The DORIS Project

Conceptual Design Report

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DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

For our senior mechanical engineering capstone, our team was tasked with designing and creating a drone utilizing commercially available parts. The drone must be able to engage and deploy different payloads while remaining airborne. These payloads will include a camera for potential surveying, a payload that must be equal or greater in weight to 30% of the drone's empty weight, and a 3D-printed cruise missile that must be able hit a target after being deployed. The drone must be able to complete a predesignated course where it will take off, deploy the cruise missile, fly to the first payload, pick it up, fly across the field, drop the payload, fly to the next payload, pick it up, fly across the field, drop the payload, pick up a camera, fly to the team, take a picture, and land safely. We have codenamed this project DORIS – Drone Operated Reconnaissance and Interchange System.

The budget for this project is $3000, sponsored by the Mechanical Engineering Department at Northern Arizona University. On top of the $3000, the team was also required to fundraise 10% of that budget, or $300. For the fundraising, the team decided to use GoFundMe to raise these funds and have already exceeded the $300 needed. The advisor and instructor for our project is Professor David Willy at Northern Arizona University.

The importance of this project is that it satisfies a need for a more affordable and easier to manufacture payload-capable drone. This could allow for an easier and cheaper way to deliver and receive any kind of consumer package, to deliver first aid materials or other emergency supplies, and can be used for many military applications.

Over the course of this project so far, we have benchmarked designs for the drone, compiled a list of literature that will be useful to our project, calculated the thrust due to our selected motors and propellers, calculated the size of the battery that will be needed to power the drone, calculated the shear stress, bending moment, moment of inertia, and the maximum deflection of the drone arms, created a variety of designs for each subsystem, weighed each design against five criteria, selected the best design based on the weighting, and started prototyping.

The design that our team has decided on is a quadcopter with a simplistic carbon fiber frame, octagonal carbon fiber arms, a magnetic payload attachment system that can be turned off using a servo motor, a Pixhawk 6C Flight Controller, iFlight XING X4214 660KV Motors, and HQProp 16X8X3 tri-blade propellers. With this design, we believe that it will be capable of picking up large payloads, have a significant flight time, and being able to resist any damage that may occur. If damage does occur, the design allows for easy repairability.

Moving forward into the project, the team plans to continue prototyping, do material testing on the carbon fiber selected and various types of 3D printing filament, build the drone, test fly it, iterate on any problems that we can find on the drone, and do our final course run.

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1. BACKGROUND

This section contains information pertaining to the overall project description, deliverables, and success metrics.

1.1 Project Description

The project involves designing and developing a utility drone capable of carrying variable payloads, sponsored by the Boeing Company. The goal is to create a drone that can engage and deploy different payloads while airborne, such as a camera for surveying and a heavier payload that must be at least 30% of the drone's total weight. The drone will be required to perform specific tasks, such as payload delivery, retrieval, and returning to its starting point, while meeting Federal Aviation Administration (FAA) regulations. The total budget for this project is $3,000, with an additional $300 or more successfully raised through a GoFundMe campaign. From the project description, we developed a project name: Drone Operated Reconnaissance and Interchange System, or DORIS for short.

1.2 Deliverables

The major deliverables for this project include a functional drone capable of completing the defined tasks and operating within legal regulations. Key outputs will include an assessment of FAA drone laws, thrust-to-weight ratio calculations, a center of mass analysis, and payload capacity estimations. The project will also involve failure mode analysis, the development of a project website, and the completion of various reports and presentations, culminating in a final report detailing lessons learned and potential real-world applications.

1.3 Success Metrics

The project's success will be assessed based on several key metrics that encompass design, performance, and compliance criteria. Firstly, the drone must demonstrate its ability to perform various mission-critical tasks, including taking off, engaging payloads, and deploying them while airborne without human intervention other than RC signals. The payloads include a camera for aerial surveying and a heavy cargo that must constitute at least 30% of the drone's total empty weight.

Flight performance is another critical metric; the drone must sustain a minimum of 10 minutes of continuous flight without battery failure, ensuring it has adequate endurance for practical applications. The drone's thrust-to-weight ratio and center of mass must also meet predefined standards to maintain stability during payload deployment and retrieval. Testing will involve multiple flight trials under different load conditions to confirm these parameters.

Further, the project will be evaluated based on regulatory compliance, requiring the drone to adhere to FAA regulations for registration and operational safety. This includes the use of the B4UFLY app for outdoor flight tests, ensuring legal operation in designated airspace. Data from these tests, alongside calculations for payload handling capabilities, center of mass, and failure mode analysis, will be compiled in reports that benchmark the drone's actual performance against design requirements. Overall, the combination of

successful task execution, regulatory compliance, and validated engineering calculations will define the project's achievement.

2. REQUIREMENTS

This chapter outlines the key aspects of the drone project by breaking down the requirements and design goals into three main sections: Customer Requirements, Engineering Requirements, and the House of Quality. The Customer Requirements focus on the essential features that the drone must possess according to the client. The team used these requirements to look for quantifiable goals for the project. The Engineering Requirements translate these customer needs into technical specifications, such as achieving a specific thrust-to-weight ratio, keeping the drone's dimensions compact, ensuring it can operate for a minimum of 10 minutes, and maintaining a budget limit. These engineering goals are designed to ensure that the drone can complete its mission effectively while meeting regulatory standards by setting quantifiable guidelines for the final product. In the final section, the House of Quality serves as a framework that links customer expectations with the engineering targets. It ensures that all design decisions reflect the customer's priorities, helping the team make informed trade-offs between performance, cost, and regulatory compliance during the development process.

3.1 Customer Requirements (CRs)

High Mobility – The drone needs to be highly maneuverable. Able to turn sharply and easy to control to be able to pick up and drop the payload at the waypoints.

Small – The drone needs to be small and still fit all essential parts such as battery and receivers as well as the payload pick-up system.

Complete Recon Mission – The drone must be able to fly to and pick-up a payload then fly it to another waypoint to drop it off. The drone must also be capable of flying with a camera and taking at minimum one photo of the team below. Lastly, it must be able to carry and launch a steerable cruise missile.

Payload Capacity – The drone can carry a significantly heavy payload, a third of its own weight.

Battery Capacity – The battery must be efficient/large enough to power the full mission and land back at home point.

Cost Efficiency – There is a limited budget for this project, so the team needs to watch their purchases and look for cheaper options if possible.

Thrust Efficiency – The drone should have a high thrust to weight ratio to be able to move easily and lift heavy payloads.

FAA Registered – The team must meet the regulations set by the Federal Aviation Administration for Unmanned Aircraft Systems (UAS). The most important ones are that the team cannot fly it above 400 ft and the drone must weigh less than 55 lbs. If necessary, the drone should be registered with the FAA.

3.2 Engineering Requirements (ERs)

Thrust to Weight Ratio – The goal ratio is for the thrust to be at least 3 times the weight of the drone. This

goal was set so that we can lift the payload and still fly with high mobility.

Compact Design – The drone should be under 3 feet in height, width, and length. If the drone gets too large it will become heavier which gets harder to counter with thrust. Also, maneuverability will be more difficult.

Complete Course in Time Limit – The time limit is 10 minutes. The team must operate the drone to complete all tasks within this time constraint.

Payload Weight – The payload must be at least 30 % of the weight of the drone. To do this the drone needs to have powerful motors with efficient propellors to give it high thrust.

Time of Flight – The minimum requirement for the time in the air is 10 min. This test will be done with a full battery and keeping the drone at a hover.

Total Cost – The budget is $3,000 so all purchases must be tracked to make sure the spending does not exceed the limit.

Meet FAA Requirements - The team must meet the regulations set by the FAA for UAS. The drone cannot fly above 400 ft and it must weigh less than 55 lbs.

3.3 House of Quality (HoQ)

Roof / Correlation Matrix (3 Highest on scale)

	Thrust : weight > 3:1	Compact Design under 3'x3'x3'	Complete Course < 10 min	Payload > 30% of weight	Time of flight > 10 min	Total Cost under $3,000	Meets FAA requirements (weight < 55 lbs)
Thrust : weight > 3:1							
Compact Design under 3'x3'x3'							
Complete Course < 10 min	3						
Payload > 30% of weight	1		1				
Time of flight > 10 min	3		1	1			
Total Cost under $3,000		3			1		
Meets FAA requirements (weight < 55 lbs)	3	3		1	3	3	

Technical Requirements Matrix

Customer Needs	Customer Weights: 1-5	Thrust : weight > 3:1	Compact Design under 3'x3'x3'	Complete Course < 10 min	Payload > 30% of weight	Time of flight > 10 min	Total Cost under $3,000	Meets FAA requirements (weight < 55 lbs)
High mobility	4	5	5	5	1	2	1	
Small	1	4	5	3		5	5	5
Complete Boeing Recon Mission	5	5	3	2	4	2		
Payload Capacity	5	5	1	2	5	1	2	
Battery Capacity for small mission	4	3	2	4	4	5	1	1
Cost Efficiency	3	1	2	3		2	5	4
Thrust Efficiency	4	5	3	5	4	5	2	
FAA Registered	5		3					5
Technical Requirement Units			Feet	minutes	% weight	minutes	USD	pounds
Technical Requirement Targets		3:1	< 3x3x3	< 10	> 30	> 10	>3000	< 55
Absolute Technical Importance		28	24	24	18	22	16	15
Relative Technical Importance		1	3	3	5	4	6	7

4 Research Within Your Design Space

4.1 Benchmarking

4.1.1 Drone System

The three drone designs that the team considered state-of-the-art were: NAU Capstone 2022 Team Hi-Jax's drone, the Aurelia X8 Pro drone, and the Aurelia X6 standard drone. Design 1, the Hi-Jax drone, a 4-rotor drone picture in Figure 3.1, is considered state-of-the-art because it is light weight, compact for its size, it was durable for lower flight altitudes. It is a good jumping off point for the current team's project as it was provided to the team for reference and the flight controller and other electronics were taken from this design to be used on the team's final drone design.

Figure 4.1: Hi-Jax drone [2]

Design 2, the Aurelia X8 Pro, an 8-rotor drone pictured in Figure 3.2, is considered state-of-the-art because it is designed to carry a very large payload of 10 kilograms or approximately 22 pounds [3].

Figure 4.2: Aurelia X8 Pro drone [3]

Design 3, the Aurelia X6 Standard, a 6-rotor drone pictured in Figure 3.3, is considered state-of-the art because, even though it has a small payload capacity of 3 kilograms, it is lighter than the X8, less complicated than it with 2 less rotors (less likely to break), it is also cheaper, and it has an integrated payload release mechanism [4].

Figure 4.3: Aurelia X6 Standard drone [4]

4.1.2 Magnets

The three magnet designs that the team evaluated were: the Mag-switch MAGJIG 60, the MAGMATE ER202, and the MAG-MATE AR1504. The mag-switch MAGJIG 60 is a mechanical magnet, weighing 0.2 pounds, measuring 1.7 inches in height, 1.6" in length, 1.1" in width, with a max hold force of 60 pounds, and a price of 26 dollars [5]. This mechanical magnet would require some type of actuator to engage and disengage its magnetic properties, whereas the following magnets are electro-magnets, which means they only need current to be applied to them to engage/did-engage them. The MAG-MATE ER2-202, is a non-shielded electro-magnet (so the other electronic components on the drone will require shielding) weighing 2 pounds, measuring 2.5 inches in height, 2" in diameter, with a max hold force of 100 pounds, and a total cost of $158 [6]. The MAGMATE AR1504, is a shielded electro-magnet, weighing 1 pound, measuring 1.3 inches in height, 2.5" in diameter, with a max hold force of 35 pounds, and a price of $136 [7]. Ultimately, for its price to max hold force ratio, the team decided on the mag-switch MAGJIG 60 for implementation into the project design.

4.1.3 Propellers

For this assessment, the team assessed three different propeller designs for the three-blade type propeller. The three propeller designs that the team evaluated were: the T-Motor P 17 by 5.8, the Gemfan 16 by 5.5, and the HqProp 16 by 8 by 3. The T-motor P 17x5.8 propeller is made of carbon fiber, weighing 26.5 grams, measuring 17 inches in diameter, with a pitch of 5.8 inches, a thrust limit of 7.5 kilograms, an optimum RPM range of 3500-6000, and a cost of 14.38 dollars per unit [8]. The Gemfan 16x5.5 propeller is made of carbon fiber, weighing 53 grams, measuring 16 inches in diameter, with a pitch of 5.4 inches, a thrust limit of 7 kg, an optimum RPM range of 3000-5000, and a cost of 62.39 dollars for 2 units [9]. The HQProp 16x8x3 propeller is made of black-glass fiber-reinforced nylon, weighing 66.5 grams, measuring 16 inches in diameter, with a pitch of 8 inches, a thrust limit of 7.2 kilograms, an optimum RPM range of 3500-6000, and a cost of 26.28 dollars per unit [10]. Ultimately, the HQProp 16x8x3 was selected because of its low price and comparable thrust limit and optimum RPM range.

4.1.4 Motors

The three motor designs that the team evaluated were: the T-Motor f-1000, the iFlight XING X4214 660KV, and the SunnySky X4120 650KV. The T-Motor f-1000 has a max thrust rating of 6875 grams, it weighs 404 grams, operates with a max current of 125 amps, a max power rating of 4000 watts, and a total cost of 119.90 dollars per unit [11]. The iFlight XING X4214 660KV has a max thrust rating of 7900 grams, it weighs 213 grams, operates with a max current of 98 amps, a max power rating of 2352 watts, and a total cost of 82.99 dollars per unit [12]. The SunnySky X4120 650KV has a max thrust rating of 6592 grams, it weighs 290 grams, operates with a max current of 100 amps, a max power rating of 2750 watts, and a total cost of 136.65 dollars per unit [13]. Ultimately, the iFlight XING was selected due to its lower cost, lower weight, and greater max thrust rating.

4.2 Literature Review

4.2.1 Dylan Boeholt

Websites:

"How to Calculate & Measure Propeller Thrust" [14]

This blog on TYTO Robotics outlines how to calculate and measure propeller thrust. The writer includes necessary equations for our design process. Jeremy and Andre will use this to design the drone rotors.

Journals:

"Design and Analysis of a Topology-Optimized Quadcopter Drone Frame" [15]

This paper is a report on 3 different designs of a drone frame and uses simulations to analyze the stress and strain of the different designs. The frame technicians (Jeremy and Dylan) will use this source.

"A thrust equation treats propellers and rotors as aerodynamic cycles and calculates their thrust without resorting to the blade element method" – ERAU [16]

This source provides equations to calculate the thrust of propellers. A thrust equation treats propellers and rotors as aerodynamic cycles and calculates their thrust without resorting to the blade cycles and calculates their thrust without resorting to the blade. Jeremy and Andre will use this information to analyze the rotors.

"Quadcopter Body Frame Model and Analysis" [17]

This paper discusses the use of computer frame modelling to determine the type of rotor and propeller to assure the necessary flight acceleration. Jeremy and Andre will use this information to pick the right rotors for the drone.

Standard:

Code of Federal Regulations Title 14 Chapter 1 Subchapter F Part 107 [18]

This CFR has all the rules on small, unmanned aircraft. We will use this to understand the rules of recreational drones before flying our drone. The flight engineer (Dylan) will use this.

ASM Handbook: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. [19]

This handbook serves as a comprehensive guide for understanding the characteristics, performance, and applications of nonferrous alloys and specialized materials. For drone frame design, this resource provides critical insights into material selection by detailing the mechanical properties, corrosion resistance, weight considerations, and manufacturability of alloys like aluminum, titanium, and magnesium, which are commonly used for lightweight and durable structures. The handbook facilitates an informed decision-making process by outlining the trade-offs between strength, stiffness, and cost. Its thorough exploration of thermal and fatigue properties is particularly relevant for drones, as these factors affect performance and longevity under varying environmental and operational stresses. This helped our team choose a material for the drone frame that is lightweight and structurally sound.

ASTM F2910-14: Standard Specification for Design and Construction of a Small Unmanned Aircraft System (sUAS). [20]

The ASTM F2910 standard is crucial for the construction of our drone as it provides a comprehensive framework to ensure safety, reliability, and airworthiness during the design and build phases. This standard defines essential parameters, including structural integrity, weight limits, and flight stability, offering guidelines for selecting materials, assembling components, and integrating electronics. By adhering to ASTM F2910, developers can create drones that comply with performance and operational requirements while minimizing risks associated with failure or instability during flight. This standard also ensures that the drone is robust enough to handle environmental stresses like wind or temperature fluctuations, making it a valuable tool for achieving both regulatory compliance and user satisfaction in recreational applications.

ASTM Aerospace Material Standards [21]

The ASTM Aerospace Material Standards are invaluable for constructing small drones, as they provide detailed testing methods and specifications for materials used in aerospace applications. These standards ensure that materials selected for drone components meet rigid requirements for thermal stability, mechanical strength, corrosion resistance, and electrical conductivity. For instance, lightweight alloys and composite materials, critical to drone frames, can be evaluated for their performance under operational stresses such as vibration and temperature variations. By adhering to these standards, manufacturers can optimize material selection to achieve a balance between durability, weight, and cost, resulting in drones that are both efficient and reliable for recreational use. Moreover, the standards promote consistency and quality, aligning recreational drone manufacturing practices with industry-grade benchmarks.

Books:

Engineering Statics: Chapter 4 Moments and Static Equivalence [22]

This source will be used to understand moments of a structure. This information will be used to analyze the force applied to the arms of the drones. This information will be used by the flight engineer (Dylan) and manufacturer (Jeremy).

Engineering Statics: Chapter 7 Centroids and Centers of Gravity [23]

This source will be used to understand how important the center of gravity is to flight and how it can be changed to improve control. The flight engineer (Dylan) will use this information.

4.2.2 Andre Bonillas

Websites:

"Payloads for Drones in Emergency Response: Guide to what UAVs Carry." - dslrpros.com [24]

This guide provides a comprehensive overview of the types of payloads used by unmanned aerial vehicles (UAVs) in emergency response scenarios. It categorizes payloads into several key areas, including sensors, cameras, communication equipment, and delivery systems. The document emphasizes the flexibility of UAVs in carrying different payload types, depending on the mission's objectives, whether it is surveillance, search and rescue, or the delivery of medical supplies. Additionally, it highlights the technological advancements in sensor accuracy, range, and payload capacity, which have expanded the utility of drones in time-sensitive and critical situations. This resource is particularly useful for engineers and emergency planners looking to integrate UAVs into disaster management systems, as it not only lists common payloads but also provides insight into regulatory considerations and operational constraints. The team will utilize this information when considering the final drone's design importance in within the industry, as well as when evaluating the different type of payloads that the final drone design will carry.

"Heavy Lift Payload Drones." Uavsteminternational.com [25]

This website page details existing drone designs that are intended to carry large payloads (>10kgs). This webpage offers an in-depth technical analysis of heavy drones, focusing on their design, operational capabilities, and applications across various industries. It details the engineering specifications of heavy-lift UAVs, including payload capacities, flight endurance, and propulsion systems. Key use cases are discussed, such as logistics, construction, and emergency response, where heavy drones play a critical role in transporting large or sensitive materials. The guide also addresses the challenges associated with the deployment of these drones, including battery efficiency, regulatory hurdles, and the need for advanced control systems to ensure safe and efficient operations. This reference is highly relevant for engineers involved in drone development, providing a solid technical foundation for understanding the requirements and potential of heavy UAVs. The team will use this source when benchmarking, to gather information on state-of-the-art designs that can be used as benchmarking for the team's final design.

"Best Drones using a payload release mechanism." – uavsystemsinternational.com [26]

This document provides an overview of various drop mechanisms used in UAVs, detailing their design and operational features. It highlights applications such as cargo delivery, emergency supplies, and precision payload deployment. The document is relevant for engineers designing UAVs for delivery and emergency services, offering insights into mechanism reliability and safety. The team will use this resource in the development of the payload interchange system as reference to existing methods of

transporting and releasing payloads from a drone.

Journal Papers:

<u>"A Practical Perspective on the Drone-with-a-Slung-Load Problem." [27]</u>

This paper addresses the control and stability challenges involved when drones transport payloads using slung-load systems. The authors propose a control strategy that accounts for unknown or unmeasured variables like the cable deviation angle and the load mass, making it highly applicable to real-world scenarios. The paper's insights are valuable for engineers working on drone logistics, offering solutions for managing dynamic instabilities in cargo transport. The team will use this resource when considering the flight stability of the drone when it is carrying the payload.

<u>"Quadcopter Design for Payload Delivery." [28]</u>

This paper examines the design and control strategies for a quadcopter optimized for payload delivery. The authors focus on mathematical modeling of the quadcopter's flight dynamics, particularly in relation to altitude and attitude adjustments when carrying different payloads. The study also explores motor efficiency and stability, making it valuable for engineers developing UAV systems for logistics and transport. It provides key insights into managing varying payload capacities while maintaining flight control. The team will use this resource when designing the drone to integrate a payload in its operation.

<u>"Package Retrieval system with funneling mechanism." [29]</u>

This patent describes a system designed to retrieve payloads delivered by unmanned aerial vehicles (UAVs) using a funneling mechanism. The system includes sloped surfaces that guide the payload into a secure position, ensuring precision during retrieval. The design improves alignment and stability when handling tethered packages, making it useful for drone-based delivery systems. This innovation enhances efficiency in automated payload handling and retrieval for logistics applications. The team will use this patent for consideration as a state-of-the-art design for a payload retrieval system when designing the final drone payload interchange system.

Standard:

<u>"FAA small, unmanned aircraft weight requirements for registration." [30]</u>

The standard presented by the FAA is as follows: (0.55 - 55 lbs) or (0.25 - 25 kg), which specifies the weight range for the FAA classification of a small, unmanned aircraft (a drone in the case of project DORIS). This FAA regulation/standard will dictate the max weight of the team's final drone design, as the objective is to not exceed this weight standard with the total system weight including a payload. With the project requirement of carrying a heavy payload that weighs a minimum of 30% of the drone's dry weight, means that this FAA regulation will also dictate the maximum weight that the team's final drone will be able to carry. The maximum possible drone dry weight, payload weight, and total system weight are calculated in section 3.3.4.

IEEE UAS Standards (IEEE 1937.1 and IEEE 1939.1) [31]

The IEEE 1937.1 standard serves as a foundational framework for UAS, emphasizing modularity, interoperability, and system integration. This standard is designed to ensure that drones can maintain reliable communication with operators, accommodate a variety of payloads, and integrate seamlessly with other systems in the operational ecosystem. It promotes scalability, allowing for easy customization or upgrades to the drone's payload systems, which is essential for a project that involves deploying diverse payloads, such as a camera, a weighted object, and a cruise missile. Moreover, IEEE 1939.1 focuses on the secure and efficient exchange of data, a crucial aspect for payloads that transmit real-time information, such as cameras or sensors. By addressing communication protocols and data security measures, this standard ensures that critical payload operations, such as the accurate deployment of a cruise missile, are executed reliably and safely. Applying these standards to the drone project will enhance its operational reliability and adaptability. The IEEE 1937.1 standard supports the modular design of the payload attachment system, enabling smooth transitions between different payloads without compromising stability or functionality. IEEE 1939.1 ensures that data from payloads like cameras is transmitted securely and efficiently, improving real-time decision-making capabilities. Overall, adherence to these standards benefits the project by ensuring robust design, secure operations, and adaptability for future enhancements.

ANSI UAS Standards (Unmanned Aircraft Systems Standardization Collaborative – UASSC) [32]

The ANSI UAS standards, developed under the Unmanned Aircraft Systems Standardization Collaborative (UASSC), provide essential guidelines for drone safety, airworthiness, and operational risk assessment. These standards emphasize maintaining structural integrity through robust design, implementing maintenance protocols to ensure long-term reliability, and managing noise levels to improve public acceptance. By incorporating hazard mitigation measures and risk assessment protocols, these standards enhance the safety and functionality of drones performing diverse tasks, such as payload deployment. Applying these standards to the utility drone project ensures compliance with industry best practices, minimizes risks during payload operations, and improves societal acceptance for non-military applications like emergency supply delivery.

Books/chapters:

Make: Getting Started with Drones – Chapter 12: Advanced Drone Programming and Control [33]

In this chapter, the author delves into advanced techniques for programming and controlling drones, emphasizing autonomous flight capabilities. The chapter covers essential programming frameworks, particularly Python, and details the integration of various sensors, such as GPS and cameras, to enhance navigational accuracy and environmental awareness. Through a series of practical projects and illustrative code examples, the author guides readers in implementing sophisticated flight algorithms and real-time data processing, highlighting the potential applications in engineering and robotics. This chapter serves as a valuable resource for engineers seeking to expand their understanding of drone technology and its programmable features, promoting innovation in unmanned aerial vehicle (UAV) design and application. The team will use this resource for the design of the drone when integrating the required camera payload.

Building Your Own Drones: A Beginner's Guide to Drones, UAVs, and ROVs - Chapter 12: Advanced Drone Design and Customization [34]

In this chapter, the author explores the intricacies of advanced drone design, focusing on customization for specific applications and performance enhancements. The chapter provides detailed guidance on selecting components, optimizing flight dynamics, and implementing modifications to improve stability, range, and payload capacity. It addresses common challenges encountered during the building process and offers troubleshooting strategies to resolve issues related to hardware and software integration. By emphasizing practical techniques and the importance of iterative design, this chapter serves as a crucial resource for engineers and hobbyists aiming to innovate in drone technology and improve their UAVs' operational effectiveness. The team will use this resource for consideration when designing the payload system and integrating the payload into the design while considering of these will affect the flight dynamics such as stability and range.

4.2.3 Connor Davidson

Websites:

"Aircraft Inquiry" - FAA.gov [35]

The FAA.gov website is useful for our project because it is the place where we can register our drone at. This is important because it is stated in the customer requirements as well as to be able to fly the drone.

"5 Best Heavy Lift Drones [Updated 2020] Large Drones High Lift Capacity" [36]

This website discusses 5 of the best heavy lift capacity drones as of 2020. This website is useful for our project because it gave us good baselines for our drone by giving us similar drones to our project requirements.

Journal Papers:

"The Current Opportunities and Challenges in Drone Technology" [37]

This paper discusses the current opportunities and challenges in drone technology today. It goes into detail on how drones can be used in a variety of different areas like agricultural, medical, and military. The paper also examines some of the risks that drones can have. This paper is useful for our project because it outlines the consequences of making a drone recklessly and helps remind us that we are not building a toy, we are building something that can hurt people if we are reckless.

"Emerging technologies and the use case: A multi-year study of drone adoption" [38]

This journal evaluates drone technology over a 5-year study on economic and strategic factors, operational and supply chain factors, and organizational and behavioral factors. This paper is useful for our project because it evaluates how our drone and payload systems can be adapted to other fields like for supply chains.

"A payload based detail study on design and simulation of hexacopter drone" [39]

This journal is an in-depth analysis of a payload based hexacopter drone. The journal provides calculations like trust per motor, power, performance, torque on the propellers, pitch of the propellers, and total trust. It also shows CAD drawings of the drone, performance graphs, and deformations after loads. This journal will be very useful for our project because it contains the groundwork for a good number of calculations, drawings, and simulations that we will need in our own project.

Standards:

"IEEE Approved Draft Standard for Drone Applications Framework" [40]

This journal explains the IEEE approved draft standards for drone application. This will be very useful for our team because it outlines all the steps we need to fill out to be able to get our drone registered.

"Carbon Fiber | Density, Strength, Melting Point" [41]

This website describes and demonstrates the standards for carbon fiber. These included density, strength, and melting point. This helped our team with calculations in the arms and base of the drone because they are made from carbon fiber.

"Y14.6 - Screw Thread Representation" [42]

This source is the ASME standard for screw thread representation for the screws that the team will be using for our drone.

Books:

2024 - 2025 FAA Drone License Exam Guide [43]

This book is an exam guide for the FAA drone license exam. It explains every part of the exam and what we will need to know to fly our drone. This will be very useful for our team because we will need a license to be able to fly our drone and this book will help us get that license.

Remote Pilot - Small Unmanned Aircraft Systems Study Guide (Federal Aviation Administration): FAA-G-8082-22 [44]

This book is a guide for FAA regulations for small, unmanned aircraft systems. It explains in depth everything we need to know about getting our drone within FAA regulations. This is useful for our team because we need to register our drone with the FAA, and we cannot register it if we are not within regulations.

4.2.4 Jeremy Malmo

Websites:

https://oscarliang.com/motors/ (accessed Sep. 16, 2024). [45]

This guide provides an in-depth look at FPV drone motor selection, focusing on specifications like KV rating, motor size, and weight. It also offers recommendations for specific motor types based on different drone applications.

https://uav.jreyn.net/ Step 7: Electronics Section (accessed Sep. 17, 2024). [46]

This article outlines the steps involved in selecting proper motors for UAVs, discussing thrust requirements, efficiency, and motor configurations to optimize flight performance for different (heavy) payloads. Specifically it goes in depth into electronic speed controllers (ESCs), power distribution boards (PDBs), and flight controllers.

Journals:

Journal of Advanced Mechanical Design, Systems, and Manufacturing, vol. 12, no. 1. [47]

The journal discusses a 3D-printed device designed to evaluate the aerodynamic performance of rotary wings. The research contributes to understanding how 3D-printed components impact aerodynamic efficiency in drone applications.

D. BBVL, D. Pal Singh, S. Kumar Kuppa, and M. Jayanthi Rao, "Design optimization of drone BLDC motor for delivery service applications." [48]

This article focuses on brushless DC (BLDC) motors for drone applications in delivery services, using advanced materials and design techniques to enhance motor performance, power efficiency, and load capacity. This is a useful source to reference modern benchmarking for payload drones.

Books:

W. H. Yeadon and A. W. Yeadon, Handbook of Small Electric Motors. [49]

This comprehensive book provides technical knowledge about small electric motors, covering their design, operation, and applications in various fields, including drones and UAVs. This has all the basic equations that are needed to design a stable flying drone theoretically.

Source: New York: McGraw-Hill, 2001.

N. Barrera, S. Martin, and M. Stewart, Unmanned Aerial Vehicles. [50]

This book explores the design, engineering, and operational aspects of unmanned aerial vehicles, offering insights into their technological development and practical applications across different industries. This book is relatively new compared to other sources and has new insights into drone optimization.

Source: New York: Nova Science Publishers, Inc, 2021.

Standard:

"The Ultimate Guide to Heavy Lift Drone Motors," JOUAV. [51]

This guide provides information on selecting heavy-lift drone motors, emphasizing the importance of motor power, thrust-to-weight ratio, and efficiency for stable and controlled flight. It is aimed at building drones with higher payload capacities with drone examples and motor capabilities.

Source: https://www.jouav.com/blog/heavy-lift-dronemotors.html (accessed Sep. 17, 2024).

"Xing 4214 2-8s X class FPV Motor," - iFlight.com [52]

iFlight supplies the make and specifications of the 4214 Xing motors we have selected to use. This motor is specifically designed for X-Class Racing, offering exceptional performance and durability. Constructed with oxidation-colored 7075 T6 milled aluminum for the bell and base, and 420 stainless steel components, it features a Japanese Kawasaki 1200 iron core for robust operation. The motor utilizes solid Pacific 220°C heat-resistant copper wire and winding, along with long-life Japanese EZO bearings for reliability. N45SH high-temperature tegular magnets and an electromagnetically matched stator and magnets ensure efficiency, with a small air gap for optimal performance. Its heat dissipation structure reduces heat by 20%, supporting sustained high performance. The motor delivers up to 7.9 kg of thrust at

660 kV, with peak efficiency between 50% and 90% thrust. A single-piece 6mm shaft prevents bell warping during impacts, and a hex bolt shaft set screw simplifies maintenance. The motor is dynamically balanced and features protected wiring for enhanced durability.

"IEEE Guide for Test Procedures for Synchronous Machines Including Acceptance and Performance Testing and Parameter Determination for Dynamic Analysis," -ANSI.org [53]

IEEE 115, *Standard Test Procedures for Synchronous Machines*, provides a comprehensive framework for evaluating the performance of electric motors, including brushless designs commonly used in UAVs. The standard outlines methods for testing efficiency, power output, and thermal performance, ensuring consistent and reliable motor performance metrics. This is especially relevant for drone motors, where precision in thrust and efficiency is critical. Leveraging IEEE 115 ensures adherence to industry-recognized practices for motor validation and optimization, making it a cornerstone reference for UAV motor design and testing.

"ISO 1940-1 Mechanical vibration — Balance quality requirements for rotors in a constant (rigid) state," – dcma.mil [54]

This standard provides guidelines for assessing and correcting the balance of rotating components, such as the rotor and shaft in a drone motor. Proper balancing is critical to minimize vibration, reduce wear on bearings, and improve overall motor efficiency and lifespan. ISO 1940-1 specifies balance quality grades and acceptable residual unbalances, ensuring that drone motors operate smoothly even under high rotational speeds. Referencing this standard will help ensure the motor meets precision requirements for high-performance applications.

4.2.5 Michael Zielinski

Websites:

"ArduPilot Copter" – Ardupilot.org [55]

ArduPilot is an open-source flight control software with a large community of users that provides a simple and easy setup and maintenance of the drone flight control system. For our project, the team will either use ArduPilot or another open-source software called PX4, but it was determined that ArduPilot has better community support so the team will likely be using this software. This page on the ArduPilot site provides the portal to all the documentation on the setup and tuning of the version of ArduPilot that is tailored for multi-rotor applications.

uav.jeryn.net – Step 6: Battery Selection [56]

This website has no specific title or name for their drone project but is curated by two engineering graduates who set out to design a consumer budget-friendly DIY drone. The Battery Selection step includes educational information on the types of LiPo batteries and a detailed, data-driven comparison of a variety of cell counts and capacities to show how there are diminishing returns as you go higher in capacity, which also increases weight significantly. This will be helpful to the team by helping us in our own battery selection process.

Oscar Liang – oscarliang.com [57]

Oscar Liang is a DIY FPV (First Person View) drone enthusiast that has published his website to provide a comprehensive record on how to buy, build, and fly FPV drones. Although FPV is not the current focus of the DORIS project, the information pertaining to electronics is still relevant. As there are many pages within his blog related to electronics, I have only cited the home page of the website. The team will use the information from this website to assist in the assembly of the electronics system.

Journal Papers

"A Review on the State of the Art in Copter Drones and Flight Control Systems 2024" [58]

This paper reviews a wide selection of current drone designs from fixed wing to octocopter. It also provides detail on the variety of uses of drone technology from aerial surveillance to precision planting in agricultural settings. The team found this very useful in determining real-world applications of the DORIS project and how our system could be adapted to different mission settings.

"Development of Drone based Delivery System using Pixhawk Flight Controller" [59]

This paper presents the application of a delivery drone utilizing a flight controller of the same brand that DORIS currently uses. It provides a simple outline of the capabilities of the Pixhawk series of flight controllers and the viability of their use in delivery applications. The team found this useful to confirm that the Pixhawk controller is a viable option for use in what is essentially payload delivery – the same mission set we are designing for.

"Payload Manipulation for Seed Sowing Unmanned Aerial Vehicle through interface with Pixhawk Flight Controller" [60]

This article provides the same confirmation as the previous reference that the Pixhawk flight controller is a viable option for payload delivery missions. In addition to this general confirmation, the article provides key information regarding the integration of a peripheral system (in the article's case, a seed sower) into the flight control system and operating environment. The drone used in the study was operated semi-autonomously, but the team would not like to rule out autonomous flight from our own design and will keep the lessons learned in the article in mind after the initial project goals have been achieved. Autonomous flight would be an addition to the project and is not a concern during the initial design phases.

Books

"Building Your Own Drones: A Beginner's Guide to Drones, UAVs, and ROVs" – Chapter 8: Building a Quadcopter III: Flight Control [61]

This book, although a little older (published in 2015), provides a detailed description of ESCs, receivers, and (now dated) flight controllers. The information useful to this project is the description of how programmable ESCs are programmed and what they can be programmed to do. The DORIS drone will have four ESCs in its current design, all of which will likely need to be programmed to store settings such as throttle range on the receiver and others.

"Make: Getting Started with Drones: Build and Customize Your Own Quadcopter" – Chapter 4: Flight Controller [62]

As textbook literature on drone construction is somewhat sparse, this book is also published in 2015. Despite its age, it provides information specific to the ArduPilot program and its Mission Planner software. It is also a good source of information regarding what each pinout on the flight controller is and what it is used for (i.e. I2C, CANBUS, JP1, etc.). The team will use this, in addition to the documentation specific to our flight controller, to assist in wiring up our flight controller correctly.

Standards

ASTM F3005-22 Standard Specification for Batteries for Use in Small Unmanned Aircraft Systems (sUAS) [63]

This American Society for Testing and Materials standard tells the team the requirements set for the construction and maintenance of batteries used in drones. It also helps the team understand the common terminology found in the world of LiPo batteries (i.e. 6S for 6 cells), which is very beneficial in our battery selection. Throughout the project, the team will strive to meet this standard regarding the charging and general maintenance of our LiPo batteries.

FCC 22-101A1 Spectrum Rules and Policies for the Operation of Unmanned Aircraft Systems [64]

Although the DORIS project does not currently operate in the 5000MHz band, it is a distinct possibility that if this design becomes mass produced and used commercially that the radio communications may need to be within this range. The release of this band for UAS use is relatively new, as this preliminary policy was published in January of 2023. This policy will eventually guide the future development of the DORIS project and allow the users of this system to communicate with the drone over extended distances beyond visual line of sight.

4.3 Mathematical Modeling

4.3.1 Motor, Propeller, and Frame Arms Sub-Assembly – Jeremy Malmo

To manage motor selection, battery capacity, and drone flight time a MATLAB code was created called UAVtoolboxtest that utilizes selected parameters to simulate a drone at hover. (Appen. 6.1)

Overview of Code Functionality: Motor Selection and Battery Compatibility.
The code performs calculations to verify whether a quadcopter design meets its thrust-to-weight ratio requirement, ensuring the system can hover and perform well. It uses parameters like the drone's weight, motor thrust, and the desired thrust-to-weight ratio (3:1). Additionally, it checks the required throttle for hovering and whether the total available thrust is sufficient for stable flight. It also estimates the flight time at different throttle percentages (50%, 75%, 100%) and the required throttle to sustain flight.
1. Physical Constants:
   - The code defines gravitational acceleration as 9.81 m/s^2, which is needed to convert between weight in kilograms and force in Newtons.
2. Quadcopter Parameters:
   - Thrust per Motor: $motor_{thrust_{per_{motor}}} = 7.9kg * 1000$ (grams), which is the maximum thrust a single

motor can provide (iFlight XING X4214 660KV).
   - Number of Motors: num_motors $= 4$, for a standard quadcopter configuration.
3. Weight Estimation:
   - Payload Weight: `payload_weight = 4.5kg * 1000` (grams), converting the payload weight from kilograms to grams.
   - Drone Frame Weight: drone_frame_weight $= 6kg * 1000$ (grams), converting the estimated frame weight from kilograms to grams.
   - Total Weight: The total system weight is calculated as the sum of the payload and frame:
      This is then converted to kilograms.
4. Thrust-to-Weight Ratio:
   - Available Thrust: The total available thrust from all four motors is calculated by multiplying the thrust per motor by the number of motors:
   - Thrust-to-Weight Ratio: The thrust-to-weight ratio is then calculated as the amount of total thrust divided by the total system weight. The code checks if this ratio meets the design requirement of 3:1.
5. Hover Check:
   - Thrust Needed for Hovering: To hover, the total thrust must equal the total weight of the system:
   - Hover Throttle: The throttle percentage required to maintain a hover is calculated.
   The code prints out whether the available thrust is sufficient for hovering and displays the hover throttle in percentage.

7. Battery Selection and Flight Time Calculations:
- Battery Capacity: The code uses a predefined battery capacity (in mAh) and a voltage rating (6S, 22.2V). The total energy stored in the battery is calculated based on this capacity and voltage, typically expressed in watt-hours (Wh).

- Power Consumption: The power consumption of the motors is based on the current draw at different throttle percentages (e.g., 50%, 75%, and 100% throttle). Power is calculated using the formula:

$$P = V * I \tag{1}$$

where P is power, V is voltage, and I is current. The code estimates the current required for different throttle levels and calculates the total power consumption of the motors.

-Flight Time Estimation: Using the battery's total energy and the motor's power consumption, the flight time is estimated for different throttle percentages. This is done using the formula:

$$Flight_{Time} = \frac{battery\_capacity\ (Wh)}{Power_{consumption}(W)} \tag{2}$$

The code prints the estimated flight times at 50%, 75%, and 100% throttle. These estimates help determine how long the drone can stay airborne under different flying conditions, balancing efficiency and performance.

```
>> UAVtoolboxtest
Total available thrust (31600.00 g) is enough for hovering.
Throttle required to hover: 33.23%
Total Weight: 103.01 N (10.50 kg)
Available Thrust: 31600.00 g (31.60 kg)
Thrust-to-Weight Ratio: 3.01
Design meets the thrust-to-weight requirement.
Estimated flight time at 100% throttle: 2.65 minutes
Estimated flight time at 75% throttle: 4.41 minutes
Estimated flight time at 50% throttle: 9.56 minutes
Adjusted estimated flight time at hover: 14.39 minutes
```

Figure 4.4: Output of the motor selection code.

4.3.2 Flight Controller, Power, & Sensor Sub-Assembly – Michael Zielinski

One of the first things the team needed to figure out was how much battery capacity is needed to both complete the flying course and the minimum endurance time limit for flight. Equation 3 is the power formula for determining the number of watts P based on the voltage V and current (in amps) I output of a battery. From that equation, you can then use Equation 4 to find the energy consumption over time in watt-hours Wh by multiplying P by the time T in hours. The battery capacity in amp-hours (Ah) C can then be found from Equation 5.

$$P = V \cdot I \tag{3}$$

$$E = P \cdot T \tag{4}$$

$$C = \frac{E}{V} \tag{5}$$

We assumed a 700-watt max draw per motor for 15 minutes of flight from a 22.2-volt battery to match the motors we selected, which led to the apparent need of at least 31.53 Ah of battery capacity. The team purchased a 22 Ah battery to begin with, and further practical testing may lead to the decision to purchase another and run them in parallel. These calculations also assumed that there is no step down in voltage using Battery Eliminator Circuits since our selected motors take 22.2 volts directly.

Additionally, the team needed to investigate more into the flight controller that we received from the previous capstone drone team: a Pixhawk 6C. Figure 2.5 shows the graphic from the HolyBro website (where Pixhawk 6C's are sold) demonstrating the overall capability in the number of connections from the flight controller. Appendix C contains a bulleted list of the technical specifications of the flight controller from the HolyBro website.
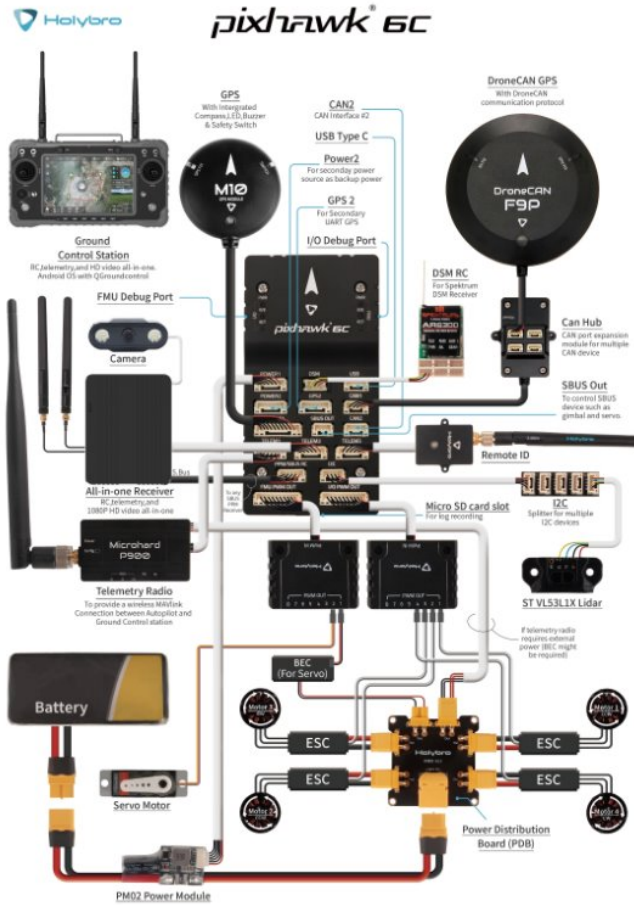
Figure 4.5: HolyBro Pixhawk 6C ecosystem chart [65].

Based on the sensors included (accelerometer, gyroscope, inertial measurement units, magnetometer, and barometer) as well as the number of interfaces (16 Pulse Width Modulated [PWM] outputs, 3 serial ports, 3 telemetry ports, 2 GPS ports, and S.BUS output), the team determined that we can continue to use the Pixhawk 6C as our primary flight controller and avoid having to purchase a new one.

4.3.3 Frame & Body Sub-Assembly – Connor Davidson
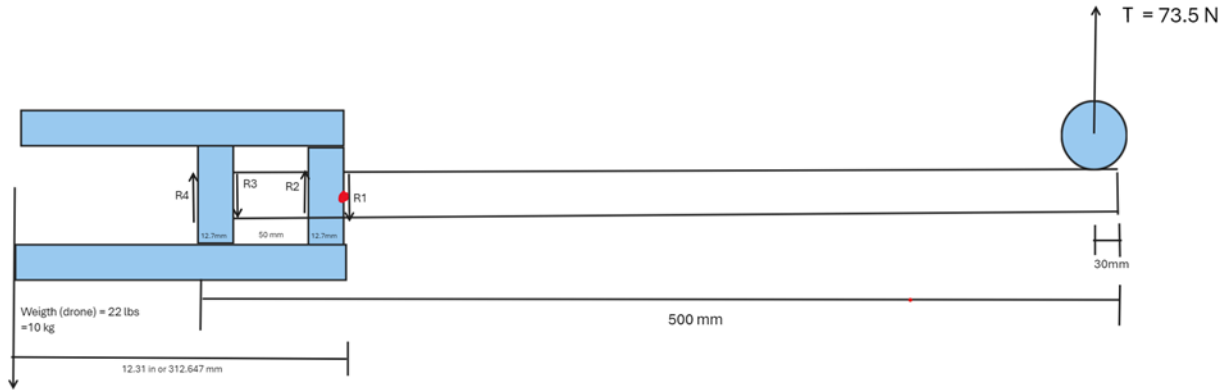
Figure 4.5: Free body diagram of arms

Assuming the total weight of the drone is 22 lbs or 10 kg, the total maximum thrust from the motor and propeller on one arm is 73.5 N to reach a 3:1 thrust to weight ratio, and the mounts are 12.7 mm thick and spaced 50 mm apart, we can use our force and moment equations to find the resulting stresses on the arms at the contact points. We are also assuming that the distance between the center of mass and the seconds support is 12.31 inches or 312.674 mm. The red dot is the focal point of the calculations.

Solving for the weight force we use the equation

$$\text{Weight (N)} = ma = mg = 10(\text{kg}) * 9.81\ (\text{m/s}^2) = 98.1\ \text{N} \qquad (6)$$

Because we are looking at only a fourth of the drone, we will use that the weight is equal to 24.525 N

For static equilibrium the sum of the forces in the y direction must be equal to zero because of newtons laws of motions so,

$$\Sigma F_y = 0 = T - W - R_1 + R_2 - R_3 + R_4 = 73.5 - 24.525 - R_1 + R_2 - R_3 + R_4 \qquad (7)$$

This means that,

$$R_1 - R_2 + R_3 - R_4 = 48.975\ \text{N} \qquad (7\ \text{simplified})$$

Because R_1 and R_3 should be the same and R_2 and R_4 should the same, this equation simplifies to,

$$2R_{13} - 2R_{24} = 48.975\ \text{N} => R_{13} - R_{24} = 24.4875\ \text{N} \qquad (8)$$

Next, we can move to moment calculations. As with the force calculations, the sum of the moments must add to zero as well. So,

$$\Sigma M = 0 = T(.3946\text{m}) + W(.312647\text{m}) - R_4(.0754\text{m}) + R_3(.0627\text{m}) - R_2(.0127\text{m}) \qquad (9)$$

This simplifies to,

$$29\ (\text{N*m}) + 7.668(\text{N*m}) - 0.0881R_{24} + 0.0627R_{13} = 0 \qquad (10)$$

$$0.0881R_{24} - 0.0627R_{13} = 36.668 \text{ N*m} \quad (11)$$

Using equations 8 and 11 we can now solve for the reaction forces. Rearranging equation 8, we know,

$$R_{13} = R_{24} + 24.4875 \text{ N} \quad (8)$$

So, we can plug this into equation 2.3,

$$0.0881R_{24} - 0.0627(R_{24} + 24.4875) = 36.668 \quad (11)$$

Solving for R_{24} we get $R_{24} = 1504.07$ N, which means that $R_{13} = 1528.56$ N

This leads to the question; can the arms survive this force? The area that touches the arms is 254 mm^2 so the pressure that the arms feel is,

$$\text{Pressure} = F/A = 1528.56 \text{ N} / 0.000254 \text{ m}^2 = 6,017,952.76 \text{ Pa} = 6.017 \text{ MPa} \quad (12)$$

This means the carbon fiber arms will be ok, because the yield strength of 2,500 MPa

Using this knowledge we can calculate the factor of safety,

$$\text{FOS} = \text{fail/allowable} = 2,500\text{MPa}/6.017\text{MPa} = 415.5 \quad (13)$$

The last force that we want to know is the maximum drag force on the arm. To find this we need can use the drag equation [4],

$$D = (C_D * \rho * V^2 * A)/2 \quad (14)$$

Assuming $\rho = 1.337$ kg/m^3, $C_D = 1$, A = .01 m^2, V = .5 m/s,

$$D = (1 * 1.337 \text{ kg/m}^3 * (.5 \text{ m/s})^2 * .01 \text{ m}^2)/2 = .00167 \text{ N} \quad (15)$$

With this number being so small, the drag due to the arms themselves are pretty much negligible compared to the entire drone.

Assuming the inner radius of the carbon fiber tube (d_i) is 0.02m and the outer radius (d_o) is 0.022m:

$$E = 250\text{GPa} - 350\text{GPa} \quad (16)$$

From the engineering toolbox we can solve for the moment of inertia for a hollow rod.

$$I = \frac{\pi}{4}\left(d_o^4 - d_i^4\right) = \frac{\pi}{4}\left[(0.022m)^4 - (0.02m)^4\right] = 5.832 \cdot 10^{-8} \ m^4 \quad (17)$$

Using this, we can solve for the maximum defection.

$$\Delta_{max} = \frac{PL^3}{3EI} = \frac{100\text{N}\cdot(0.5\text{m})^3}{3\cdot(300\cdot10^9\text{Pa})\cdot(5.832\cdot10^{-8}\text{m}^4)} = 0.2381\text{mm} \approx 0.01\text{in} \quad (18)$$

The equations above calculate the maximum defection that the arms will deflect when the motors are maxed using the moment of inertia equation for a circular hollow pipe. This is important to know because if the arms bend too much, it could cause devastating problems for the drone.

4.3.4 Payload Attachment & Carrier Design Sub-Assembly – Dylan Boeholt & Andre Bonillas

The team needs to understand the limits on the payload weight, the dry drone weight, and the total weight of the drone system. Then from the predicted weight of the drone, the theoretical thrust to weight ratio can be calculated.

For Maximum weight calculations based off of FAA regulations:
$$W_D + W_P = W_S => W_D + 0.3W_D = 25kg => W_D = 19.2 \ kg \ and \ W_P = 5.8 \ kg \quad (19)$$

Where W_D is the dry weight of the drone, W_P is the weight of the payload, and W_S is the total weight of the drone system, the 0.3 in the equation denotes that the payload will be 30 percent of the drone's dry weight without the payload attached. 25 kilograms denotes that maximum weight measurement for a small, unmanned aircraft from the FAA regulations.

For desired weight calculations based on customer requirements:
$$W_P = 5 \ lbs; W_D = \frac{W_P}{0.3} = 16.7 \ lbs; \ 16.7lbs + 5lbs = 21.7 \ lbs = W_S \quad (20)$$

The desired weight of the drone unloaded will be 16.7 pounds, which means the total loaded weight will be 21.7 pounds.

For the force of the payload acting on the connection apparatus:
$$F = m * g, \ 5lbs = 2.268 \ kg = m; g = 9.81\frac{m}{s^2}; F = 22.25 \ N \quad (21)$$

For thrust calculation:
$$Thrust \ to \ Weight \ ratio = 3:1; T = W_S * ratio = 21.7lbf * 3 = 65.1 \ lbf \quad (22)$$

Where W_S is the total system weight derived earlier in pound-force, 21.7 lbf, ratio equals the desired thrust to weight ratio, 3:1, and the variable, T, is the theoretical thrust force requirement for the drone based off the desired ratio and desired drone weight, which was found to be 65.1 lbf.

5 Design Concepts

5.1 Functional Decomposition

Figure 5.1: Black Box Model outlining inputs and outputs of Drone System
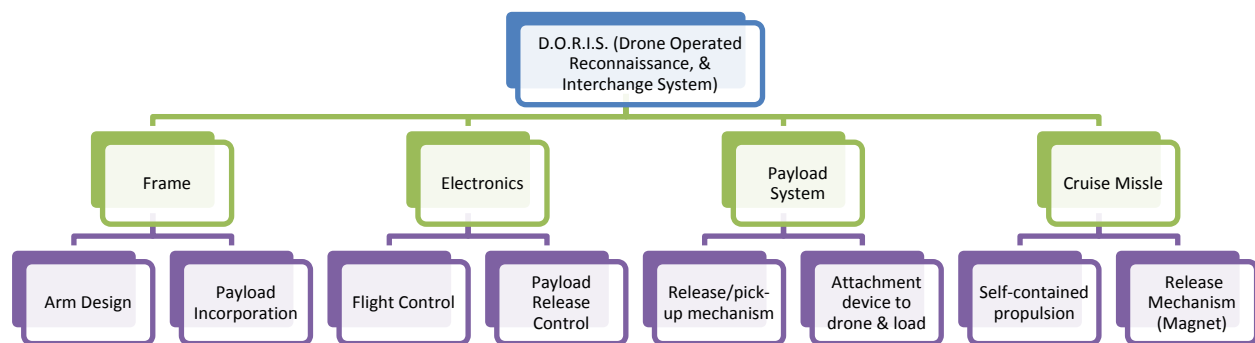
Figure 5.2: DORIS Functional Decomposition Chart

Above, Figure 3.1, shows D.O.R.I.S. (Dynamic, Overhead, Reconnaissance, & Interchange System) functional decomposition chart, outlining the functions required for the project's success. The chart divides the system into four primary areas: Frame, Electronics, Payload System, and Cruise Missile. The Frame section focuses on structural design, addressing components like Arm Design and Payload Incorporation, both essential for maintaining the drone's stability and integrating the payload system. The Electronics section covers control and operational functions, such as Flight Control and Payload Release Control, ensuring the systems can operate and be effective at payload delivery. In the Payload System section, the emphasis is on mechanisms like the Release/Pick-up Mechanism and the Attachment Device, which play a key role in secure payload handling. Lastly, the Cruise Missile section involves propulsion and release mechanisms, ensuring that the drone can perform missions involving self-propelled payloads.

5.2 Concept Generation

Frame (Main Body)
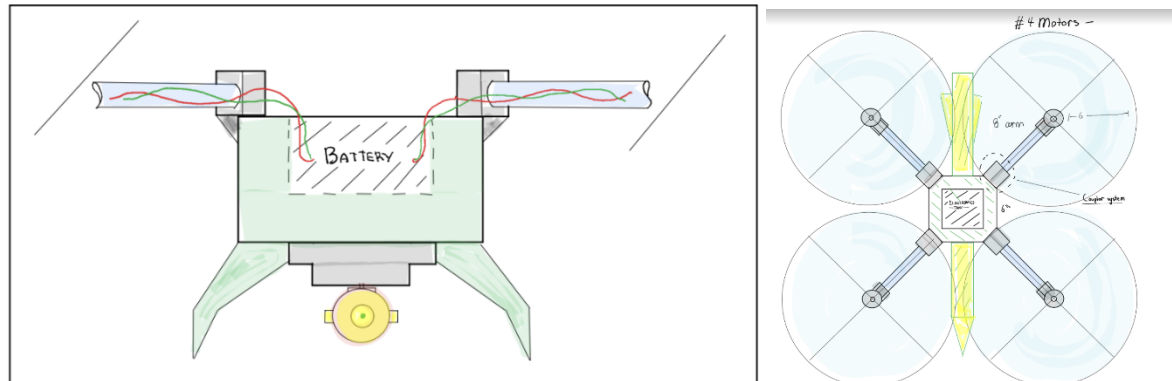
Figure 5.3: Design 3

Design 3: This design encompasses a square body design that has attachment points for arms protruding at 45 degrees from the frame creating a symmetric pattern. Legs will be positioned so the drone can land and take off with payload 1 (MC-01F30). The frame itself will be an 8 inch by 8 inch plate to start and will be optimized for weight reduction depending on the positioning of the 22000 mAh battery. The next iteration to be tested will involve a "sandwich" style frame to create the least amount of wasted space.

Payload Attach/Detach System
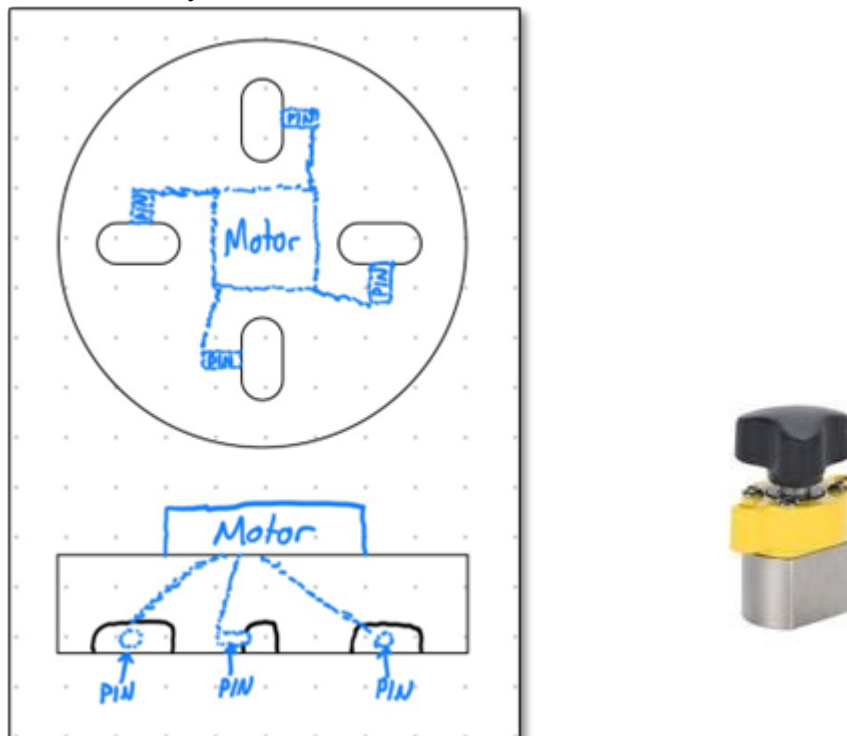
Figure 5.4: Design 5 and a Magswitch MAGJIG 60.

Design 5: This design uses magnets that are aligned with using servo motors to activate and deactivate the release. The payload for this design is required to have a metal plate for the magnet to attach too. This design was chosen for its simplicity and assured release with minimal contact. The magnet chosen can support up to 60 lb which will be enough to support a 20 lb payload with a safety factor of 3. (Thrust Ratio 3:1 → 20lb x 3 = 60lb). For prototyping one magnet will be used for proof of concept and initial cost reduction. Pictured above is the Magswitch MAGJIG 60.

Arm Design
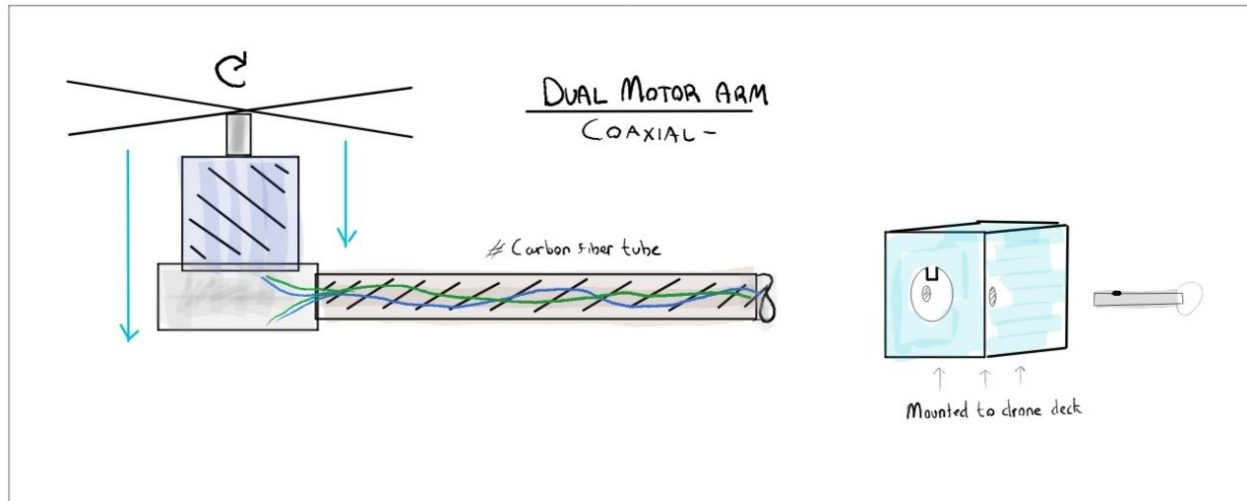
Figure 5.5: Arm Design 3

Design 3: The arm design selected uses carbon fiber tubes (20mm in diameter and 500mm in length with a 6mm wall thickness) and is attached to the main (middle) frame using 3D printed connections. The purpose of this design is to allow the carbon fiber tubes to be replaced easily if they receive damage that compromises their strength. This also allows all electronics to be run inside the tubes to protect them from the elements. Displayed is a "pin" style attachment system to ensure the motors face perpendicular to the drone frame.

5.3 Selection Criteria

Motor Selection

The motors required for the quadcopter will need to have a thrust to weight ratio of 3:1 to meet the projects requirements. The projected total system weight is 23.15 lb or 10.5 kg, with 4.5kg being the payload and 6 kg being the drone weight (43% of system). For these specifications the drone motors must have individual max thrust capacities of 7.9 kg or a combine's system of 31.6 kg.

Battery Selection

The battery choice for the quadcopter is critical in determining the flight time and ensuring the motors receive adequate power. The battery must provide enough voltage and capacity to sustain the current draw from the motors while balancing the overall weight of the system. Given the power requirements of the selected motors (T-Motor F1000, iFlight XING X4214 660KV, and SunnySky X4120 650KV), the battery should be able to provide a continuous discharge rate that matches or exceeds the combined current draw of the motors under load. Additionally, flight time will depend on the battery's capacity (measured in mAh) and the drone's total power consumption. Lithium polymer (LiPo) batteries will be used due to their high energy density and power output. So now we must consider different LiPo batteries of varying voltages and amp-hours for use in our drone.

Propeller Selection

Propeller selection is another crucial factor in optimizing the performance of the drone. To achieve the required 7.9 kg of thrust per motor while maintaining efficiency, the propeller must be well-matched to the motor's KV rating and power output. For the selected motors (T-Motor F1000, iFlight XING X4214 660KV, and SunnySky X4120 650KV), the propeller size will likely need to be between 15 and 18 inches in diameter, depending on the specific motor characteristics and thrust curves. For the Iflight selected motor, the recommended propeller for 7.9kg is 16 inches diameter. For the propeller selection, we compared three options: the T-Motor P17x5.8, Gemfan 16x5.4, and HQProp 16x8x3. The HQProp 16x8x3 was chosen due to its ideal diameter and pitch configuration for maximizing thrust (7.2 -8.1 kg) at the target RPM range (3000-5000), crucial for our payload capacity. Additionally, it was made from a durable glass fiber-reinforced nylon, which balances strength and weight, at 66.5 grams per prop. Though the T-Motor prop offered slightly higher thrust.

Arm Material Selection

The material used for the drone arms is critical for maintaining structural integrity while minimizing weight. The selected material needs to have a high strength-to-weight ratio and stiffness. This material needs to provide the necessary rigidity to support the motor mounts while withstanding the stresses from motor vibrations, propeller torque, and potential impacts during flight.

ESC Selection

The electronic speed controllers (ESCs) selected for the drone must be capable of handling the power requirements of the motors. For this project, each ESC will need a capacity of 120 amps to handle the current draw from the high-powered motors safely. The ESCs will ensure smooth power delivery and control, with features like active braking and motor timing adjustments to optimize performance. The ESCs must also be compatible with the desired battery configuration and ensure efficient heat dissipation to prevent overheating during heavy use, especially when lifting payloads and maintaining stable flight under load.

Evaluation Matrices Criteria

The criteria that will be used to evaluate the team's designs were generated using the customer and engineering requirements. The team decided to evaluate each design using the following criteria: weight, cost, simplicity, aesthetics, durability, and repairability. Repairability was ranked the highest with a weight of 30%, and then weight and repairability where weighted at 20% each, durability was weighted at

15%, and aesthetics was ranked the lowest with a weight of 5%.

5.4 Concept Selection

Evaluation Matrices

Frame (Main Body)

Table 1: Decomposition Matrix for Center Frame Construction

	Weight	Cost	Simplicity	Aesthetics	Durability	Repairability	Total
Weights	0.2	0.3	0.1	0.05	0.15	0.2	1
Design 1	2	2	3	4	3	4	2.75
Design 2	4	3	2	4	2	2	2.8
Design 3	5	4	4	3	4	4	4.15
Design 4	4	4	3	2	3	3	3.45
Design 5	3	4	4	3	3	4	3.6

Table 1 shows the decomposition matrix for the center frame design of the drone. The evaluation criteria include weight, cost, simplicity, aesthetics, durability, and repairability. Design 3, which balances cost and simplicity with durability, was selected for further prototyping.

Payload Attach/Detach System

Table 2: Decomposition Matrix for Payload Attach/Detach System

	Weight	Cost	Simplicity	Aesthetics	Durability	Repairability	Total
Weights	0.05	0.15	0.2	0.1	0.2	0.3	1
Design 1	4	3	2	4	2	1	2.15
Design 2	4	2	1	5	3	3	2.6
Design 3	3	2	2	4	2	3	2.55
Design 4	2	2	1	3	2	2	1.9
Design 5	3	2	4	3	4	4	3.35

Table 2 presents the evaluation matrix for the payload attach/detach system. The criteria assessed include weight, cost, simplicity, aesthetics, durability, and repairability. Design 5 scored the highest, making it the preferred option for further development.

Arm Design

Table 3: Decomposition Matrix for Arm Design

	Weight	Cost	Simplicity	Aesthetics	Durability	Repairability	Total
Weights	0.05	0.25	0.15	0.05	0.3	0.3	1
Design 1	4	2	3	4	4	2	3.15
Design 2	4	3	3	4	2	4	3.4
Design 3	5	3	4	3	4	4	4.15
Design 4	4	3	2	3	2	2	2.6
Design 5	4	1	3	5	4	2	2.9

Table 3 evaluates different designs for the drone's arms based on weight, cost, simplicity, aesthetics, durability, and repairability. Design 3 is the chosen concept due to its high scores in durability and simplicity.

Propellers

Table 4: Decomposition Matrix for Propeller Design

	Weight	Cost	Simplicity	Aesthetics	Durability	Performance	Total
Weights	0.1	0.2	0.05	0.05	0.3	0.3	1
Tri-blade	3	4	3	3	3	3	3.2
toroidal	3	2	2	5	3	4	3.15
Var-pitch	2	2	2	4	2	4	2.7
2-blade	4	4	5	3	4	2	3.1

Table 4 compares propeller design concepts, assessing factors such as weight, cost, simplicity, aesthetics, durability, and performance. The tri-blade propeller design ranked highest, offering a balance between performance and durability.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	motormount_assembly		4
2	ESC_120A	ESCs	4
3	M3 x 0.5mm Thread 50mm LONG SOCKET HEAD CAP SCREW	Motor Mount Screws	16
4	Arm_legs_V3	Legs	4
5	MOtormount_plate	Motor Mount Plate	4
6	hex bolt_ai		4
7	payload_sub_assembly		1
8	Frame_Subassembly		1
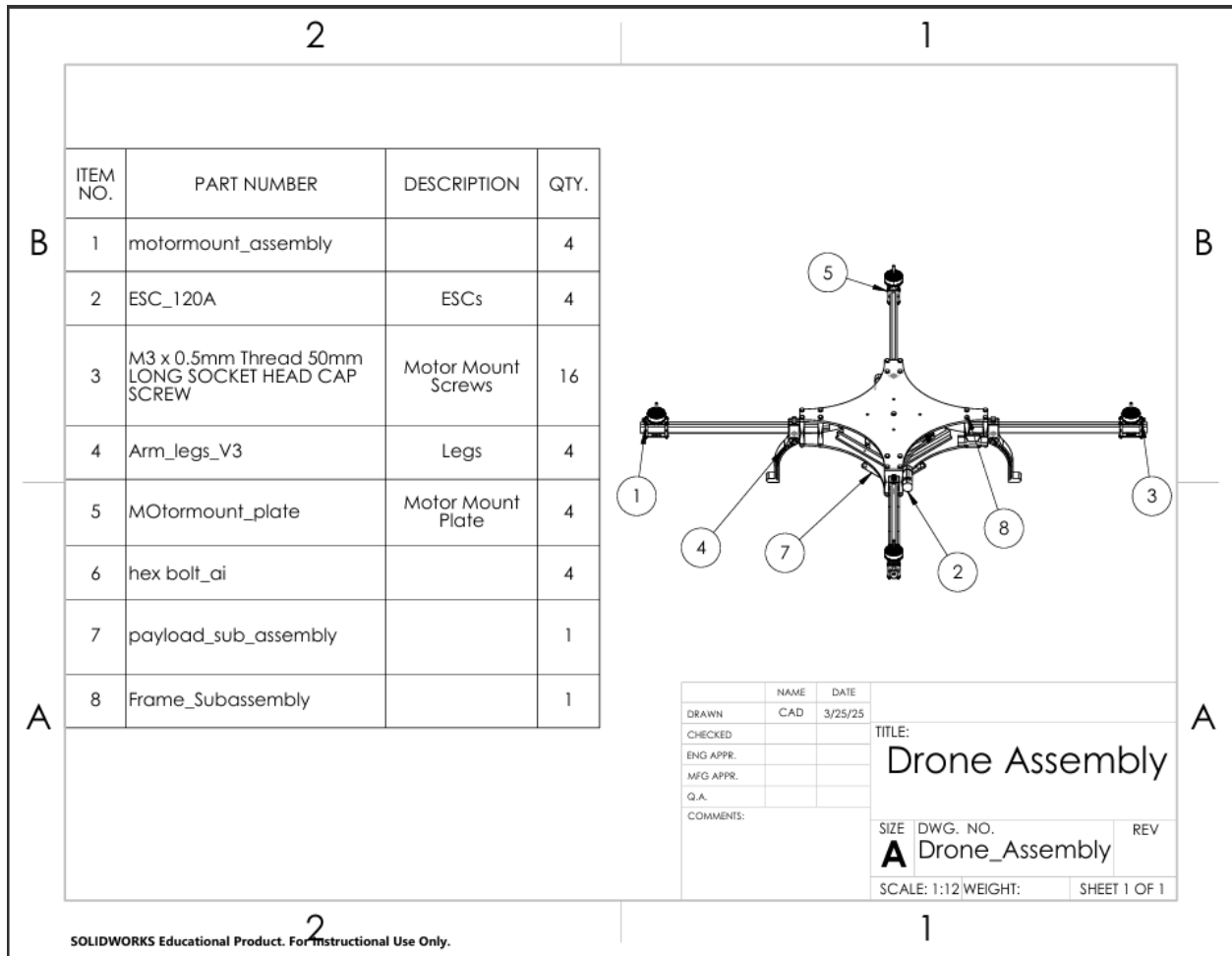
Figure 5.6: Final CAD

Our final CAD design for the DORIS quadcopter represents a foundational layout of the project's structural and functional components. The design prioritizes essential elements such as frame durability, stability, and payload integration, utilizing lightweight materials like carbon fiber to balance strength with efficiency. This design serves as a visual blueprint to guide future iterations and refinements as we begin prototyping our design and bringing it to life. It provides a flexible starting point for improvements and iterations, ensuring that all parts will eventually work together to meet the quadcopter's final goals.

6 Schedule and Budget

6.1 Schedule

6.1.1 First Semester

Boeing Drone V2 Gantt Chart (Semester 1)
(TEAM ASSIGNMENTS)
(INDIVIDUAL ASSIGNMENTS)
(NEEDS EDITING)

Tasks	DUE DATE	Hours Est	Hours Actual	Tasks Assigned To	Week 1	Week 2	Week 3	Week 4
HW00 - Academic Integrity Assignment	29-Aug	2	2	Team				
HW01 - Project Signup	30-Aug	0.5	0.5	Team				
Timecard Wk1	3-Sep	0.5	0.5	Team				
Staff Meeting #1 (Wk2)	4-Sep	2.5	2.5	Team				
Team Charter	6-Sep	2	3	Team				
HW02 - Solidworks Review	8-Sep	5	5	Team				
Timecard Wk2	9-Sep	0.25	0.25	Team				
Staff Meeting #2 (Wk3)	11-Sep	2.5	2.5	Team				
Timecard Wk3	16-Sep	0.25	0.25	Team				
Presentation 1	18-Sep	8	12	Team				
P1 (Overview and Background)	18-Sep	0.5	0.5	Jer, Dyl, Andre				
P1 (Lit Review)	18-Sep	2	3	Team				
P1 (Mathmatical Modeling)	18-Sep	1	2	Team				
P1 (Schedule/Gantt Chart)	18-Sep	2	3	Connor				
P1 (Budget)	18-Sep	2	2	Micheal				
P1 (Summary)	18-Sep	0.5	0.25	Andre				
Presentation 1 - feedback to other teams	18-Sep	0.5	2	Team				
Peer Eval 1	19-Sep	0.5	1	Team				
Timecard Wk4	23-Sep	0.25	0.25	Team				

Figure 6.1. Weeks 1 to 4 of the first semester Gantt Chart.

Tasks	DUE DATE	Hours Est	Hours Actual	Tasks Assigned To	Week 5	Week 6	Week 7	Week 8
Presentation 1 - feedback to other teams	18-Sep	0.5	2	Team				
Peer Eval 1	19-Sep	0.5	1	Team				
Timecard Wk4	23-Sep	0.25	0.25	Team				
Staff Meeting #3 (Wk5)	25-Sep	2.5	2.5	Team				
Timecard Wk5	30-Sep	0.25	0.25	Team				
Staff Meeting #4 (Wk6)	2-Oct	2.5	2.5	Team				
HW03	4-Oct	5	6	Team				
Timecard Wk6	7-Oct	0.25	0.25	Team				
Presentation 2	9-Oct	10		Team				
P2 (Overview and Background)	9-Oct	0.25	0.25	Connor				
P2 (Funcional Decomposition)	9-Oct	0.5	1	Dylan				
P2 (Concept Generation)	9-Oct	2	1.5	Team				
P2 (Engineering Calculations)	9-Oct	2	1	Team				
P2 (Concept Evaluations)	9-Oct	1	2	Team				
P2 (CAD Design)	9-Oct	2	2	Jer, Conn				
P2 (Scheduling)	9-Oct	1	1	Connor				
P2 (BOM)	9-Oct	1	1	Michael				
P2 (Budgeting)	9-Oct	0.5	0.5	Michael				
P2 (Conclusion)	9-Oct	0.25	0.25	Dylan				
Presentation 2 - feedback to other teams	9-Oct	3	3.5	Team				
Peer Eval 2	10-Oct	1	1	Team				
Timecard Wk7	14-Oct	0.25	0.25	Team				
Staff Meeting #5 (Wk8)	16-Oct	2.5	2.5	Team				
Report #1	18-Oct	8	10	Team				
Timecard Wk8	21-Oct	0.25	0.25	Team				

Figure 6.2. Weeks 5 to 8 of the first semester Gantt Chart.

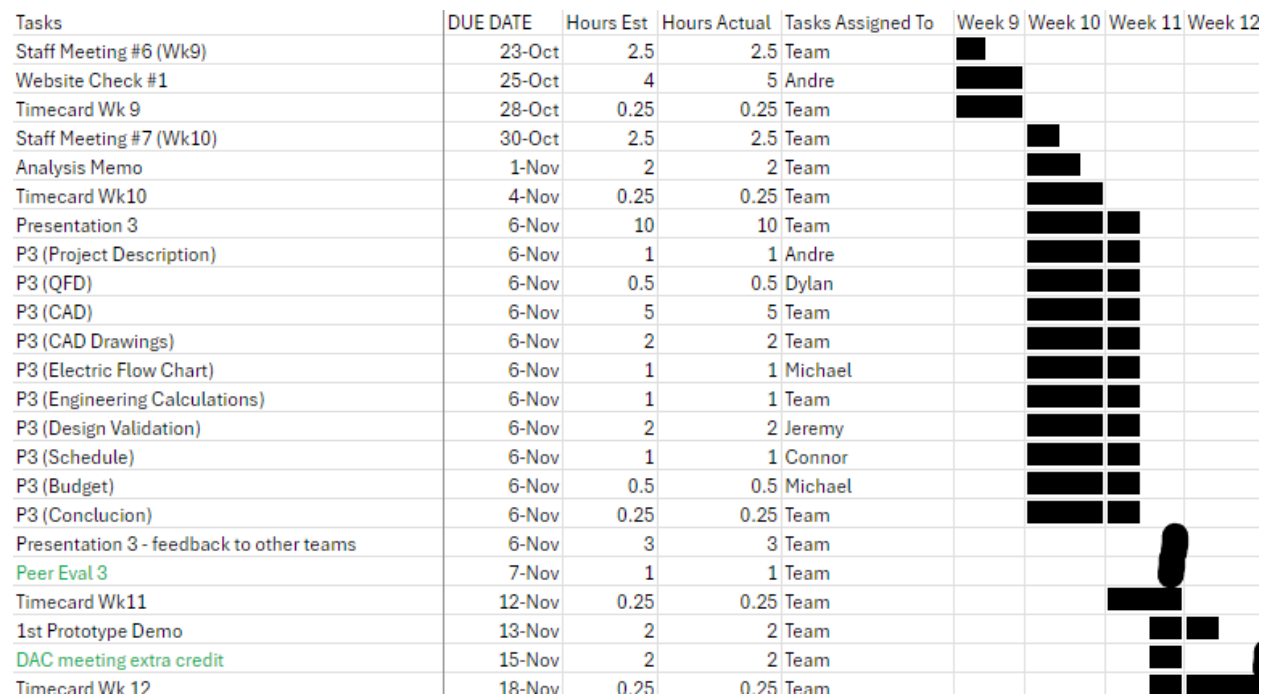| Tasks	DUE DATE	Hours Est	Hours Actual	Tasks Assigned To	Week 9	Week 10	Week 11	Week 12
Staff Meeting #6 (Wk9)	23-Oct	2.5	2.5	Team				
Website Check #1	25-Oct	4	5	Andre				
Timecard Wk 9	28-Oct	0.25	0.25	Team				
Staff Meeting #7 (Wk10)	30-Oct	2.5	2.5	Team				
Analysis Memo	1-Nov	2	2	Team				
Timecard Wk10	4-Nov	0.25	0.25	Team				
Presentation 3	6-Nov	10	10	Team				
P3 (Project Description)	6-Nov	1	1	Andre				
P3 (QFD)	6-Nov	0.5	0.5	Dylan				
P3 (CAD)	6-Nov	5	5	Team				
P3 (CAD Drawings)	6-Nov	2	2	Team				
P3 (Electric Flow Chart)	6-Nov	1	1	Michael				
P3 (Engineering Calculations)	6-Nov	1	1	Team				
P3 (Design Validation)	6-Nov	2	2	Jeremy				
P3 (Schedule)	6-Nov	1	1	Connor				
P3 (Budget)	6-Nov	0.5	0.5	Michael				
P3 (Conclucion)	6-Nov	0.25	0.25	Team				
Presentation 3 - feedback to other teams	6-Nov	3	3	Team				
Peer Eval 3	7-Nov	1	1	Team				
Timecard Wk11	12-Nov	0.25	0.25	Team				
1st Prototype Demo	13-Nov	2	2	Team				
DAC meeting extra credit	15-Nov	2	2	Team				
Timecard Wk 12	18-Nov	0.25	0.25	Team				

Figure 6.3. Weeks 9 to 12 of the first semester Gantt Chart.

Tasks	DUE DATE	Hours Est	Hours Actual	Tasks Assigned To	Week 13	Week 14	Week 15
Staff Meeting #9 (Wk13)	20-Nov	2.5	2.5	Team	■		
HW04 - Individual Analysis	22-Nov	5	7	Team	■		
Timecard Wk13	25-Nov	0.25	0.25	Team	■		
Report #2	27-Nov	5	6	Team	■ ■		
Staff Meeting #10 (Wk14)	27-Nov	2.5	2.5	Team		■	
Timecard Wk14	2-Dec	0.25	0.25	Team		■	
Final CAD and Final BOM	3-Dec	4		Team	■ ■	■	
[Insert Sub Tasks for Final CAD and Final BOM here]					■ ■	■	
2nd Prototype Demo	4-Dec	5		Team			
[Insert Sub Tasks for 2nd Prototype Demo here]							
2nd Proto Demo - feedback to other teams	4-Dec	3		Team			
E-fest Extra Credit	6-Dec	2		Team			
Project Management for 486C	6-Dec	3		Team			■
Website Check #2	7-Dec	4		Andre			■
(FINAL) Peer Eval 4	8-Dec	1		Team			■
Course Eval Extra Credit/Close	8-Dec	0.5		Team			■
Timecard Wk15	9-Dec	0.25		Team			■

Figure 6.4. Weeks 13 to 15 of the first semester Gantt Chart.

6.1.2 Second Semester

Boeing Drone V2 Gantt Chart (Semester 1)							
(TEAM ASSIGNMENTS)							
(INDIVIDUAL ASSIGNMENTS)							
(UGRADS)							
Tasks	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
486C Kickoff meetings	■						
Project Management	■						
Wk 2 Staff Meeting		■					
Engineering Model Summary		■					
Wk 3 Staff Meeting			■				
Self Learning / Individual Analysis	■	■	■				
Wk 4 Staff Meeting				■			
Hardware Status Update 33+% build					■		
Peer Eval 1					■		
Wk 6 Staff Meeting						■	
Wk 7 Staff Meeting							■
Website Check 1							■

Figure 6.5. Weeks 1 to 7 of the second semester Gantt Chart.

Tasks	Week 8	Spring Break	Week 9	Week 10	Week 11	Week 12
Hardware Status Update 67+% build	███					
UGRADS Registration	🟥					
Peer Eval 2	🟩					
Testing Plan	███	███	███			
Wk 9 Staff Meeting			███			
Wk 10 Staff Meeting				███		
Draft of Poster			🟥	🟥		
Final Testing Plan				███		
Hardware Status Update 100% build					███	
Peer Eval 3					🟩	
Final CAD Packet					███	
Initial Testing Results						███
Final Poster & PPT					🟥	🟥

Figure 6.6. Weeks 8 to 12 of the second semester Gantt Chart.

Tasks	Week 13	Week 14	Week 15
Product Demo & Final Testing Results	███		
Final Report & Website Check	███		
In class presentaion practice		███	
Symposium		███	
Peer Eval 4			🟩
Client Handoff			███

Figure 6.7. Weeks 13 to 15 of the second semester Gantt Chart.

6.2 Budget

Team:	DORIS	Total Budget:	$ 3,717.70	Total Donations:	$ 717.70
Team Number:	F24toSp25_13	Total Expense:	$ 3,599.29	Left in SCE:	$ 108.75
Speedchart:	2920381F25	Total Remaining:	$ 118.41	Left in donations:	$ 9.66
Sub-Debt:	CP19				

Date	Vendor	Item	Quantity	Cost	Status	Notes
9/10/2024	Amazon	PLA Filament	1	$ 15.26	Delivered	Jeremy Paid
9/17/2024	Staples	64GB EliteX CL10 microSD (2 pack)	1	$ 16.46	In-Store	Jeremy Paid
9/25/2024	Online	MC-01F30 Cruise Missile Design	1	$ 42.52	Downloaded	Michael Paid
	Amazon	Tattu 6S LiPo Battery 1050mAh	1	$ 29.25	Delivered	Connor Paid
9/26/2024	Aliexpress	50pcs M3 12mm hex heads	1	$ 1.87	Delivered	Michael Paid
		10pcs 150mm extension wires	3	$ 15.87	Delivered	
		1350pcs Set C Black screws	1	$ -	Delivered	Refunded (case damaged)
		3-axis Gyro	1	$ 14.26	Delivered	
		7000KV 30mm motor	1	$ 23.64	Delivered	
		2g motor servo	3	$ 20.54	Delivered	
10/1/2024	Venmo	Direct Donation	1	$ -	Used ($150)	In Dylan Venmo
	GoFundMe	Transfer	1	$ (9.66)	Not Used ($303.76)	In Michael Ravalli
10/2/2024	Amazon	Lightweight PLA	1	$ 36.02	Delivered	Jeremy Paid
10/3/2024	Amazon	Magswitch MagJig 60	1	$ 84.60	Delivered	Capstone PO#1
		Lipo Battery Charger	1	$ -	Delivered	
		2-4S 20A Brushless ESC	1	$ 25.10	Delivered	
	AliExpress	Iflight XING T4214	1	$ 251.74	Delivered	
		TATTU 22000mAh 22.2V	1	$ 238.48	Delivered	
10/7/2024	GoFundMe	Transfer	1	$ -	Used ($48.25)	In Michael Ravalli
10/17/2024	Amazon	Octagonal carbon fiber tubing	1	$ 108.09	Delivered	Capstone PO#2
		ApisQueen 120A ESC w/ BEC	4	$ 213.91	Delivered	
		SunLu TPU Filament Orange	1	$ 26.19	Delivered	
		XT90 Connectors (10pr)	1	$ 13.94	Delivered	
		12 Gauge wire kit	1	$ 27.08	Delivered	
10/22/2024	AliExpress	HotRC controller/receiver for missile	1	$ -	Delivered	Michael Paid, GoFundMe funds ($20.44)
11/4/2024	Target	Gorilla glue for missile	1	$ -	Delivered	Michael Paid, GoFundMe funds ($6.54)
11/13/2024	HQProp	16in propellers	4	$ 144.13	Delivered	Capstone PO#2
11/15/2024	Amazon	Pinecil Soldering Iron	1	$ -	Delivered	Michael Paid, GoFundMe funds ($43.66)

Date	Vendor	Item	Qty		Price	Status	Notes
12/2/2024	AliExpress	Iflight XING T4214	1	$	-	Delivered	Dylan paid, Direct Donation funds ($109.99)
12/3/2024	HomeCo	Sandpaper	1	$	-	In-Store	Michael Paid, GoFundMe funds ($6.21)
12/5/2024	NAPA	Snap Terminal Male	1	$	4.36	In-Store	Jeremy Paid - Filed for Reimbursement
		Snap Terminal Female	1	$	7.63	In-Store	Capstone PO#3
	Home Depot	1/4 2x4 MDF	1	$	16.10	In-Store	
		M6 Lock Nut	8	$	5.46	In-Store	
		M6 x 100mm	8	$	21.02	In-Store	
		Scotch Extreme Fasteners	1	$	13.03	In-Store	
	Amazon	Threaded Inserts	1	$	18.55	Delivered	
		ELEGOO UNO Project Super Starter Kit	1	$	49.11	Delivered	
12/5/2024	Amazon	Magswitch MagJig 60	1	$	88.95	Delivered	Capstone PO#4
		Polymaker LWPLA Gray	1	$	-	Delivered	
		SunLu TPU Filament Orange	1	$	-	Delivered	
	AliExpress	TATTU 22000mAh 22.2V	1	$	231.18	Delivered	
	Sky Drones	SmartAP PDB	1	$	105.04	Delivered	
	HolyBro	Pixhawk 6C Cable Set	1	$	35.34	Delivered	
1/15/2025	3DR	6 pin JST-GH to 6 pin Microblade	1	$	-	Delivered	Michael Paid (GoFundMe funds $8.76)
1/29/2025	Home Depot	Fiberglass resin	1	$	71.94	In-Store	Andre Paid - filed for reimbursement
		Flat brush	2	$	-	In-Store	
		Multi-purpose glove	1	$	-	In-Store	
		Fiberglass cloth	1	$	-	In-Store	
		Paint stirring stick	1	$	-	In-Store	
		Birch markerboard	1	$	-	In-Store	
		N95 masks 2pk	1	$	-	In-Store	
		80G sandpaper	1	$	-	In-Store	
2/14/2025	GoPro	Hero 4K	1	$	192.41	Delivered	
2/22/2025	HomCo	Sanding block	1	$	-	In-Store	Michael Paid (GoFundMe funds $22.17)
		Flat brush	2	$	-	In-Store	
		Command velcro strips	1	$	-	In-Store	
		4mm x 15mm hex screws	4	$	-	In-Store	
		4mm nuts	4	$	-	In-Store	
2/24/2025	Amazon	150A ESC	4	$	524.04	Delivered	
		MG995 servos 4pk	1	$	19.64	Delivered	
	Direct	FAA UAS Test	1	$	-	Delivered	Michael & Dylan Paid ($175 - $134.99 from M, 40.01 from D)

3/17/2025	Home Depot	Acetone	1	$	10.98	In-Store	PO#8 - Jeremy Reimbursement
		Fiberglass resin	1	$	59.98	In-Store	
		Birch panel	1	$	21.98	In-Store	
		Flat brush	2	$	3.74	In-Store	
		Fiberglass Cloth	3	$	24.84	In-Store	
		Tax	1	$	11.15	In-Store	
	Home Depot	Flat brush	2	$	-	In-Store	Michael Paid (GoFundMe funds $16.36)
		Tear-resistant gloves	1	$	-	In-Store	
		Bullet connectors (10AWG) 6pk	2	$	-	In-Store	
3/24/2025	Home Depot	Socket cap screw M6x100mm 4pk	5	$	-	In-Store	Michael Paid (GoFundMe funds $83.22)
		Socket cap screw M4x20mm 4pk	2	$	-	In-Store	
		Socket cap screw M4x60mm 3pk	2	$	-	In-Store	
		Socket cap screw M3x50mm 4pk	4	$	-	In-Store	
		Socket cap screw M3x10mm 3pk	1	$	-	In-Store	
		Socket cap screw 1/4x7 in	1	$	-	In-Store	
		M6 Nut 4pk	5	$	-	In-Store	
		M4 Nut 4pk	4	$	-	In-Store	
		M3 Nut 4pk	5	$	-	In-Store	
		1/4 Nut	1	$	-	In-Store	
		Male wire disconnects (12AWG) 10pk	2	$	-	In-Store	
		Female wire disconnects (12AWG) 10pk	2	$	-	In-Store	
3/25/2025	Amazon	PLA Filament (Black)	1	$	18.55	Delivered	PO#9
		ABS Filament (Black)	1	$	18.55	Delivered	
		7lb dumbell pair	1	$	18.95	Delivered	
	Bambu Labs	PLA Basic (Bambu Green)	1	$	19.64	Delivered	
		PETG HF (Black)	1	$	19.64	Delivered	
		PETG HF (Orange)	1	$	16.37	Delivered	
		Bambu Reuseable Spool	1	$	8.71	Delivered	
		PLA Basic (Red)	1	$	19.64	Delivered	
4/18/2025	eBay	iFlight XING 4214 motors	2	$	81.47	Shipped	PO#10 - Connor Reimbursement

Figure 6.8. Current Budget and Expenses.

Currently, the team sits with $118.41 remaining available funds. $9.66 of this comes from money currently held in team member private accounts from GoFundMe and other donations. The remaining $108.75 sits in the Sanghi College of Engineering capstone fund account for this project. The team anticipates no more expenses as of 18 April 2025.

6.3 Bill of Materials (BoM)

Figure 5.9 shows the current state of the bill of materials for one drone, plus the heavy payload and the camera payload. The cargo payload is not included as it is deemed that the builder will have their own payload they wish to move that will vary in cost and manufacturer.

Purchased Item	Primary Vendor	Manufacturer	Lead Time	Qty	Unit Cost	Total Cost	Part Status	Weight (g)
DRONE ONLY					**Total Cost:**	**$2,276.37**		**4677**
22Ah 6S LiPo Battery	Aliexpress	Tattu	2 weeks	2	$ 240.00	$ 480.00	Installed	2460
Flight Controller (Pixhawk 6C)	HolyBro	HolyBro	7-10 business days	1	$ 231.46	$ 231.46	Installed	34.6
10pcs 150mm DuPont extension wires	Aliexpress	Any	2 weeks	1	$ 5.29	$ 5.29	Installed	
Pixhawk Wiring Kit	HolyBro	HolyBro	7-10 business days	1	$ 35.00	$ 35.00	Installed	
6-pin Molex PicoBlade to 6-pin JST-GH wire	3DR	3DR	7-10 business days	1	$ 8.76	$ 8.76	Installed	
XING 4214 660KV Motor	iFlight	iFlight	2 weeks	4	$ 62.75	$ 251.00	Installed	1080.4
6-channel RC receiver	Any	Any	7-10 business days	1	$ 35.00	$ 35.00	Installed	
Power Distribution Module (Sky-Drones SmartAP PDB)	Sky-Drones	Sky-Drones	7-10 business days	1	$ 90.00	$ 90.00	Installed	40
Electronic Speed Controller (150A)	Amazon	Flycolor	7-10 business days	4	$ 119.00	$ 476.00	Installed	572
RC Controller (must be compatible w/ receiver)	Any	Any	7-10 business days	1	$ 50.00	$ 50.00	Installed	
Wiring kit (12AWG, 60ft)	Amazon	NAOEVO	3 business days	1	$ 25.00	$ 25.00	In use	50
LiPo Battery Charging Kit	Amazon	SmartCharger	3 business days	1	$ 52.00	$ 52.00	In use	
4pk)	Amazon	ZSJ	2 weeks	2	$ 25.00	$ 50.00	Installed	40
3D Printing Filament (ABS)	Amazon	Any	3 business days	2	$ 20.00	$ 40.00	In use	
3D Printing Filament (PLA)	Amazon	Any	3 business days	1	$ 24.00	$ 24.00	In use	
3D Printing Filament (TPU 95A)	Amazon	Any	3 business days	1	$ 26.19	$ 26.19	In use	400
XT90 Connectors (10pk)	Amazon	Amass	3 business days	1	$ 14.17	$ 14.17	Installed	
Propellers (16", tri-blade)	HQProp	HQProp	7-10 business days	4	$ 35.68	$ 142.72	Installed	
Extreme Fasteners	Home Depot	Scotch	0 days	2	$ 13.03	$ 26.06	Installed	
M6 locking nut	Home Depot	Any	0 days	8	$ 0.68	$ 5.44	Installed	
Birch markerboard (4ft x 4ft x 1/4in)	Home Depot	Any	0 days	2	$ 15.98	$ 31.96	Installed	
Fiberglass cloth (8 sq ft)	Home Depot	Any	0 days	4	$ 8.28	$ 33.12	Installed	
Fiberglass resin (1gal)	Home Depot	Any	0 days	1	$ 59.98	$ 59.98	In use	
Socket cap screw M6x100mm 4pk	Home Depot	Any	0 days	5	$ 3.25	$ 16.25	Installed	
Socket cap screw M4x20mm 4pk	Home Depot	Any	0 days	2	$ 3.25	$ 6.50	Installed	
Socket cap screw M4x60mm 3pk	Home Depot	Any	0 days	2	$ 3.25	$ 6.50	Installed	
Socket cap screw M3x50mm 4pk	Home Depot	Any	0 days	4	$ 3.25	$ 13.00	Installed	
Socket cap screw M3x10mm 3pk	Home Depot	Any	0 days	1	$ 2.25	$ 2.25	Installed	
Socket cap screw 1/4x7 in	Home Depot	Any	0 days	1	$ 1.99	$ 1.99	Installed	
M6 Nut 4pk	Home Depot	Any	0 days	5	$ 1.25	$ 6.25	Installed	
M4 Nut 4pk	Home Depot	Any	0 days	4	$ 1.25	$ 5.00	Installed	
M3 Nut 4pk	Home Depot	Any	0 days	5	$ 1.25	$ 6.25	Installed	
1/4 Nut	Home Depot	Any	0 days	1	$ 0.75	$ 0.75	Installed	
12 -10 AWG 0.25 in. Tab Male Fully-Insulated Disconnect (10pk)	Home Depot	Any	0 days	2	$ 4.62	$ 9.24	Installed	
12 -10 AWG 0.25 in. Tab Male Fully-Insulated Disconnect (10pk)	Home Depot	Any	0 days	2	$ 4.62	$ 9.24	Installed	
REGULAR PAYLOADS					**Total Cost:**	**$ 443.11**		
GoPro Hero 4K	GoPro	GoPro	7-10 business days	1	$ 220.00	$ 220.00	Installed	
MG995 Servo Motor 4pk	Amazon	Any	7-10 business days	1	$ 16.99	$ 16.99	Installed	
Magswitch MagJig Magnet	Amazon	Magswitch	3 business days	2	$ 26.73	$ 53.46	Installed	
3D Printing Filament (PLA)	Amazon	Any	3 business days	2	$ 19.64	$ 39.28	In use	
3D Printing Filament (PETG)	Amazon	Any	3 business days	1	$ 19.64	$ 19.64	Installed	
5lb dumbell	Amazon	Any	3 business days	1	$ 18.95	$ 18.95	Installed	
2-4S 20A Brushless ESC	Aliexpress	Surpass Hobby	2 weeks	1	$ 25.10	$ 25.10	Installed	
RC controller/receiver	Aliexpress	HotRC	2 weeks	1	$ 20.44	$ 20.44	Installed	
1050mAh LiPo battery	Amazon	Tattu	3 business days	1	$ 29.25	$ 29.25	Installed	
TOTAL OVERALL COST:						**$2,719.48**		

Figure 6.9. Bill of Materials

7 Design Validation and Initial Prototyping

7.1 Failure Modes and Effects Analysis (FMEA)

Before prototyping, the team validated our design by completing a Failure Modes and Effects

Analysis (FMEA). To complete this, we broke our design into 3 categories, the electrical system, the payload system, and the arms. We then evaluated each of the parts in the subsystem on its potential failure modes/effects, the mechanisms of failure, likelihood of occurrence, and what actions the team should take to ensure it won't fail. In the tables below, the results are as follows.

Part	Potential Failure Mode	Potential Failure Effects	Mechanisms of Failure	Likelihood of Occurrence	Recommended Action
Flight Controller	Software Failure	Loss of control	Incorrect programming, firmware bug	Low	Ensure programming accurate before flight
Regular Payload Release	Servo Failure	Unreleasable/ Early released payload	Servo not strong enough, not receiving enough power	Moderate	Test all servos before flight, use factor of safety during selection
RC Communication (Missile and Drone)	Loss of signal	Loss of manual control	Loose connections, malfunctioning part	Low	Ensure all connections secure before flight, test on ground
Battery	Reduced Voltage	Reduced power	Aging, improper charging	Moderate	Ensure storage charge when not in use

Figure 7.1. Electrical System FMEA

Part	Potential Failure Mode	Potential Failure Effects	Mechanisms of Failure	Likelihood of Occurrence	Recommended Action
Mounting bracket	Cracking/ breaking	Loss of stability and alignment	Stress concentration, fatigue cracks, impact	medium	Use strong material, ensure sufficient load capacity
Actuator wheel	Misalignment	Poor fitment & vibration	Uneven torque, part wear	medium	Ensure secure install, frequently check alignment
Stand-offs	Material fatigue & loosening	Loss of control of magnet, potential payload drop	Vibration, material fatigue	medium	Use strong material, verify secure install
Switched magnet (x2)	Misalignment & loss of force	Vibration loosening & exposure to high heat	Demagnetization & mechanical shock	low	Ensure magnet is fully engages, protect from heat & impact
Servo motors (x2)	Over heating, electrical failure	Reduced performance, loss of control	Excessive current draw, high load, over-voltage, short-circuit	medium	Ensure proper wiring, monitor cooling

Figure 7.2. Regular Payload FMEA

Part	Potential Failure Mode	Potential Failure Effects	Mechanisms of Failure	Likelihood of Occurrence	Recommended Action
Frame Arm Mount	Twisting/Deformation of TPU mount	Unstable Flight	Part (TPU) infill density to low.	Not likely, TPU density is at 35%	Increase infill density.
Octagonal Carbon Fiber Arm	Carbon fiber critical failure.	Highly unstable flight/ inoperable drone	Cracked carbon fiber arm	Likely after testing.	Purchase extra carbon fiber tubes
Motor Mount	Twisting/Deformation of TPU mount	Misaligned motors causing unstable flight	Part (TPU) infill density to low.	Unlikely, infill density will be rigid enough to counteract	Increase infill desnity

Figure 7.3. Arm Bracket to Motor Mount FMEA

7.2 Initial Prototyping

Motor Mounts

The goal for the motor mounts was to determine a design that balanced manufacturability with functionality. In this iteration, the mounts were made using 1/16th inch aluminum by cutting 5" x 2" plates and bending them at a 90-degree angle. While simple and functional, the design revealed some issues, such as insufficient security to withstand the forces exerted by the motors. Future iterations will feature 3D-printed TPU mounts to reduce vibrations, along with a top plate skeletonized to improve cooling.
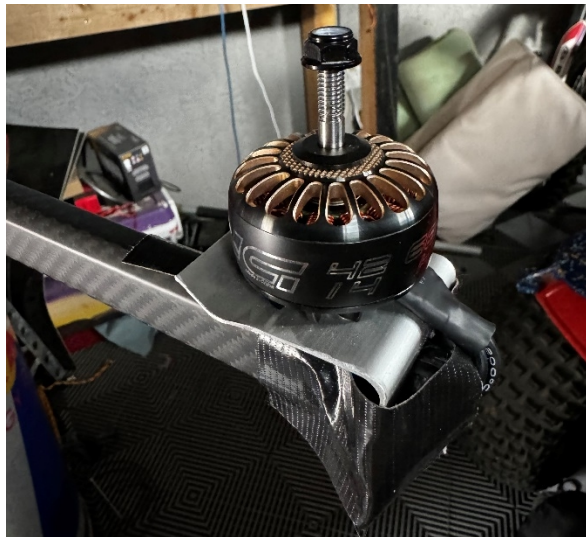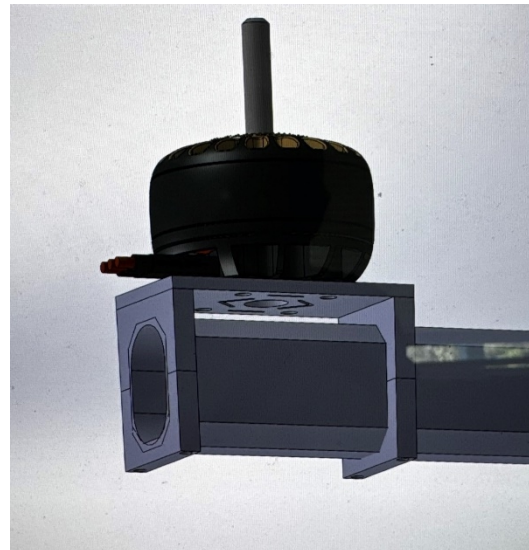

Figure 7.4. Aluminum Motor Mount (design 1)

Figure 7.5. Redesign for 3D printing and added stability

Arm Mounts

The arm mounts were evaluated for stability, and while functional, initial testing suggested that shorter arms might enhance structural performance. Reducing arm length could also lower the moment acted on the frame, improving overall durability and stability during operation.
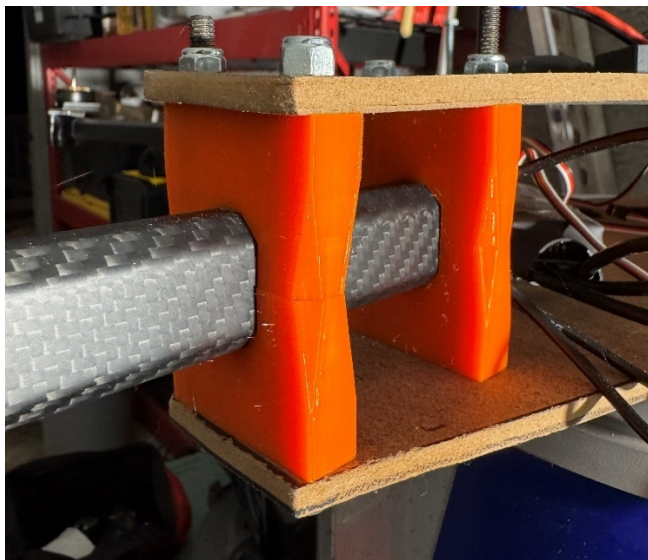

Figure 7.6. Current Design with 2.5 inch gap for added stability.   Figure 7.7. Arm mount design 1.

Frame

The prototype helped establish the drone's overall dimensions at approximately 44 inches across and 15 pounds in weight. This configuration confirmed the feasibility of integrating components while highlighting areas for improvement. Future iterations will use fiberglass-reinforced wood markerboard plates to reduce weight and improve durability. Additionally, more standardized hardware will simplify assembly and improve structural consistency.

Figure 7.8. Prototype #1, without propellers, legs, and payload.

Payload Detachment System

The payload detachment system utilized a custom ABS plate to press-fit two MagSwitches, which were securely attached via bolts. This design demonstrated functionality but left room for improvement. Future iterations will consider adding a third MagSwitch to improve shear force resistance and test servo motor integration with the flight controller for enhanced operational control.
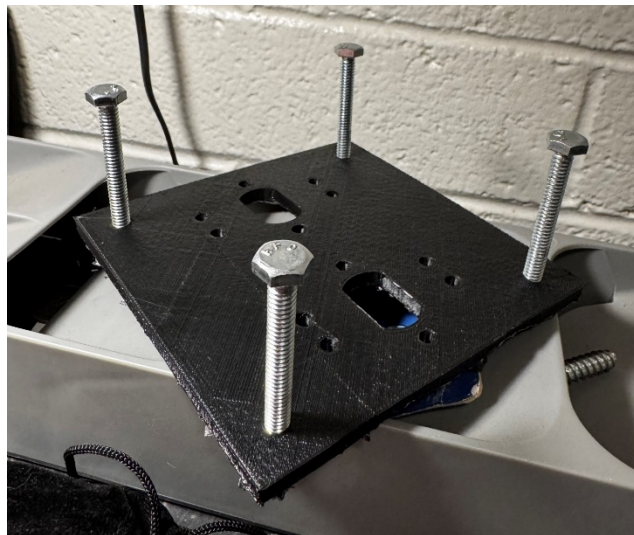

Figure 7.9. Payload bracket assembly with holes for MagJig 60s.

7.3 Other Engineering Calculations

7.3.1 Time of Flight and Battery Capacity Calculations – Michael Zielinski

Since the team now has a final design and a rough weight for the system, it is prudent to recalculate the

flight time with our current battery selection to determine if a second battery is required. To perform these calculations, a MATLAB program was utilized to collate and relate Equations 3, 4, and 5 in order to analyze both how much battery would be required for a 10-minute flight at various power settings and how long our current battery would last at these power settings (and by extension what power setting allows for the required 10 minute flight time). Figure 6.10 shows the graph produced when looking at what our current battery can produce in terms of flight time. To achieve 10 minutes of flight, a constant 27% throttle must be held; this number is lower than what we require to lift the system in its current configuration.
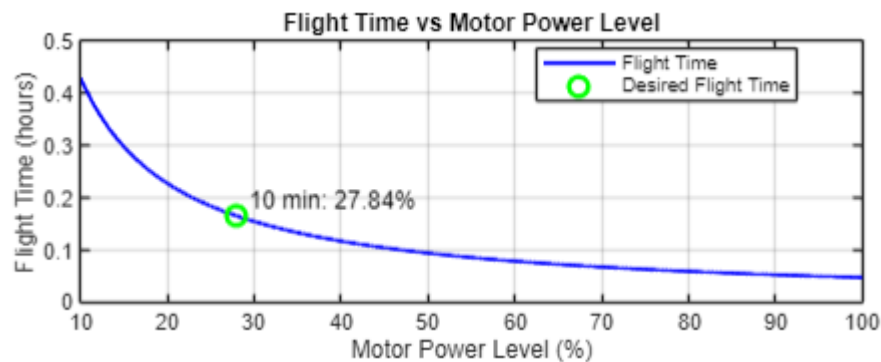
Figure 7.10. Flight Time vs. Motor Power Level

Based on this, it was determined that a second battery will be required. Figure 6.11 shows the graph that helps us determine what amp-hour battery will be required for our estimated average power setting. The graph provides a spread of 25% to 100% that we can interpolate from.
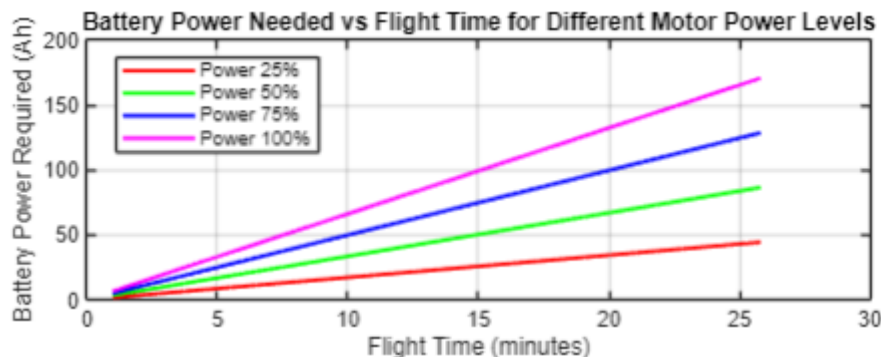

Figure 7.11. Flight Time vs. Battery for different power settings

The team opted to purchase a second 22Ah battery to supplement the first to not cause any incompatibility issues. With both batteries, the maximum power rating is now 61% and is acceptable to the team.

7.3.2 Thrust Test Stand

A custom motor test stand with a load cell assembly was designed to measure thrust, incorporating an Arduino and HX711 amplifier for precise data acquisition. The experimental setup tested three propeller sizes (13"x8", 14"x8", and 16"x8") at throttle increments from 0 to

60% due to thermal and deformation constraints. Calibration involved using weights (500 g to 1500 g), generating a calibration factor of 185.71 with adjustments for accuracy.

Results showed that thrust increased with propeller size, with the 13"x8" propeller producing a maximum of 5168.16g at 60% throttle, the 14"x8" achieving 5689.77g, and the 16"x8" propeller yielding the highest thrust of 6779.42g. However, larger propellers imposed greater loads on the motor. Future work includes incorporating angular speed measurements via a tachometer, conducting further efficiency calculations by using an oscilloscope to track the voltage being distributed to the individual motors, and redesigning the test stand for improved stability and heat dissipation.
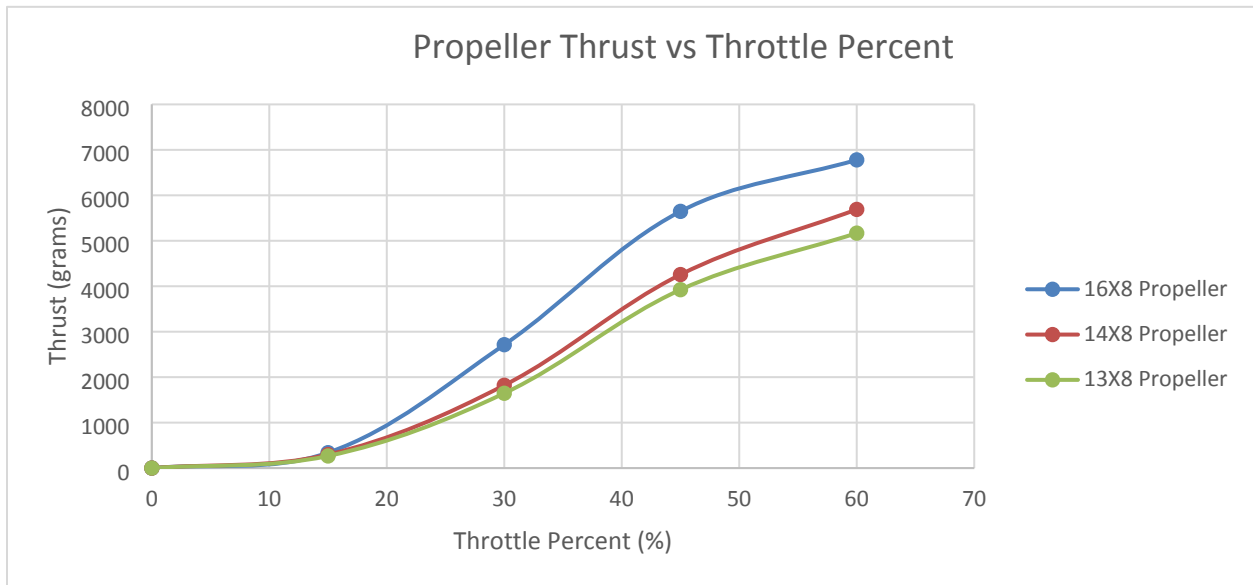

Figure 7.12. Prop thrust vs throttle percent for three different propellers.

At roughly 30% throttle, the 16 inch propellers produce ~2700 grams of thrust. In configuration of 4 motors, that equates to 10800 grams of lift force or 23.8 pounds. This shows that our motors will be able to produce the required lift and is expected to reach our thrust to weight ratio of 3:1.

16x8 Propeller	
Percent Thrust (%)	Average Thrust (g)
0	0
15	338.635
30	2714.2425
45	5646.908
60	6779.416667

8 PROJECT MANAGEMENT

8.1 Manufacturing Plan

The manufacturing process for the DORIS drone project focused on delivering a strong and efficient design that met the specified payload and performance requirements. Key tasks include 3D printing the payload missile and drone legs, comparing cost and material properties to make an informed decision for the drone's frame, and procuring laser-cut carbon fiber or fiberglass composite components for the frame to replace the MDF composite board. The plan emphasized precision, cost-effectiveness, and material optimization to ensure the drone's structural integrity and functionality, while keeping the team organized and efficient. Below is a list of when each part was printed and put together. As stated above, the BoM already includes raw materials for purchase, so the sorted BoM here shows $0 for each part. 100% of required items have been manufactured.

Manufactured Item	Vendor	Manufacturing M	Lead Time	Qty	Unit Cost	Total Cost	Part Status	Deadline	Printer	Member Responsible	Manufacturing Location
DRONE ONLY					Total Cost:	$ -					
Outer Arm Mount (TPU)	In-House	3D FDM Printing	4 hours	8	$ -	$ -	Installed	2/2/2025	Qudi Tech	Jeremy	Personal Residence
Motor Mount (TPU & ABS)	In-House	3D FDM Printing	2 hours	4	$ -	$ -	Installed	2/3/2025	Qudi Tech	Jeremy	Personal Residence
Drone Legs (TPU)	In-House	3D FDM Printing	4 hours	4	$ -	$ -	Installed	2/4/2025	Qudi Tech	Connor	Personal Residence
Body Plates (Fiberglass on birch)	In-House	Jigsaw cutting, la	10 hours	2	$ -	$ -	Installed	3/7/2025	-	Jeremy/Andre	Personal Residence
Battery Holder	In-House	3D FDM Printing	4 hours	1	$ -	$ -	Installed	3/28/2025	Bambu Lab A1	Andre	Personal Residence
REGULAR PAYLOADS					Total Cost:	$ -					
Magswitch Turning knob (PLA)	In-House	3D FDM Printing	1 hour	2	$ -	$ -	Installed	2/25/2025	Bambu Lab A1	Michael	Personal Residence
Magswitch/servo Attachment Plate (PETG)	In-House	3D FDM Printing	16 hours	1	$ -	$ -	Installed	2/4/2025	Bambu Lab A1	Michael	Personal Residence
GoPro Payload (PETG)	In-House	3D FDM Printing	8 hours	1	$ -	$ -	Installed	3/7/2025	Bambu Lab A1	Michael	Personal Residence
Weight Payload (PLA)	In-House	3D FDM Printing	22 hours	1	$ -	$ -	Installed	3/7/2025	Bambu Lab A1	Michael	Personal Residence
Payload Magnetic Plates	In-House	Saw and Drill	3 hours	2	$ -	$ -	Installed	4/18/2025	-	Dylan	Machine Shop
TOTAL OVERALL COST:						$ -					

Figure 8.1. Manufacturing Plan

8.2 Purchasing Plan

Our purchasing plan includes all the items we have purchased for this project. The Bill of Materials (BoM) below shows the items required to construct one unit of the DORIS drone in its current configuration. It is important that we have the BoM so that we can hand off the project to a client and they will be able to source all the parts required. The DORIS project is designed more toward allowing someone to construct their own drone from our files rather than purchase a pre-constructed unit. Because of this, the BoM includes costs for raw materials (i.e. 3D printing filament) and not per design costs. It also excludes the make/buy column as all items bought are on the table below, and all made items are in the Manufacturing Plan section. 100% of required items were purchased.

Purchased Item	Primary Vendor	Manufacturer	Lead Time	Qty	Unit Cost	Total Cost	Part Status	Weight (g)
DRONE ONLY					**Total Cost:**	**$2,276.37**		4677
22Ah 6S LiPo Battery	Aliexpress	Tattu	2 weeks	2	$ 240.00	$ 480.00	Installed	2460
Flight Controller (Pixhawk 6C)	HolyBro	HolyBro	7-10 business days	1	$ 231.46	$ 231.46	Installed	34.6
10pcs 150mm DuPont extension wires	Aliexpress	Any	2 weeks	1	$ 5.29	$ 5.29	Installed	
Pixhawk Wiring Kit	HolyBro	HolyBro	7-10 business days	1	$ 35.00	$ 35.00	Installed	
6-pin Molex PicoBlade to 6-pin JST-GH wire	3DR	3DR	7-10 business days	1	$ 8.76	$ 8.76	Installed	
XING 4214 660KV Motor	iFlight	iFlight	2 weeks	4	$ 62.75	$ 251.00	Installed	1080.4
6-channel RC receiver	Any	Any	7-10 business days	1	$ 35.00	$ 35.00	Installed	
Power Distribution Module (Sky-Drones SmartAP PDB)	Sky-Drones	Sky-Drones	7-10 business days	1	$ 90.00	$ 90.00	Installed	40
Electronic Speed Controller (150A)	Amazon	Flycolor	7-10 business days	4	$ 119.00	$ 476.00	Installed	572
RC Controller (must be compatible w/ receiver)	Any	Any	7-10 business days	1	$ 50.00	$ 50.00	Installed	
Wiring kit (12AWG, 60ft)	Amazon	NAOEVO	3 business days	1	$ 25.00	$ 25.00	In use	50
LiPo Battery Charging Kit	Amazon	SmartCharger	3 business days	1	$ 52.00	$ 52.00	In use	
4pk)	Amazon	ZSJ	2 weeks	2	$ 25.00	$ 50.00	Installed	40
3D Printing Filament (ABS)	Amazon	Any	3 business days	2	$ 20.00	$ 40.00	In use	
3D Printing Filament (PLA)	Amazon	Any	3 business days	1	$ 24.00	$ 24.00	In use	
3D Printing Filament (TPU 95A)	Amazon	Any	3 business days	1	$ 26.19	$ 26.19	In use	400
XT90 Connectors (10pk)	Amazon	Amass	3 business days	1	$ 14.17	$ 14.17	Installed	
Propellers (16", tri-blade)	HQProp	HQProp	7-10 business days	4	$ 35.68	$ 142.72	Installed	
Extreme Fasteners	Home Depot	Scotch	0 days	2	$ 13.03	$ 26.06	Installed	
M6 locking nut	Home Depot	Any	0 days	8	$ 0.68	$ 5.44	Installed	
Birch markerboard (4ft x 4ft x 1/4in)	Home Depot	Any	0 days	2	$ 15.98	$ 31.96	Installed	
Fiberglass cloth (8 sq ft)	Home Depot	Any	0 days	4	$ 8.28	$ 33.12	Installed	
Fiberglass resin (1gal)	Home Depot	Any	0 days	1	$ 59.98	$ 59.98	In use	
Socket cap screw M6x100mm 4pk	Home Depot	Any	0 days	5	$ 3.25	$ 16.25	Installed	
Socket cap screw M4x20mm 4pk	Home Depot	Any	0 days	2	$ 3.25	$ 6.50	Installed	
Socket cap screw M4x60mm 3pk	Home Depot	Any	0 days	2	$ 3.25	$ 6.50	Installed	
Socket cap screw M3x50mm 4pk	Home Depot	Any	0 days	4	$ 3.25	$ 13.00	Installed	
Socket cap screw M3x10mm 3pk	Home Depot	Any	0 days	1	$ 2.25	$ 2.25	Installed	
Socket cap screw 1/4x7 in	Home Depot	Any	0 days	1	$ 1.99	$ 1.99	Installed	
M6 Nut 4pk	Home Depot	Any	0 days	5	$ 1.25	$ 6.25	Installed	
M4 Nut 4pk	Home Depot	Any	0 days	4	$ 1.25	$ 5.00	Installed	
M3 Nut 4pk	Home Depot	Any	0 days	5	$ 1.25	$ 6.25	Installed	
1/4 Nut	Home Depot	Any	0 days	1	$ 0.75	$ 0.75	Installed	
12 -10 AWG 0.25 in. Tab Male Fully-Insulated Disconnect (10pk)	Home Depot	Any	0 days	2	$ 4.62	$ 9.24	Installed	
12 -10 AWG 0.25 in. Tab Male Fully-Insulated Disconnect (10pk)	Home Depot	Any	0 days	2	$ 4.62	$ 9.24	Installed	
REGULAR PAYLOADS					**Total Cost:**	**$ 443.11**		
GoPro Hero 4K	GoPro	GoPro	7-10 business days	1	$ 220.00	$ 220.00	Installed	
MG995 Servo Motor 4pk	Amazon	Any	7-10 business days	1	$ 16.99	$ 16.99	Installed	
Magswitch MagJig Magnet	Amazon	Magswitch	3 business days	2	$ 26.73	$ 53.46	Installed	
3D Printing Filament (PLA)	Amazon	Any	3 business days	2	$ 19.64	$ 39.28	In use	
3D Printing Filament (PETG)	Amazon	Any	3 business days	1	$ 19.64	$ 19.64	Installed	
5lb dumbell	Amazon	Any	3 business days	1	$ 18.95	$ 18.95	Installed	
2-4S 20A Brushless ESC	Aliexpress	Surpass Hobby	2 weeks	1	$ 25.10	$ 25.10	Installed	
RC controller/receiver	Aliexpress	HotRC	2 weeks	1	$ 20.44	$ 20.44	Installed	
1050mAh LiPo battery	Amazon	Tattu	3 business days	1	$ 29.25	$ 29.25	Installed	
TOTAL OVERALL COST:						**$2,719.48**		

Figure 8.2. Purchasing Plan

9   FINAL HARDWARE

9.1 Drone Assembly & Changes from Initial Prototyping

Figure 9.1. Fully assembled final design.

9.1.1 Frame

After initial prototyping, it was determined that for the final design, MDF board was insufficient in strength to support the loaded drone. The team briefly looked at carbon fiber plates, but the price on such plates had skyrocketed since the previous semester. Because of this, the team decided to manufacture our own fiberglass plates. Birch markerboard was used as the base to layer two layers of fiberglass cloth and resin. Markerboard was used as a base to provide strength that fiberglass alone could not provide, and to avoid having tens of layers instead of just two.

9.1.2 Legs

The legs went through two iterations after initial prototyping. Initially, a "peg-leg" design was used, but this was found to be too weak to support any lateral forces. The final design consisted of a 3D printed curve with internal trusses and an extended footpad to provide strength. This was printed out of PLA.

9.1.3 Arm Mounts

The initial design of an ABS plate attached to two TPU brackets was kept, but an additional ABS plate was added to the bottom for stability. These motor mounts were also moved four inches closer to the drone body, both as an effort to increase stability and to provide rudimentary protection to the propellers from ground strike.

9.1.4 Electronics

It was found that the flight controller needed to be programmed specifically to know what propellers were supposed to turn in what direction based on the PWM channel used. This method replaced our previous method of just switching two of the three wires from the ESC to the motor. Additionally, a metal cage was added on top of the major electronics to provide protection in case of a crash or propeller becoming free from its attachments. The battery holder was also 3D printed that holds both main batteries inside the frame and eliminates any risk of them falling out or moving around during flight. This holder also has a removeable bracket on one side that allows removal of the batteries for inspection and charging.
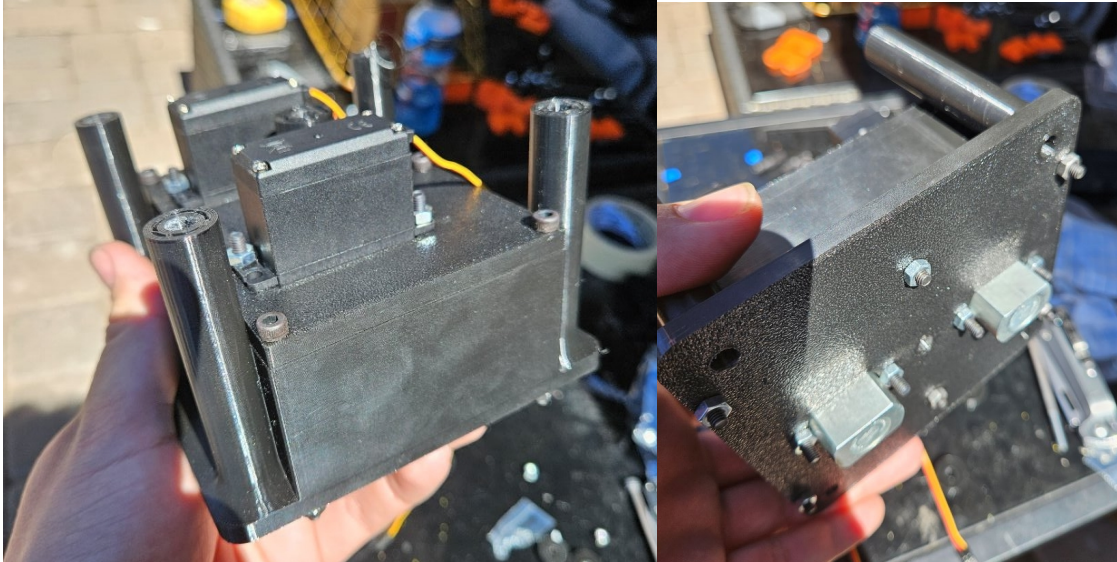
9.2 Payload System

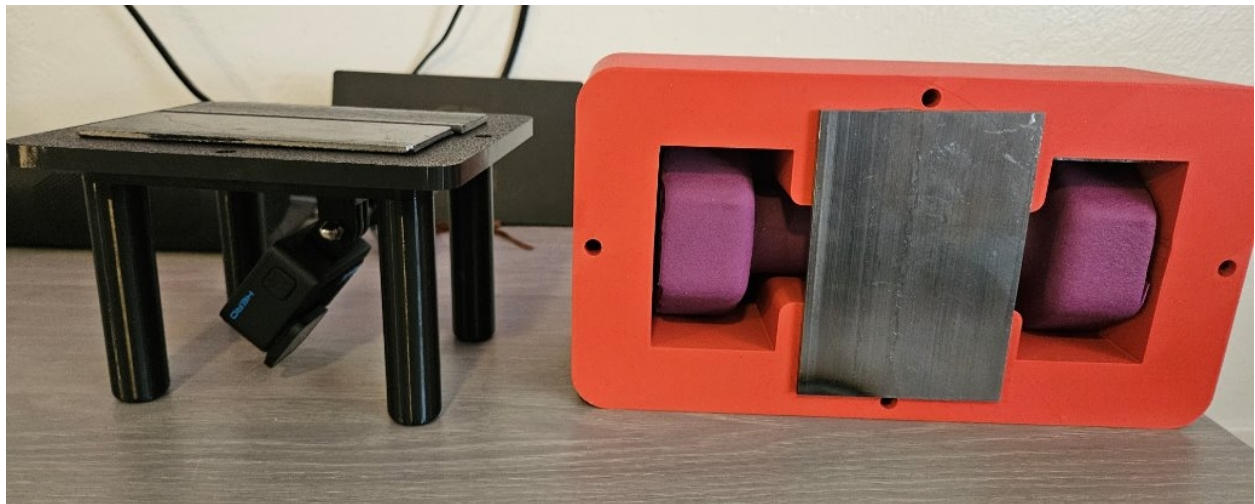Figure 9.2. Drone-side payload attachment (Left: top, Right: bottom).

Figure 9.3. Payloads (Left: GoPro, Right: Heavy).

9.2.1 Drone-Side Payload Attachment System (Mechanical)

It was decided that the initial one-level plate from initial prototyping was insufficient to housing the servos and MagJigs. The new design is shown in Figure 8.2. The MagJigs are housed completely within the 3D printed PETG box where the servos interface with them. A 3D printed knob interfaces the two (servo and MagJig) with one side being the four-pronged servo end effector and the other side being

shaped to press fit the knob of the MagJig. This ensures that the MagJigs do not move around and are secure the whole time.

9.2.2 Drone-Side Payload Attachment System (Electrical)

A 1050mAh LiPo battery was used to power the payload system in a circuit completely removed from the electronics of the drone itself. This was to place the responsibility of payload attachment/removal with a party other than the pilot so the pilot themselves may focus on flying. The LiPo was attached to a 20A ESC that in turn powered an RC receiver from HotRC. This receiver is paired with a controller that has buttons linked to RC channels 3 through 6. The two servos were plugged into channels 3 and 5 so that when these buttons were pressed, they would actuate and thus engage/disengage the MagJigs. All these electronics are attached to the payload housing using hook-and-loop fasteners to keep them away from the main drone electronics and any radio interference therein.

9.2.3 Payloads

9.2.3.1 Camera Payload

A simple four-legged table structure was 3D printed with the standard GoPro/action camera three-pronged bolt attachment integrated on the bottom. This allows any action camera with this attachment, not just GoPros, to be used. Metal plates were adhered to the top surface for the drone-side system MagJigs to attach to.

9.2.3.2 Heavy Payload

A large housing was 3D printed for a 5-pound dumbbell. This dumbbell is press fit into the housing and extra scrap metal pieces were slotted around it to further secure it and add weight. A metal plate was adhered to the surface to interface with the drone-side MagJigs

10 TESTING

10.1 Top Level Testing Plan

The team created a testing plan that included 5 experiments/tests that would help ensure that all the customer and engineering requirements were met. This plan can be shown below in Figure 9.1.

Experiment/Test	Relevant DRs	Testing Equipment Required	Other Resources
Exp 1: Take-off Test	ER – 4 ER – 6 CR – 3 CR – 5	-Drone System -FlySky Remote -Recording Device (iPhone) -stopwatch	-Good weather or large indoor location -certified drone pilot -Level Ground
Exp 2: Landing	ER – 4 ER – 6 CR – 3 CR – 5	-Drone System -FlySky Remote -Recording Device (iPhone) -stopwatch	-Good weather or large indoor location -certified drone pilot -level ground
Exp 3: Thrust Dyno Testing	ER – 1 CR – 7	-Strain gauge test stand/dynamometer -Motor + propeller -Digital multimeter	-excel spreadsheet -Ear Protection -Eye Protection -Video Camera
Exp 4: Side-to-side mobility test	ER – 2 CR – 1 CR – 2	-Drone System -FlySky Remote -Recording Device (iPhone)	-Good weather or large indoor location -certified drone pilot
Exp 5: Payload pickup and deployment	ER – 3 CR – 4	-Drone System -FlySky Remote	-weighted payload (hand weight) -camera payload

Figure 10.1: Top Level Testing Plan

The table above shows each of the tests, the design requirements that the team was testing for, the testing equipment required, and other resources that were needed to complete each test.

10.2 Detailed Testing Plan

10.2.1 Experiment 1: Take-off Test

10.2.1.1 Main Objective

The main objective of this test was to determine if the drone can achieve lift off by itself and with the various payloads.

10.2.1.2 Testing Focus

The focus of this test was being able to get the drone off the ground and achieving stable flight after take-off.

10.2.1.3 Testing Setup

This test was set up by taking the drone out to a field that was within FAA regulations and attempting to fly it while recording the test. The recording was taken so the team could diagnose any of the issues that occurred during take-off.

10.2.1.4 Pass Criteria

This test was considered a success if the drone was able to achieve lift-off and stable flight both with a payload and without a payload.

10.2.1.5 Results

This test was unsuccessful because the drone was not able to get off the ground. There was a power distribution issue that the team worked out but during testing 2 of the motors were broken. Due to supply chain problems, the replacement motors were delayed and to date, the motors still have not come in. This means that this test will remain incomplete until they arrive.

10.2.2 Experiment 2: Landing Test

10.2.2.1 Main Objective

The main objective of this test was to determine if the drone could land without damaging any component on the drone like the legs, arms, or mounts.

10.2.2.2 Testing Focus

The focus of this test was being able to get the drone back on the ground without damage.

10.2.2.3 Testing Setup

This test was set up by taking the drone out to a field that was within FAA regulations and attempting to land it while recording the test. The recording was taken so the team could diagnose any of the issues that occurred during landing.

10.2.2.4 Pass Criteria

This test was considered a success if the drone was able to land without damage.

10.2.2.5 Results

This test was unsuccessful because the drone was not able to get off the ground. There was a power distribution issue that the team worked out but during testing 2 of the motors were broken. Due to supply chain problems, the replacement motors were delayed and to date, the motors still have not come in. This means that this test will remain incomplete until they arrive.

10.2.3 Experiment 3: Thrust Dynamometer Test

10.2.3.1 Main Objective

The main objective of this test was to determine if the motors and propellers on the drone had enough lift force to lift the drone and the payload.

10.2.3.2 Testing Focus

The focus of this test was a static thrust test using a custom thrust test stand and ensuring that the lift was reliable and consistent.

10.2.3.3 Testing Setup

This test was set up by mounting a motor on a linear rail that had a 10 kg load cell for thrust measurement. The system was controlled by an Arduino and an ESC to control the throttle of the motor. It was all powered by a LiPo battery and collected thrust and current draw data.

10.2.3.4 Pass Criteria

This test was considered a success if the thrust output was greater than the total weight of the drone and payload system and it had a repeatable lift force across all test runs

10.2.3.5 Results

The results of this test were successful and the data for the motor combined with a 16x8 propeller can be shown below in Figure 9.1.

16x8 Propeller		
Percent Thrust (%)	Average Thrust (lbf)	Average Current (A)
0	0	0.31
15	0.747	3.65
30	5.984	12.5
45	12.449	29.89
60	14.946	54.61

Figure 10.2: Thrust Dynamometer Testing Results

10.2.4 Experiment 4: Drone Mobility Test

10.2.4.1 Main Objective

The main objective of this test was to determine if the drone with a payload could fly and maneuver in the air reliably and without failure.

10.2.4.2 Testing Focus

The focus of this test was being able to get the drone to turn and maneuver through the air while carrying a payload without failure.

10.2.4.3 Testing Setup

This test was set up by taking the drone out to a field that was within FAA regulations and attempting to fly and turn the drone while a member of the team recorded. The recording was taken so the team could diagnose any of the issues that occurred during flight.

10.2.4.4 Pass Criteria

This test was considered a success if the drone was able to obtain stable flight while turning and maneuvering through the air.

10.2.4.5 Results

This test was unsuccessful because the drone was not able to get off the ground. There was a power distribution issue that the team worked out but during testing 2 of the motors were broken. Due to supply chain problems, the replacement motors were delayed and to date, the motors still have not come in. This means that this test will remain incomplete until they arrive.

10.2.5 Experiment 5: Payload Reliability Test

10.2.5.1 Main Objective

The main objective of this test was to test reliability of magnet-based payload attachment and release system.

10.2.5.2 Testing Focus

The focus of this test was to confirm payload stays securely attached during flight, to test the repeatability of magnetic engagement and release system, and to observe any shifts or instability during hover and movement.

10.2.5.3 Testing Setup

This test was set up by taking the drone out to a field that was within FAA regulations and flying the drone over the payload. The system would then be activated, and the payload would be flown around the field. This would be recorded by a team member to diagnose any problems that arose.

10.2.5.4 Pass Criteria

This test was considered a success if the payload remained attached during full-thrust lift, there was a clean and controlled disengagement when triggered, and there was no interference with drone balance or control.

10.2.5.5 Results

It was determined that this test was a success. The drone was able to engage and disengage the system without issues and the drone was able to carry the payload without issues.

11   LOOKING FORWARD

11.1 Future Testing

Quantified frame strength testing to failure, arm and leg strength testing to failure, radio control distance test, and max payload capability testing are all potential future tests to determine the outer limits of the airframe and payload systems. These tests would help establish the operating envelope typically included with aircraft operating manuals and allow the owner/operator to know how far they can push the system before catastrophic failure.

11.2 Frame Iterations

As mentioned before, the team originally desired to use carbon fiber plates for the frame, but they were too expensive. With an increased budget that makes these plates financially viable, increased frame strength is possible. Additionally, a hole pattern could be specified for the plates that allows all electronic wiring to pass through the frame plate itself rather than around. These holes were avoided in the fiberglass design due to structural integrity concerns.

11.3 Leg Iterations

Currently, the legs are made of basic PLA. An upgrade to ABS, ASA, or PETG would provide greater thermal resistance and decreased warping over time. Additionally, a finite element analysis of the design may reveal weaknesses not considered for this project than can be corrected in another iteration.

11.4 Arm, Propeller, & Motor Iterations

The current arms have been deemed suitable for future iterations, but future tests could focus on how far from the body the motors truly should be placed for optimal performance (and thus how short the arms could be cut to).

The current X-class motors need to be updated. X-class motors are becoming less prominent in the hobby world, so a professional-grade motor is suggested (i.e. those used in agricultural or movie film drones). The team recommends a low KV rating, much less than the current 660KV, which means higher torque.

Along with new motors, new propellers will likely be needed due to the lack of standardization between companies in motor-prop connections. The team recommends a carbon fiber propeller for high strength and low weight. There are many options for 2-bladed propellers with similar performance to 3-bladed propellers of similar size. The team believes the 16-inch propeller to be sufficient based on our thrust stand testing, but the size could be analyzed further and considered when determining optimal arm length.

For a suggested total budget increase for new propellers and motors, the team recommends $3000 or more dedicated to solely these items.

11.5 Drone Electronics

The Pixhawk 6C is a very capable and suitable flight controller for this project. Despite this, the team recommends upgrading to a CubePilot system that utilizes the Herelink and Herelink Air Unit for RC communication. The Cube Orange, along with the Kore carrier board, eliminates the need for a separate Power Distribution Board and a multitude of the wires associated with the current setup. The Herelink also enables more advanced and real-time telemetry such as altitude, position, and the ability to link a live camera feed from the drone via HDMI. To obtain a GPS position, the addition of a GPS (Here4 or similar) is required. Beyond normal operations, the Cube and Herelink can plan autonomous missions without the need for pilot input. In this case, the independent nature of the payload electronics is beneficial because it eliminates the need for extra, complicated programming of the autopilot.

It is recommended to add an additional $2,500 to the budget for this system. Parts can be interchanged for cheaper options (i.e. GPS and Cube flight controller), but the team believes the Herelink to be an essential upgrade for continued operations of this system.

11.6 Payload System (Drone & Payloads)

11.6.1 Drone-Side System

The current payload system works very well for the team. The one point of issue is the servos and how far they actuate. Currently, the servos self-center to the middle of their documented 180-degree range. Because of this, when they are activated by the RC controller, they only move 90 degrees in one direction, then move back 90 degrees when activated again. In the current setup, this only half activates

the MagJigs. This is sufficient for the payloads the team has been lifting but is not ideal for practical use. The team recommends looking more into how servos can be programmed to ignore their self-centering procedure and/or how they can be actuated one direction after they center (say to the leftmost end point) and then back all the way to the other side (the rightmost end point). The team also recommends iterating the attachment system design to include more secure compartments for all the associated electronics (ESC, battery, and receiver) so that they are not simply fastened to the side of the box. It is also suggested to look at adding additional MagJigs to increase both the lifting power and in-flight stability of payloads. Another option is to look at electromagnets, but those can also be expensive.

11.6.2 Payloads

The camera payload has worked flawlessly; the only recommendation for this is to add flared feet on the table legs so that it is more stable on uneven ground during set down/pickup. The weighted payload has also been effective; the team's only recommendation here is to iterate on the design to make it more practical. By this, it is recommended that a payload be designed that can take actual items in a storage compartment (i.e. medical equipment, food, water) that make this drone more than a demonstration model.

12 CONCLUSIONS

In conclusion, with a $3000 budget sponsored by the Boeing Company, our team was tasked with designing and creating a drone utilizing commercially available parts. The drone must be able to engage and deploy different payloads while remaining airborne. These payloads will include a camera for potential surveying and a payload that must be equal or greater in weight to 30% of the drone's empty weight. The drone must be able to complete a predesigned course where it will pick up the various payloads and drop them off at a separate location. The design that our team has decided on is a quadcopter with a simplistic fiber glass reinforced birch wood frame, octagonal carbon fiber arms, a magnetic payload attachment system that can be turned off using a servo motor, a Pixhawk 6C Flight Controller, iFlight XING X4214 660KV Motors, and HQProp 16X8X3 (3 prop) propellers. With this design, we believe that it will be capable of picking up large payloads, have an extended 10-minute flight time, and being able to resist any damage that may occur. If damage does occur, the design allows for easy repairability.

12.1 Reflection

After two semesters working on this project and following the entire engineering design and development process, the team has learned a significant amount. Each team member would like to give their own individual reflection on this project below.

12.1.1 Andre Bonillas

My experience over the last two semesters working on this project has taught me resilience and perseverance. This project challenged us in ways that went beyond just technical skills; it tested our patience, our adaptability, and our ability to work together through uncertainty. From supply chain delays to system failures, we faced moments where progress felt out of reach. But each setback became a chance to regroup, learn, and move forward with a better understanding of the engineering process. For me, one of the most valuable lessons was how to stay committed to the bigger picture, even when the day-to-day work got difficult or discouraging. I learned to take initiative in problem-solving, to ask better questions, and to support my teammates when things got stressful. This experience also reinforced the importance of documentation, communication, and organization. Looking back, I'm proud of how we kept pushing and how far we came as a team. The process wasn't always easy, but it was real engineering: messy, complex, and incredibly rewarding. I'll carry these lessons of persistence and teamwork with me as I move into my professional career.

12.1.2 Dylan Boeholt

This capstone project challenged me to balance tight schedules for manufacturing, testing, and meetings alongside other responsibilities like AFROTC and coursework. One of the toughest moments came when we had to reorder motors last-minute, only to face delays due to tariffs. Still, I'm proud of how our team presented to Boeing engineers and impressed them, and I take pride in my hands-on work with the mill and studying FAA regulations to earn my license. The project pushed me to apply physics concepts from class and taught me to communicate and problem-solve as a teammate, even during difficult conversations. If I could go back, I'd start manufacturing earlier to allow more time for testing. Overall, this experience has prepared me to work better in teams and manage complex engineering projects in my future career.

12.1.3 Connor Davidson

Reflecting on the year working on this capstone project, my biggest takeaway is that failure and problems are a big part of the engineering process and should be used as learning opportunities. The team delt with many issues along the way like broken motors, power distribution issues, and supply chain problems. All these problems taught us something different and we learned more from our failures than from successes. Something else I took away from this project was that engineering really is a team-based profession. Every part of this project was team based, and you cannot survive as an engineer if you cannot work as a team.

12.1.4 Jeremy Malmo

Working on the DORIS heavy payload drone over the past year has significantly strengthened my manufacturing skills and deepened my understanding of the research and development involved in the engineering design process. This project also gave me a greater appreciation for the interdisciplinary nature of engineering, whether it's manufacturing, electrical systems, programming, aerospace principles, or project management. I've come to realize that successful engineering projects rely on the seamless integration of all these elements. As an aspiring mechanical engineer, I now better understand the importance of leveraging diverse skills and collaborating across disciplines to develop the most effective and practical solutions for real-world challenges.

12.1.5 Michael Zielinski

Over the course of the year, it has been fun being able to apply all the engineering skills and processes we learned toward creating something. This year has also made me see how much work besides construction goes into every project from the biggest airplane down to the bracket for the cupholders in your car. It's impressive now seeing how many independent systems come together in any given product to give it life, and how design choices influence whether to buy something off the shelf or fabricate it yourself. I wish that we had more time to test, and a bigger budget to purchase nicer equipment with, but I am proud of what we made with what we had. I believe we also had an advantage not being on a competition capstone team because we were able to work more directly with our client and have the flexibility to change things if we needed. Overall, I am proud of our team and proud to be a part of this process.

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14   APPENDICES

14.1 Appendix A: MATLAB Code: UAVtoolboxtest

```matlab
%% Parameters`
% Physical constants
g = 9.81; % Gravitational acceleration (m/s^2)


% Quadcopter parameters
motor_thrust_per_motor = 7.9 * 1000; % Thrust per motor (grams)
num_motors = 4; % Number of motors


% Weight estimation
payload_weight =  4.5*1000; % Payload weight (grams)
drone_frame_weight = 6 * 1000; % Frame weight (grams)
total_weight_g = payload_weight + drone_frame_weight; % Total weight (grams)
total_weight_kg = total_weight_g / 1000; % Total weight (kilograms)
total_weight_n = total_weight_kg * g; % Total weight in Newtons


% Desired thrust-to-weight ratio
desired_ratio = 3; % Design requirement (3:1 thrust-to-weight)
available_thrust_g = motor_thrust_per_motor * num_motors; % Total available thrust in grams
thrust_to_weight_ratio = available_thrust_g / total_weight_g; % Thrust-to-weight ratio


%% Hover Check
% Total thrust needed to hover (equal to total weight in grams)
required_thrust_hover_g = total_weight_g; % Total thrust needed in grams
hover_throttle = required_thrust_hover_g / available_thrust_g; % Throttle required to hover


% Check if available thrust is enough for hover
if available_thrust_g >= required_thrust_hover_g
    fprintf('Total available thrust (%.2f g) is enough for hovering.\n', available_thrust_g);
else
    fprintf('WARNING: Total available thrust (%.2f g) is NOT enough for hovering.\n', available_thrust_g);
end


fprintf('Throttle required to hover: %.2f%%\n', hover_throttle * 100);


%% Debug Information for Thrust and Weight
fprintf('Total Weight: %.2f N (%.2f kg)\n', total_weight_n, total_weight_kg);
fprintf('Available Thrust: %.2f g (%.2f kg)\n', available_thrust_g, available_thrust_g / 1000);
fprintf('Thrust-to-Weight Ratio: %.2f\n', thrust_to_weight_ratio);


% Check if the design meets the thrust-to-weight ratio
if thrust_to_weight_ratio >= desired_ratio
    disp('Design meets the thrust-to-weight requirement.');
else
    disp('Design does NOT meet the thrust-to-weight requirement.');
end


%% Motor Efficiency and Flight Time Estimation
efficiencies = [3.359, 4.2, 6.066]; % Efficiency in g/W at 100%, 75%, 50% throttle
throttle_levels = [1.0, 0.75, 0.5]; % Throttle levels


% Battery parameters
battery_capacity_mah = 22000; % Battery capacity (mAh)
battery_voltage = 22.2; % Battery voltage (V)
usable_capacity_factor = 0.85; % Usable battery capacity percentage
```

```matlab
battery_capacity_wh = (battery_capacity_mah / 1000) * battery_voltage * usable_capacity_factor; % Capacity in Wh
battery_capacity_joules = battery_capacity_wh * 3600; % Convert to Joules

%% Estimate Flight Time at Various Throttle Levels
flight_times = zeros(1, length(throttle_levels));

for i = 1:length(throttle_levels)
    throttle = throttle_levels(i);
    efficiency = efficiencies(i);

    % Adjust the required thrust based on throttle level
    thrust_at_throttle = throttle * available_thrust_g;

    % Power consumption per motor (using thrust at throttle)
    total_power_per_motor = thrust_at_throttle / num_motors / efficiency; % Power per motor (W)
    total_power_consumed = total_power_per_motor * num_motors; % Total power consumed (W)

    % Calculate flight time in hours
    flight_time_hours = battery_capacity_wh / total_power_consumed; % Flight time in hours
    flight_time_minutes = flight_time_hours * 60; % Convert to minutes
    flight_times(i) = flight_time_minutes; % Store flight time
end

% Display flight times at various throttle levels
for i = 1:length(throttle_levels)
    fprintf('Estimated flight time at %.0f%% throttle: %.2f minutes\n', throttle_levels(i) * 100, flight_times(i));
end

%% Adjusted Estimate Flight Time at Hover
% Adjust the required thrust based on hover throttle level
thrust_at_hover = hover_throttle * available_thrust_g;

% Use efficiency at 50% throttle (since hover is closer to 50% throttle)
efficiency_hover = efficiencies(3); % Efficiency at 50% throttle

% Power consumption per motor (using thrust at hover)
total_power_per_motor_hover = thrust_at_hover / num_motors / efficiency_hover; % Power per motor (W) at hover
total_power_consumed_hover = total_power_per_motor_hover * num_motors; % Total power consumed (W) at hover

% Calculate flight time in hours at hover
flight_time_hours_hover = battery_capacity_wh / total_power_consumed_hover; % Flight time in hours
flight_time_minutes_hover = flight_time_hours_hover * 60; % Convert to minutes

% Display estimated flight time at hover
fprintf('Adjusted estimated flight time at hover: %.2f minutes\n', flight_time_minutes_hover);
```

14.2 Appendix B: Thrust Efficiencies of iFlight XING X4214 660KV

Prop (inch)	Voltages (V)	Throttle (%)	Load Currency (A)	Pull(g)	Power(W)	Efficiency (g/W)	Temperature(in full throttle load 1 min)
16×6	24	50%	22.2	3232	532.8	6.066	90C°
		60%	33.8	4233	811.2	5.218	
		70%	48.1	5297	1154.4	4.589	
		80%	64.2	6246	1540.8	4.054	
		90%	83.1	7116	1994.4	3.568	
		100%	98	7900	2352.0	3.359	
15X6	24	50%	18.7	2745	448.8	6.116	85C°
		60%	29.2	3738	700.8	5.334	
		70%	40.6	4636	974.4	4.758	
		80%	55.7	5651	1336.8	4.227	
		90%	72.2	6575	1732.8	3.794	
		100%	83.5	7120	2004.0	3.553	
14X6	24	50%	14.7	2191	352.8	6.210	70C°
		60%	22.4	3008	537.6	5.595	
		70%	32.5	3880	780.0	4.974	
		80%	44	4754	1056.0	4.502	
		90%	58.8	5692	1411.2	4.033	
		100%	67.1	6179	1610.4	3.837	
15×6	12	50%	6.6	692	79.2	8.737	50C°
		60%	9.8	1001	117.6	8.512	
		70%	14.6	1384	175.2	7.900	
		80%	20.6	1785	247.2	7.221	
		90%	26.7	2162	320.4	6.748	
		100%	30.3	2383	363.6	6.554	
■Airplane			□Helicopter			■Vtol	

Figure B.1: Thrust efficiency chart of XING X4214 motors [12]

14.3 Appendix C: HolyBro Pixhawk 6C Specifications

Processors & Sensors

- FMU Processor: STM32H743
    - 32 Bit Arm® Cortex®-M7, 480MHz, 2MB memory, 1MB SRAM
- IO Processor: STM32F103
    - 32 Bit Arm® Cortex®-M3, 72MHz, 64KB SRAM
- On-board sensors
    - Accel/Gyro: ICM-42688-P
    - Accel/Gyro: BMI055
    - Mag: IST8310
    - Barometer: MS5611

Electrical data

- Voltage Ratings:
    - Max input voltage: 6V
    - USB Power Input: 4.75~5.25V
    - Servo Rail Input: 0~36V
- Current Ratings:
    - Telem1 Max output current limiter: 1.5A
    - All other port combined output current limiter: 1.5A

Mechanical data

- Dimensions: 84.8 * 44 * 12.4 mm
- Weight (Aluminum Case) : 59.3g
- Weight (Plastic Case) : 34.6g