworks costing,” *SOLIDWORKS Costing - 2021 - SOLIDWORKS Help*. [Online]. Available: https://help.solidworks.com/2021/English/SolidWorks/sldworks/c_costing_top.htm. [Accessed: 22-Oct-2022].

[6] “Introduction to Ansys (Part1) : Starting Ansys Workbench,” YouTube, 24-Aug-2019. [Online]. Available: https://www.youtube.com/watch?v=C8WvCQpzT2A. [Accessed: 23- Oct-2022].

[7] “Introduction to stress analysis | ANSYS innovation courses.” [Online]. Available: https://courses.ansys.com/index.php/courses/stress-analysis/lessons/lesson-2-about- stressanalysis/. [Accessed: 23-Oct-2022].

[8] G. Z. / J. 8, “Engineering leadership 101 - lessons from Michael Lopp ‘Rands,’” Web Application Development Agency - React, Angular, Node.js, 10-Aug-2022. [Online]. Available: https://codingsans.com/blog/engineering-leadership. [Accessed: 23-Oct-2022].

[9] “Boeing: Autonomous Systems,” Boeing. [Online]. Available: https://www.boeing.com/defense/autonomous-systems/index.page. [Accessed: 23-Oct-2022].

[10] GetFPV, “How to reduce the weight of your FPV drone,” GetFPV Learn, 01-Jul-2021. [Online]. Available: https://www.getfpv.com/learn/fpv-in-depth-and-technical/how-to-reduce-the-weight-of-your-fpv-drone/. [Accessed: 23-Oct-2022].

[11] Michael Vogelsang. (2022). Boeing Autonomous Drone Weight Reduction Capstone [PowerPoint].

[12] Reed Esper. (2022). Boeing Autonomous Drone Weight Reduction Capstone Components List [PowerPoint].

[13] *Dreamweaver tutorials: Learn how to use Dreamweaver*. Dreamweaver tutorials | Learn how to use Dreamweaver. (n.d.). Available: https://helpx.adobe.com/dreamweaver/tutorials.html . [Accessed: October 23, 2022]

[14] *W3Schools*. HTML tutorial. (n.d.). [Online]. Available: https://www.w3schools.com/html/default.asp. [Accessed: October 23, 2022]

[15] Drop Test Analysis in Ansys Workbench: Simulation Tech Tamil. (2021). *YouTube*. [Online]. Available: https://www.youtube.com/watch?v=S0PCB8VAhRE. [Accessed: October 23, 2022]

[16] W. Parker, "What is manufactured wood?: Types, uses, Pros and Cons," WoodWorkly, 20-Oct-2022. [Online]. Available: https://woodworkly.com/what-is-manufactured-wood/. [Accessed: 23-Oct-2022].

[17] "MakerLab 3D Printing," Cline Library. [Online]. Available: https://nau.edu/library/3d-printing/#:~:text=Print%20Cost,shipping%20prints%20(NAU%20affiliates%20only). [Accessed: 23-Oct-2022].

[18] "How much does 3D printing cost? TIPS for reducing your manufacturing costs," Hubs- A Prototyping Company, 2022. [Online]. Available: https://www.hubs.com/knowledge-base/how-much-does-3d-print-cost/. [Accessed: 23-Oct-2022].

[19] E. Ciobanu, "5 ways to make your drone more powerful," Droneblog, 15-Jun-2021. [Online]. Available: https://www.droneblog.com/5-ways-to-make-your-drone-more-powerful/. [Accessed: 23-Oct-2022].

[20] "Direct Metal Printing ," Quickparts, 03-Jun-2022. [Online]. Available: shorturl.at/coFQZ

[21] Dassault Systems, "Training Catalog," Solidworks. [Online]. Available: https://my.solidworks.com/training/catalog. [Accessed: 23-Oct-2022].

[22] Not Real Engineering. "ANSYS 2020 Workbench Tutorial | Introduction to Static Structural | 2020 R2," *YouTube*, Feb. 8, 2021. Available: https://www.youtube.com/watch?v=YfxRzRB346k. [Accessed: Oct. 9, 2022].

[23] Tom Stanton. "Optimizing a VTOL," *YouTube*, Aug. 18, 2022. Available: https://www.youtube.com/watch?v=XPXN0QejqM0. [Accessed: Oct. 23, 2022].

[24] V. Kumar, "Robotics: Aerial Robotics," Coursera, 2016. [Online]. Available: https://www.coursera.org/learn/robotics-flight?action=enroll. [Accessed: 23-Oct-2022].

[25] Michael Vogelsang. (2022). Boeing Autonomous Drone Weight Reduction Capstone [PowerPoint].

[26] "Phantom 4 RTK - DJI," *DJI Official*. [Online]. Available: https://www.dji.com/phantom-4-rtk. [Accessed: 08-Oct-2022].

[27] "Typhoon h plus – yuneec." [Online]. Available: https://us.yuneec.com/typhoon-h-plus/. [Accessed: 08-Oct-2022].

[28] "Anafi USA," *Parrot*. [Online]. Available: https://www.parrot.com/us/drones/anafi-usa. [Accessed: 08-Oct-2022].

7 APPENDICES

7.1 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**	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*
			Technical Requirements										**Customer Opinion Survey**				
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					

7.2 Appendix B: Concept Generation

Table 1: Morph matrix

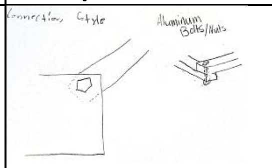
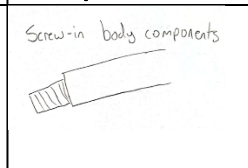
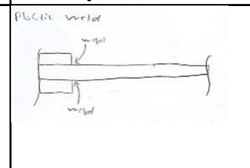
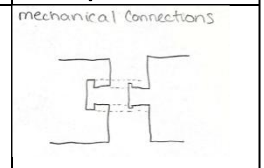
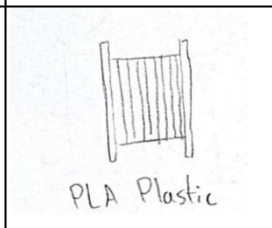
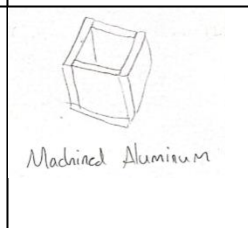
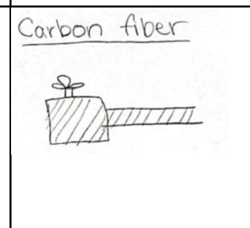
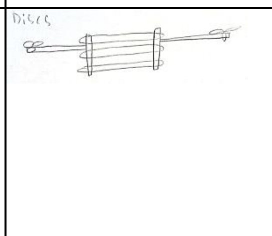
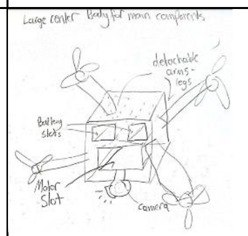
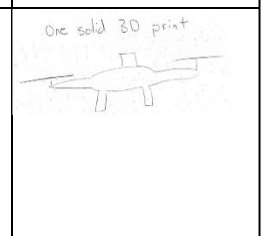
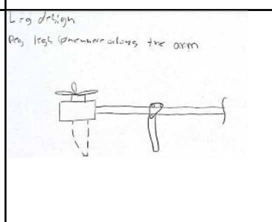
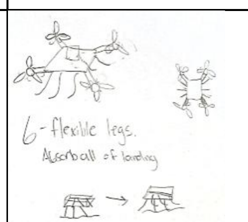
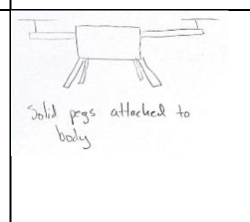
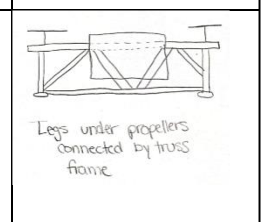
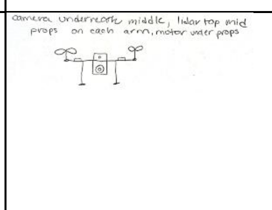
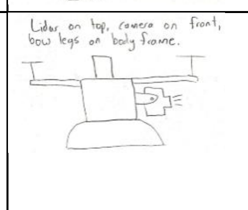
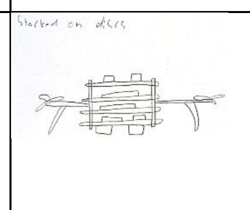
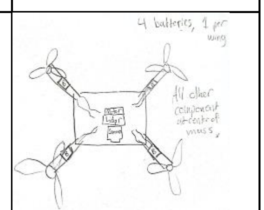
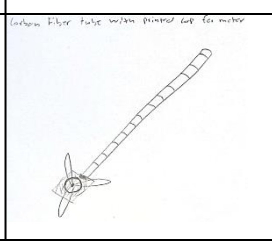
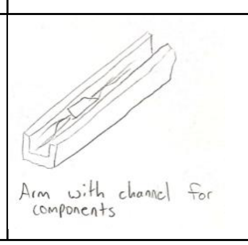
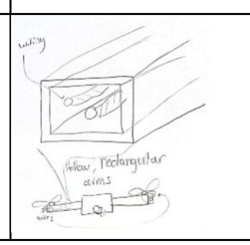
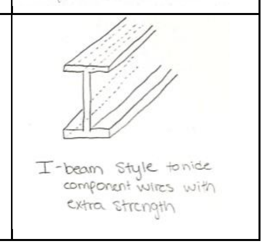
Subcategories	Concept 1	Concept 2	Concept 3	Concept 4
Arm Connection Style				
Material				
Body Configuration				
Leg Style				
Component Configuration				
Arm Style				

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