Aerial Screw VTOL Rotorcraft

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Aerial Screw VTOL Rotorcraft

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ISYE 4803/4900 Aeronautics/Senior Design Project

April 22, 2020
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Executive Summary

Known as the “Renaissance Man,” DaVinci’s impressive knowledge of mechanics and inventive prowess would influence engineers and innovators hundreds of years later to make human flight a reality. However, due to the limited capacity of engineering and manufacturing at the time, his invention had been shallowly investigated in a production setting. This project strove to properly acknowledge DaVinci’s invention by thorough examination and critical analysis of his concept with the hopes of gaining a better understanding of why it is considered the “foundation of vertical flight” [1].

An iterative design approach was employed, utilizing faculty and university resources, team knowledge from previous courses, and computational software to conceptualize, analyze, and refine the rotorcraft design. The majority of the project consisted of hand calculations, FEA and CFD analyses, and project management. The performance analysis of this design resulted in clearer comprehension of the physical system and the benefits of exploring a unique design approach.

The project proved a rotor inspired by DaVinci’s aerial screw and influenced by modern technology and power storage systems could indeed produce enough lift to overcome component weight and achieve vertical flight. From simulation analysis and hand calculations, the lift per rotor was 2.24 kN, generating a total lift of 8.96 kN. This was ample lift to overcome the total helicopter weight of 311.078 kg. This is further proven with a T/W of 1.487. Additional parameters included a P_available of 6.5 kW, which was way more than the P_required of 504.7 W. These results confirm an aircraft prototype that relied on lift and thrust from a minimum of
one aerial screw was successfully engineered. In the future, the team hopes this research inspires new innovative approaches to modern rotor systems, and emboldens fellow engineers to continue researching and experimenting with unique design concepts and innovations, both past and present.
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Chapter 1

1.1 Introduction

Leonardo DaVinci is known for his contributions to various fields including art, astronomy, literature, and engineering. In his honor, the Vertical Flight Society has designed the 37th Annual Student Design Competition around DaVinci’s aerial screw concept, the first publicly acknowledged VTOL aircraft design. Since its conception, limited research has been conducted on the implementation of an aerial screw in a production flight system. The lack of research surrounding this concept provides a unique opportunity for students to research, and ultimately gain a better understanding of what an aerial screw rotor system has to offer [1].

The desired outcome, after extensive work in design and analysis of the rotorcraft, is to prove that it is possible to design a VTOL aircraft utilizing the aerial screw concept capable of sustained flight. In order to consider the design to be a success, the VFS has mandated that certain criteria be met. These criteria will be discussed in subsequent sections.

While the aerial screw may not be the most efficient design for an aircraft, a performance analysis of such a rotor system has the potential to provide a clearer comprehension of the physical system and the feasibility and benefits of a completely different type of design. The information gathered from this research has the potential to inspire new innovative approaches to modern rotor systems.
1.2 Overview

1.2.1 Major Developments

With a lack of research available explicitly relating to the use of the aerial screw concept as a primary, modern-day rotor system design, initial construction was time-consuming. The major areas of development included the design approach, the major components, and the analysis of designs.

Before delving into the actual design of the system, a systematic approach needed to be laid out. The team decided that an iterative design approach would provide the most freedom to create a suitable aircraft. This entailed repeatedly going through the stages of optimizing, analyzing, and refining until the design yielded a realistic and functional aircraft.

The major design components included the design blueprint, the primary rotor system (including the anti-torque mechanism), and the power supply. Design components will be discussed further in subsequent sections; however, it is important to note that the team hypothesized the two biggest issues encountered would be the weight of the aircraft and the amount of lift the rotors could generate. All design choices were shaped with those two things in mind.

The final major development was design analyses. Once a design was ready to be analyzed, hand calculations were done using the selected information and a CAD model was created. The CAD model was then analyzed using both CFD and FEA analysis. Based on results of the analysis, the design was either sent back for revisions or selected to move forward in the process.
Although functional models of a vertical aerial screw are nearly impossible to come by, other designs incorporating similar concepts of the aerial screw have been considered to provide an intuitive approach to design challenges. For example, several research papers on horizontal airfoil wind turbines (HAWT) were examined as a unique design approach for positioning of the rotor blades and for airfoil study [2]. These resources were helpful to reference how others have approached application of aerial screw concepts. Further investigation on these approaches can be found in subsequent sections.

1.2.2 System Block Diagram

The system block diagram is a depiction of the method followed for the design of the VTOL aerial screw rotorcraft. The first three stages required the team to brainstorm concept ideas, generate a set of design requirements, and create several “back of the napkin” concept sketches based off of those ideas and requirements. Upon selection of a concept, the initial sizing estimations were made and calculations were done to analyze the selections. The next four stages were incorporated into the iterative stages of the design process: optimization, sizing adjustments, layout adjustments, and analysis. The iterative process allowed the team to work through these stages as many times as necessary until a suitable design was produced. Once the design was deemed suitable, analyses were refined and a preliminary design was completed. This process can be seen in the block diagram shown in Figure 1.2.2-1 below.
1.2.3 Major Parts

As previously discussed, the primary design focus was on the layout, the main rotor and anti-torque systems, and the power supply. Major criteria for the parts being considered included overall impact on performance, complexity, and material selection.

The design layout was a crucial part of creating a practical concept. Many things had to be completed before any sort of selections or analysis could be done. These included:
determining the number, relative size, and placement of the rotors; the anti-torque system; the type and placement of the power supplies; the size and placement of the fuselage; and finally, the relation of all other smaller components to those main features.

It was evident that the rotor design was going to be a major area of focus as a modern VTOL aircraft sustained by an aerial screw design is unprecedented. The primary variables considered included airfoil selection and size, and whether or not the performance would increase if the rotors were enclosed in a cowling. In-depth analysis was performed on the rotor configuration, involving aspects such as airfoil design, solidity, and size.

The selection of the power supply system was the final major component that underwent extensive research and analysis. This selection was extremely important, as a major concern for the aircraft was the gross weight; gross weight was hypothesized to be a significant factor in whether the rotorcraft was capable of both vertical takeoff and sustained flight. These three components were designated as the aspects which would require the most time and effort to complete.

1.3 Objective

The overall objective of this project was to successfully build a prototype of an aircraft that satisfies all design requirements set forth by the VFS in their competition guidelines. Under these guidelines the design had to rely on lift and thrust from at least one aerial screw and be able to carry a single pilot or passenger with a minimum weight of 60 kilograms. In this case, an aerial screw was specified as a single blade rotor with a continuous surface, and a solidity greater than or equal to one. The guidelines also mandated that the rotorcraft must be able to accomplish
a vertical takeoff, maintain the position for a minimum of five seconds, sustain forward flight for one minute covering a distance of at least 20 meters at an altitude of one meter, and land vertically within a 10 meter radius of the projected landing location [1]. This mission profile is shown in Figure 1.3-1 below. In addition to these requirements, the hope was to be able to build a model of the design and test it in the aero lab at Kennesaw State University.

With the design being experimental, the specifications are relatively unknown, which introduced a wide scope of variability. However, the design and performance of the aircraft were proposed to fall in the range of a light sports or homebuilt aircraft. As more information is covered and preliminary estimations are analyzed in the following chapters, a more realistic scope of the project will be definable.

**Figure 1.3-1: Mission Profile**

### 1.4 Justification, Problem Statement

Known as the “Renaissance Man,” DaVinci clearly showed how far ahead of his time he was in designing the first VTOL aircraft. His impressive knowledge of mechanics would influence engineers and inventors hundreds of years later to make human flight a reality. However, due to the limited knowledge of engineering and physics at the time, his invention as a
whole has been shallowly investigated. This project aims to properly acknowledge DaVinci’s invention by thoroughly examining his work and performing a critical review of his idea in order to gain a better understanding of why the concept is considered the “foundation of vertical flight” [1].
2.1 Literature Review

2.1.1 Aerial Screw Analysis

DaVinci’s original design dates back to the late 1400’s and was primarily constructed of wire, thick linen cloth, and wood. The main components included a drive train, helical rotor, suspension and support components, and an operational platform. Power came from the release of a spring wound by human operators; theoretically, the tension in the spring provided enough power to propel the machine into the air.

Style of rotor arrangement is determined by the mission profile of the helicopter. With this information, it is safe to assume the machine was not intended to travel long distances, as there was no method to store power to support continued flight [3, 4]. So, a mission profile similar to a glider or home-built rotorcraft would be most appropriate. This design proposal should retain a similar mission profile until base calculations have been made and the design has been proven feasible to accomplish this original mission profile.

DaVinci’s goal was not to design a “helicopter,” but to specifically focus on an “aerial screw” in order to test his theory that air acted uniquely when compared to other fluids, and could be compressed so that one could be “pushed up” into flight. It is this concept of differential pressure producing lift that drives the design of airfoils for both fixed and rotary wing aircraft today [5].
It can be observed in Figure 2.1.1-1 above that an intentional helical shape was used for the wing. This shape was predicted to direct flow downward when spun towards the wind, producing an upward force capable of lifting the machine and its four operators once it reached a satisfactory rotational speed. Although ingenious and miles ahead of his peers, it was at wing design and power selection that DaVinci was truly limited by the knowledge of his time. In terms of power-to-weight ratio, humans were the best power supply option at the time, but by observation, it is clear the lift produced by four individuals would be unable to overcome the combined passenger and structural weight of the device.

Finally, the helical style wing was fastened using poles, introducing a new component that provided stability to the design, another aspect still applied today in fixed-wing aircraft wings and rotorcraft. These observations are not meant to strip the ingenuity of DaVinci’s design, but rather to shed light on the limitations of his time period, and to give credit to the ingenuity of the concept he generated given the severely limited resources available to him [4].
2.1.2 Alternatives

As driven as he was by his own knowledge of engineering and mechanics, DaVinci was heavily inspired by the work of Archimedes and other scholars. As it goes, other innovators were inspired by DaVinci and Archimedes and used their fundamental ideas to better their own. For example, Archimedes’ Screw concept directly influenced the design of various wind turbines. A wind turbine is used to extract power from moving air and repurpose it for powering residential and commercial areas. When broken down into individual components, a wind turbine is fairly similar to the helicopter in structure, the main difference being the angle of approach to the air with reference to the ground and its working application.

Early wind turbines used similar airfoil designs seen on helicopters and fixed wing aircraft. The teams who studied these vertical wind turbines opted to go another route and instead designed thin conical airfoils that overlap [2, 6]. This Archimedes’ screw design utilizes both lift and drag forces to extract power from the air. Figure 2.1.2-1 depicts a CAD-generated model of the team’s approach. This blade design was an attractive approach and was studied as an alternative rotor design during conceptual design and analysis for this project. Further review concerning airfoils will be covered in subsequent sections.
Figure 2.1.2-1: Geometrical model of Archimedes aerofoil wind turbine (AAWT)

As previously mentioned, there is little recorded comprehensive analysis of DaVinci’s aerial screw design in terms of rotorcraft development. Alternative approaches and applications were investigated in order to gain a more thorough understanding of the potential benefits of this design. Given the close relation to wind turbines, studying the approach researchers have taken during their development was deemed a satisfactory alternative for research and observation.

2.1.3 Airfoil Design

The original aerial screw airfoil design consisted of a thin continuous surface with constant thickness and variance only in the horizontal plane of the rotor [3, 4]. The concept of an “airfoil” would not be conceived until the 1900’s, so it was unfair to expect too much from
Leonardo concerning airfoil design. While an airfoil with uniform thickness will still produce lift (with a sufficient power source), it was hypothesized the airfoil could be more aerodynamic if geometric complexity was introduced. The goal was to explore more traditional airfoil concepts while still honoring the signature spiral shape of the Aerial Screw, with the anticipation that underlying benefits would arise from doing so, especially with the implementation of a true engine to power the aircraft.

DaVinci seemed to have investigated the effect of changing the angle of attack as his work shows an incline of the rotor. With selection of an appropriate airfoil, a high angle of attack can be used, incorporating more lift without additional drag. This phenomena can be observed on any cambered airfoil [7]. In addition, angle of attack can be manipulated on the spiral rotor as a method of directing flow downwards, ensuring ample airflow. A tradeoff to directing flow downwards will be the disk loading - this is also influenced by the weight of the helicopter, but nonetheless it must be monitored so as to not counteract the lift generated [8, 9].

Varying the span outwards as the rotor spirals up the shaft was another interesting approach. The hope would be to reduce the disk loading while still guiding flow downwards and producing lift. DaVinci can be seen experimenting with this concept in his original design, with the largest span at the bottom. Other airfoil design factors considered included lift-to-drag ratio, flow separation, and other factors ultimately affecting lift; optimizing lift will involve modifying the maximum camber, thickness, leading edge radius, and chord of the airfoil, among others. As seen in Figure 2.1.3-1, there are many aspects of an airfoil that can be altered to achieve desirable results.
It should not go without saying that Leonardo DaVinci was an inspiring engineer, enthralled with studying the mechanics of everything from humans to machines. His approaches to instruments and mechanisms are keys to understanding his motivations. A major goal of this review, this project, is to shed light on how Leonardo addressed concepts and how he clearly explained what something did and how it should function, as the method in which he did so is what truly made him a genius [10].

2.1.4 Stability and Control

Stability and control of typical rotor systems are executed using a combination of on-board computers and pilot input. Control is achieved by producing moments about the three aircraft axes: pitch, roll, and yaw. Traditional controls include a cyclic stick (longitudinal and lateral moments), collective stick (vertical force), foot pedals (yaw moment), and throttle (rotor speed and torque) [9]. Traditional control systems for turbine-powered helicopters require skill in balancing the helicopter, even with an augmented control system installed.
Multicopters do not use mechanical control elements, unlike their traditional counterparts. With this in mind, an electric control system was necessary. Electric control systems typically consist of a control interface, electronic speed controllers (ECS), control processors, sensors, actuators, and a control algorithm [29]. In the case of the aerial screw rotorcraft design, the rotors are rigid and exhibit a fixed pitch. Propulsion (forward, rearward, and sideways flight) is achieved by changing one or more rotor speeds as a function of pilot input in order to incline the rotor plane [30]. Sensors are used to monitor acceleration, positioning, and balancing. All calculations in terms of stability are done by integrated software and algorithms. Calculations are performed using data input from the sensors and cameras, and instructions are sent to the actuators and other components by the central control processor [31]. Concerning the interface, the pilot has access to a display panel similar to a homebuilt helicopter, and a joystick and switch to control the helicopter. This patent report has done a great job illustrating how a sensor and servo control system would operate on a quadcopter [30]. This configuration eliminates complex mechanical parts, lowering production costs and reducing maintenance frequency, as well as simplifies the flight control process for the pilot. A potential layout for a quadcopter control system is illustrated in Figure 2.1.4-1 below.
Control augmentation systems can also utilize gyroscopes for stability. The gyroscope is typically directly connected to the rotor and senses the inertial forces acting on the rotor. This system setup can be either purely mechanical or a sensor and electrically-powered servo combination [30]. However, in the case of a quadcopter, a gyroscope in the body of the helicopter would make more sense. This control setup was considered in addition to cameras and sensors to further improve the control system.

A detailed investigation of control system mechanics is outside the scope of the current iteration of this project, but several resources are available that go into detail on topics such as
control allocation (control algorithm development and testing) [31], in-depth electrical architecture and programming [30], and companies spearheading all-electric manned quadcopters if one wishes to know more.
3.1 Design Concepts and Trade Study Items

In terms of overall form factor, a heavy consideration was placed on a quadcopter style rotor layout, attached to a single seat cabin akin to a traditional helicopter, shown in Figure 3.1-1 below. The use of a vertical duct surrounding each screw rotor was considered, as well as hinging at each rotor to allow for thrust vectoring and in turn, forward acceleration.

Figure 3.1-1: Quadcopter design

Another design considered was a tandem rotorcraft, with two rotors in line with each other. This design alternative is shown in Figure 3.1-2 below.
Trade studies were done on cost, performance, weight, system configuration and complexity, the details of which are recorded in subsequent sections.

### 3.2 Verification Approach/Plan

A crucial step in the design process is to first perform a thorough study of any applicable historical data to understand what others had previously attempted. Analytical calculations for “first attempt” were next, laying out a general rule of thumb to reference during testing and optimization. Each design concept was modeled in Solidworks, which allowed for precise simulation built on analytical weight estimates and other initial calculations. Through each design iteration, FEA and CFD analysis was conducted to measure the lift capability and flight performance of each model. Once minimum design criteria had been met, the design underwent further refinement to improve flight performance and to test the limits of the aerial screw concept.
3.3 Minimum Success Criteria

The minimum success criteria for this project was to produce a preliminary rotorcraft design that incorporated the aerial screw concept, was capable of vertical takeoff, was able to both hover in place and travel in a forward motion for a specified period of time, and was capable of performing a controlled landing. This project should maintain an adequate budget and planning data such that the design could be pitched to a company in order to acquire a contract.

3.4 Available/Required Resources

Kennesaw State University (KSU) provided many resources to be used in order to facilitate the design and construction of all models and prototypes. A major tool was the team’s aggregate of various techniques learned in previous courses. In addition to accumulated text materials and knowledge, much of the digital designing was completed using Solidworks, a design software provided by KSU. For the physical prototype development, the AeroLab at KSU provided the proper testing & analysis tools needed to create and analyze the model. Lastly, Dr. Khalid was one of the most valuable resources used in gaining more insight and knowledge on the project task at hand. Materials and resources required for building an actual model have been recorded in later sections.

3.5 Project Management

Project Management plays a key role in providing structure and guidance for virtually every successful project. A Project Manager (PM) overlooks every aspect of a project to ensure all deliverables are met within the agreed upon scope, schedule, and budget. Given the design
requirement set forth by the VFS competition guidelines, it was important to first develop an overall plan of attack, given that the design of an aircraft can be an extensive task.

First and foremost, the overall project schedule was developed to ensure the team can be knowledgeable of what needs to be completed by predetermined dates stemming from course and competition deadlines. A detailed Project Schedule has also been utilized as the project progressed and team members began taking responsibility for specific tasks and research. Other useful tools for use in defining and tracking the project are: Gantt Charts, Flow Carts, Responsibilities, Budget, and Project/Design Requirements. Project management tools utilized in this project will be outlined in their own section.

3.6 Budget

Two budgets for the team’s final aircraft design were estimated - one covering the parts and materials required, and a second one covering estimated costs for development and production. In Table 3.6-1 below, the Parts and Materials Budget highlights every major mechanical component and material the team has selected throughout the iterative design process. Major aspects of the design were extensively researched and tested through simulation using solid works. This includes the power supply, rotor design & materials, and materials for the fuselage. Analysis of these components are further discussed in Chapters 4 & 5 of the report.
Table 3.6-1: Parts & Materials Budget

<table>
<thead>
<tr>
<th>Parts &amp; Materials Budget</th>
<th>Description</th>
<th>Cost ($/Unit)</th>
<th>Quantity</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Supply</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Motors (Brushless)</td>
<td>KDE Direct KDE8218XF-120</td>
<td>$596.95</td>
<td>4</td>
<td>$2,387.80</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>350W Brushless, DC Motor Driver Board</td>
<td>$35.75</td>
<td>1</td>
<td>$35.75</td>
</tr>
<tr>
<td>Battery</td>
<td>LiPo 3250 12S 44.4v Battery Pack</td>
<td>$269.99</td>
<td>4</td>
<td>$1,079.96</td>
</tr>
<tr>
<td>Misc Components</td>
<td>Wiring, switches, etc.</td>
<td>$200.00</td>
<td></td>
<td>$200.00</td>
</tr>
<tr>
<td><strong>Rotors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exterior Skin</td>
<td>Kevlar</td>
<td>$69.34</td>
<td>4</td>
<td>$277.36</td>
</tr>
<tr>
<td>Support (Ribs &amp; Struts)</td>
<td>Aluminum 7075-T6; -T651</td>
<td>$69.34</td>
<td>4</td>
<td>$277.36</td>
</tr>
<tr>
<td><strong>Fuselage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Body Structure</td>
<td>Aluminum</td>
<td>$5.33/kg</td>
<td>200 kg</td>
<td>$1,066.63</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Seat &amp; Harness</td>
<td>Braum® BRH-BKS5 5-Point Harness Set</td>
<td>$169.99</td>
<td>1</td>
<td>$169.99</td>
</tr>
<tr>
<td>Controls</td>
<td>Cyclic &amp; Collective Pitch</td>
<td>$1,500.00</td>
<td>1</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Personal Protection Equipment</td>
<td>Helmet, Eye Protection, gloves, etc.</td>
<td>$200.00</td>
<td>1</td>
<td>$200.00</td>
</tr>
<tr>
<td><strong>Total Investment</strong></td>
<td></td>
<td></td>
<td></td>
<td>$6,917.49</td>
</tr>
</tbody>
</table>

Estimations of development and production costs have also been listed below in Table 3.6-2. This particular budget has estimations of the project costs from the project initiation phase to the final real model testing phase. Other costs and criteria that will be assessed includes estimates for the costs of operation of the VTOL. This will give a numerical value to the costs related to need for charging the battery, maintenance, inspections, and etc. This budget was created to give an real-world estimation of what it would take cost & resource wise to complete.
this project from start to finish. The budget for parts & pieces for creation of the aircraft may seem low priced, so outlining the actual creation of the aircraft displays where a majority of the costs occur.

Many of the cost estimations in this section were derived from research of similar projects being built (DIY Projects). Costs for the design phase are under the assumption that the design team (Senior Designers & Professors) were paid for their work on the project.
### Table 3.6-2: Development & Production Budget

<table>
<thead>
<tr>
<th>Description</th>
<th>Rate ($/hr)</th>
<th>Total Hours</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aircraft Design &amp; Analysis</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Senior Designers</td>
<td>$20.00</td>
<td>300</td>
<td>$6,000.00</td>
</tr>
<tr>
<td>University Professors</td>
<td>$30.00</td>
<td>80</td>
<td>$2,400.00</td>
</tr>
<tr>
<td>Flight Simulations</td>
<td>N/A</td>
<td>N/A</td>
<td>$2,700.00</td>
</tr>
<tr>
<td><strong>Manufacturing/Development</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing Overhead</td>
<td>$15.00</td>
<td>40</td>
<td>$600.00</td>
</tr>
<tr>
<td>Direct Labor</td>
<td>$45.00</td>
<td>150</td>
<td>$6,750.00</td>
</tr>
<tr>
<td>Set-up Costs</td>
<td>$20.00</td>
<td>20</td>
<td>$400.00</td>
</tr>
<tr>
<td>Operation Cost</td>
<td>$30.00</td>
<td>30</td>
<td>$900.00</td>
</tr>
<tr>
<td>Material Handling</td>
<td>$15.00</td>
<td>15</td>
<td>$225.00</td>
</tr>
<tr>
<td><strong>Flight Operations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety Inspection</td>
<td>N/A</td>
<td>N/A</td>
<td>$1,100.00</td>
</tr>
<tr>
<td>Licensure</td>
<td>$250.00</td>
<td>40</td>
<td>$10,000.00</td>
</tr>
<tr>
<td>Insurance</td>
<td>N/A</td>
<td>N/A</td>
<td>$7,000.00</td>
</tr>
<tr>
<td>Hangar</td>
<td>N/A</td>
<td>N/A</td>
<td>$2,000.00</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Improvements</td>
<td>N/A</td>
<td>N/A</td>
<td>$200.00</td>
</tr>
<tr>
<td>Unscheduled Repairs</td>
<td>N/A</td>
<td>N/A</td>
<td>$1,000.00</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td></td>
<td>$41,275.00</td>
</tr>
</tbody>
</table>

The total cost of this project if it were to be completed can now be calculated based on the Development & Operation Budget and the Parts & Materials Budget shown above. The total cost of this project comes to be $48,192.49.
3.7 Project Schedule

An overall project schedule consisting of course milestones and the VFS Aerial Screw Design Competition dates and deadlines has been used throughout the project to ensure tasks are completed on time. Also, a detailed project schedule was used to outline specific tasks and responsibilities which required completion before any deadlines mentioned in the overall schedule. After each major in-class review, additional adjustments were made where needed in order to cover all new tasks and deadlines that arise. The overall project gantt chart can be seen in Figure 3.7-1 below, which displays where the team is in terms of completion of the project. An example of the detailed project schedule can be seen below in Figure 3.7-2.
Project Gantt Chart

Figure 3.7-1: Project Gantt chart

Figure 3.7-2: Detailed project schedule
Chapter 4

4.1 Ongoing Design Review

4.1.1 Body Design

Standard helicopter configurations consist of at least one main rotor system, fuselage, tail structure, landing gear, powerplant, and transmission. How a helicopter body is configured can completely alter its performance and mission capabilities. One body design approach investigated for the helicopter was to position two horizontal rotors in line with each other, also known as a tandem rotor configuration. Having two rotors eliminates the need for a separate anti-torque system (tail rotor), due to the counter rotation of the rotors cancelling out the torque produced. In addition, since no tail rotor is required, all the power from the engines can be utilized for lift [11].

A side-by-side was briefly considered since it was discovered while researching a tandem rotor configuration and it functioned similarly to a traditional tandem configuration in that no tail rotor was required. This configuration was a unique approach that allowed for a shorter body design compared to a traditional tandem. However, research recommended this design only when it was applied to a tilt-rotor aircraft, such as the V-22 Osprey. If implemented without a tilt-rotor configuration, unnecessary surface area is created, therefore increasing drag. This was discovered after deliberation with aerospace faculty. While this was a notably interesting design, it was clearly better to go the route of a traditional tandem rotor configuration. Both aircraft can be seen in Figure 4.1.1-1 below.
Figure 4.1.1-1: Tandem and side-by-side configurations

A tandem configuration is typically used on heavy cargo transport rotorcraft, as its large disk area produces incredible amounts of lift, a necessary feature for heavy-lifters such as the Chinook. Rotor orientation also tolerates smaller blade diameter while maintaining a large disk area in comparison to single-rotor aircraft. This leads to weight reduction in rotor design and makes negative aspects that come with designing longer blades less of a concern, such as blade droop [8]. Other elements to monitor when modeling tandem rotors is the area of blade overlap. In the overlap region, overall disk loading is intensified, which increases power loss. It is ideal to model a tandem configuration with a small amount of overlap [9]. With an experimental screw-type blade, it is wise to select a configuration that will amplify lift produced by the rotors as much as possible. Other concerns include rotor control complexities, as traditional helicopter configurations involve at least a semi-articulated rotor system that involves countless mechanical components such as a swashplate and hinges. With the spiral structure and high solidity
requirements of the aerial screw rotor, mechanical complexities like these have the potential to compromise the design.

In addition to the tandem configuration, a quadcopter arrangement was considered, which introduces several advantages. The initial conceptualization of an aerial screw quadcopter is shown in Figure 4.1.1-2.

![Initial quadcopter concept model](image)

**Figure 4.1.1-2: Initial quadcopter concept model (seat model from ref. [23])**

Similar to the tandem configuration, a quadrotor structure eliminates the need for an anti-torque system by implementing sets of counter-rotating rotors. It also eliminates any additional mechanisms required for maneuvering, as movement can be controlled by adjusting each rotor's angular velocity, relative to one another.

Increasing the number of rotors allows a smaller rotor diameter to be utilized. Additionally, the motor power requirements per rotor decrease, as the workload is split among 4 driveshafts (as opposed to 2 or 1 for tandem and coaxial configurations, respectively). This
allows for simpler, lighter motors, including commercially available electric motors that can be easily installed and maintained. These motors can be controlled by simple, light, programmable computer interfaces, which further simplifies the steering mechanisms.

Unfortunately, there are drawbacks to a quadcopter configuration. Quad-rotor systems are unstable by nature; As a consequence, stabilization programming must be implemented into the controls interface, which complicates the programming requirements, but does not affect the design physically [12]. Also, more rotors require a much wider planar area, which increases the overall size of the aircraft and adds weight from the additional framing/supports [9]. On the other hand, as the number of rotors increases, the rotor diameter can decrease while still providing adequate lift. With this data in mind, selection of a body configuration will ultimately be achieved through intensive studies. These trade-off studies and body selection can be found in later sections.

4.1.2 Airfoil Design

Airfoil design affects the overall aerodynamic performance of an aircraft, be it fixed-wing or rotorcraft. The team opted to apply the same airfoil shape to both the quadcopter and tandem configurations. This ensured that airfoil selection was a collaborative effort and confusion would be avoided concerning which airfoil had been tested on which model.

As expected, several iterations of a rotor were modeled and evaluated. One of the first iterations involved modifying the radius of a database airfoil shape to fit the initial calculated rotor design diameter. Figures 4.1.2-1 and 4.1.2-2 below depict some of the first design phases of a spiral blade influenced by a four-digit NACA airfoil (the NACA 6409 airfoil specifically).
An extensive online airfoil library was referenced, which included a software that provided visualization, graphing coordinates, and modification of current airfoils [13, 14]. Results from
this modeling approach varied as the design team struggled with finding a design process other than manual airfoil coordinate input and coordinate modifications.

A second approach was to ignore the technical airfoil shape for the time being, focusing instead on modeling a thin, constant-thickness blade. Reasoning behind this approach was that due to the spiral configuration of the rotor blade, it could be argued there technically was no leading edge or trailing edge. Therefore, any benefits from utilizing an airfoil could be annulled by the orientation of the rotor. Focus was instead placed on altering the pitch and angles of the blade to direct airflow. From observation, it made the most sense to pitch the blade upwards to direct flow downwards, but more research would need to be conducted on this theory. An additional experimental idea was to pitch the top half of the rotor upwards and pitch the bottom half of the rotor downwards in hopes of improving control over airflow, but again this was purely theoretical and must be subjected to experimentation. Figure 4.1.2-3 below illustrates a thin airfoil concept modeling attempt.

![Thin airfoil based rotor design](image)

*Figure 4.1.2-3: Thin airfoil based rotor design*
Ultimately, focus was re-centered on utilizing an airfoil from a database to incorporate appropriate airfoil data into the project for the final design. A screenshot of the finished model can be found in Figure 4.1.2-4 below. The aerial screw shape was modeled by sketching a chord-wise outline of an airfoil from the NACA database and then wrapping the airfoil around the shaft. This method allowed the cross-section of the airfoil to be easily viewed in Solidworks for data gathering purposes.

**Figure 4.1.2-4: NACA Airfoil based rotor design final attempt**

Heavy emphasis was placed on the curvature of the spiral, angle of attack, chord length, and other features to optimize lift capability. The rotor blade was angled inward resembling a funnel with the intent of directing the air down the spiral. Chord length was varied along the length of the rotor, with the longest chord length at the top of the shaft (i.e. the largest diameter was at the top). This approach was an inversion of DaVinci’s traditional design with the largest
diameter at the bottom. The anticipated result from this approach was to trap more air at the top of the rotor to push downwards, theoretically producing more lift. Concentrating the downward force of the air flowing through the rotor too intensely would produce a high disk loading, an undesirable and unsafe feature for this study. Previous research on this approach can be found in sections 2.1.3 Airfoil Design.

4.1.3 CFD Analysis

Once a satisfactory model was created, fluid dynamics simulation testing began. The team opted to use the Flow Simulation add-ins from SolidWorks, as they were the most accessible and affordable testing softwares available. Figure 4.1.3-1 depicts the first successful results from flow simulation. This test was performed on a variable diameter screw, with the largest diameter on the bottom.

The goal of this simulation was to observe flow velocity in the Y-direction when the rotor is rotating at a specific angular velocity. A rotating region was defined around the rotor to simulate rotation. The angular velocity of the region was set to a high speed (around 600 rad/s) initially. Overall, results produced a maximum velocity of 15.2 m/s and a minimum velocity in the negative, meaning air is somehow being pushed upwards through the model. The next step was to figure out why the velocity needed to be so high to get proper results.

A snapshot of flow trajectory simulation performed on an inverted rotor design - with the widest diameter of the blade on the top - can be seen in Figure 4.1.3-2. These simulations were not intended to produce numerical values per se, but more or less showed all flow would be directed downwards if an inverted design was used. Due to lack of experience with operating
simulation software and performing analysis, communicating with a CAE professor in the future will be essential. An example of some testing issues can be seen in Figure 4.1.3-3.

Figure 4.1.3-1: Flow Simulation to determine velocity in y-direction
**Figure 4.1.3-2**: Flow trajectory simulation

**Figure 4.1.3-3**: Example of roadblock in simulation testing
Further analysis continued over time in accompaniment to rotor design modifications. Advisement from Kennesaw State CAE professor Santana Roberts helped educate the team on proper model preparation for simulation, and offered helpful design input for a new rotor design. Analysis was performed on this new model, with similar goals to previously conducted tests. The angular velocity of the rotating region was that of the KDE Direct electric motor, which was 605.3 rad/s (5780 rpm). Initial goals set were to identify the average and maximum velocity the fluid achieved in the Y-direction, as well as the force produced by the rotor in the Y-direction. The force parameters depict how much thrust is produced with the provided rpm of the electric motors and will confirm if the rotor is capable of producing lift given this amount of power.

**Figure 4.1.3-4: Flow simulation to determine velocity in y-direction**

Figure 4.1.3-4 depicts a cut plot of the fluid streamlines flowing around the rotor. A maximum velocity of 14.625 m/s was detected near the edge of the main rotor (seen in the red
box in the figure), an important parameter to observe to avoid the outermost tip of the rotor experiencing transonic shock waves. This maximum velocity was close to the calculated tip speed of the rotor, confirming the simulation was functional and the data was within reasonable range.

A common issue encountered was getting the program to direct flow through the model in the right direction. Oftentimes, the same test would be run without modification and the direction of flow would come from the bottom instead of the top and flow through the model backwards. This was a frustrating issue that certainly made it difficult to gather data. Luckily, some of the data could simply be analyzed “upside down”, as in the case with Figure 4.1.3-4 above. Color coding indicates the air is being drawn in by the rotor, and fluid velocity increased as it flowed through the rotor (from the bottom up). This was enough to assume that flow would behave the same way if properly directed through the model.

In addition, a goal was set to examine force produced by the rotor in the Y-direction. Figure 4.1.3-5 graphically illustrates the force produced by the rotor. On average, the thrust was 983.73 N, quite impressive for the size of the rotor. This is another indicator that the rotor is performing correctly - a reasonable amount of downward force is being produced.
Figure 4.1.3-5: Force in the Y-direction

Figure 4.1.3-6 demonstrates the velocity difference between the top and bottom of the rotor, the results inverted by the software. Still, it can be observed that if the airflow was directed upward, a velocity difference between the top and bottom of the blade sections would occur, generating lift.
Although not reliable enough to stand on its own, CFD analysis has proven to be a useful tool in connecting hand calculations to the 3D model and to visualize how the rotor interacts with the air.

**4.1.4 Power Supply**

For this rotorcraft a lot of time was dedicated to determining whether a gas engine or a set of electric motors would be more effective for the designated mission profile. To determine which would be more suitable, both a gas engine and an electric motor were selected to undergo thorough analysis. The selected power supplies were the Compact Radial MZ201 (gas) and the KDE Direct KDE8218XF-120 (electric), respectively.
The Compact Radial MZ201, formerly the Zanzottera MZ201, is a “twin-cylinder, in-line two-stroke, dual ignition aircraft [engine] designed for ultralight aircraft and motor gliders” [15]. This engine has “one of the highest power to weight ratios available” for 45 HP engines and is currently used on the Mosquito Aviation XEL ultralight helicopter. The two most crucial variables to be considered for the rotorcraft design are the weight and performance of the engine. The MZ201 weighs 31 kg (69 lb) and has a maximum performance of 33.1 kW (45 HP) at 4700 rpm. A complete record of the technical specifications for this engine can be seen in Table 4.1.4-1 below [16].

**Table 4.1.4-1: Technical specifications for Compact Radial’s MZ201 engine**

<table>
<thead>
<tr>
<th>Compact Radial MZ201</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Displacement</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Max. Performance</td>
</tr>
<tr>
<td>Max. Torque</td>
</tr>
<tr>
<td>Carburator</td>
</tr>
<tr>
<td>Ignition System</td>
</tr>
<tr>
<td>Generator Power</td>
</tr>
<tr>
<td>Cooling</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Starting Device</td>
</tr>
<tr>
<td>Running Direction</td>
</tr>
<tr>
<td>Fuel Mixture</td>
</tr>
</tbody>
</table>

The KDE Direct KDE8218XF-120 is part of KDE Direct’s “brushless motor for heavy-lifting electric multi-rotor (UAS) series” [17]. While many electric motors have low weight restrictions, this motor was specifically designed for heavy lifting applications, and was designed with durability in mind. The motor weighs only 0.845 kg (1.86 lb) and has a maximum
performance of 5.695 kW at 5780 rpm. A complete record of the technical specifications for this motor can be seen in Table 4.1.4-2 below. Table 4.1.4-3 also shows a comparison of key features for these selected power supplies.

**Table 4.1.4-2: Technical specifications for KDE Direct’s KDE8218XF-120 motor**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kv (Motor Velocity Constant)</td>
<td>120 RPM/V</td>
</tr>
<tr>
<td>Kt (Motor Torque Constant)</td>
<td>0.0796 Nm/A</td>
</tr>
<tr>
<td>Km (Motor Constant)</td>
<td>0.4137 Nm/(W)</td>
</tr>
<tr>
<td>Maximum Continuous Current*</td>
<td>110 A (180 s)</td>
</tr>
<tr>
<td>Maximum Continuous Power*</td>
<td>5695 W (180 s)</td>
</tr>
<tr>
<td>Voltage Range</td>
<td>22.2 V (6S LiPo) - 60.9 V (14S LiHV)</td>
</tr>
<tr>
<td>Io (@10V)</td>
<td>0.8 A</td>
</tr>
<tr>
<td>Rm (Wind Resistance)</td>
<td>0.037 Ω</td>
</tr>
<tr>
<td>Stator Poles</td>
<td>24 (24S28P, HE)</td>
</tr>
<tr>
<td>Magnetic Poles</td>
<td>28 (24S28P, HE)</td>
</tr>
<tr>
<td>Bearings</td>
<td>Triple, 6901-2RS/7901C/7001C</td>
</tr>
<tr>
<td>Mount Pattern</td>
<td>M5 x φ40 mm, M6/M5 x φ55 mm</td>
</tr>
<tr>
<td>Stator Class</td>
<td>8218, 0.2 mm Japanese</td>
</tr>
<tr>
<td>Shaft Diameter</td>
<td>φ10 mm (φ12 mm Internal)</td>
</tr>
<tr>
<td>Shaft Length</td>
<td>9.5 mm</td>
</tr>
<tr>
<td>Motor Diameter</td>
<td>φ89 mm</td>
</tr>
<tr>
<td>Motor Length</td>
<td>49.2 mm</td>
</tr>
<tr>
<td>Motor Weight</td>
<td>760 g (845 g with Wires/Bullets)</td>
</tr>
<tr>
<td>Propeller Blade Size</td>
<td>Up to 30.5&quot;-TP (27.5&quot;-TP Maximum on 14S)</td>
</tr>
<tr>
<td>Motor Timing</td>
<td>22° - 30°</td>
</tr>
<tr>
<td>ESC PWM Rate</td>
<td>16 - 32 kHz (600 Hz)</td>
</tr>
</tbody>
</table>

Table 4.1.4-3 below shows a comparison of key features for these selected power supplies. Tables 4.1.4-4 and 4.1.4-5 below show the total estimated weight for each power supply selection.
Table 4.1.4-3: Key variables for selected power supply options

<table>
<thead>
<tr>
<th>Motor Options</th>
<th>Brand</th>
<th>Model</th>
<th>Weight (kg)</th>
<th>Power (kW)</th>
<th>Angular Velocity (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Motors</td>
<td>KDE Direct</td>
<td>KDE8218XF-120</td>
<td>0.845</td>
<td>2.041</td>
<td>5780.000</td>
</tr>
<tr>
<td>Gas Engine</td>
<td>Compact Radial</td>
<td>MZ201</td>
<td>31.000</td>
<td>35.109</td>
<td>4700.000</td>
</tr>
</tbody>
</table>

Table 4.1.4-4: KDE Direct motors

<table>
<thead>
<tr>
<th>Weight Estimations</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotors</td>
<td>216.804</td>
</tr>
<tr>
<td>Fuselage</td>
<td>200.000</td>
</tr>
<tr>
<td>Crew</td>
<td>60.000</td>
</tr>
<tr>
<td>Motors (x4)</td>
<td>3.380</td>
</tr>
<tr>
<td>Total</td>
<td>480.184</td>
</tr>
</tbody>
</table>

Table 4.1.4-5: Radial Compact engine

<table>
<thead>
<tr>
<th>Weight Estimations</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotors</td>
<td>216.804</td>
</tr>
<tr>
<td>Fuselage</td>
<td>200.000</td>
</tr>
<tr>
<td>Crew</td>
<td>60.000</td>
</tr>
<tr>
<td>Engine</td>
<td>31.000</td>
</tr>
<tr>
<td>Total</td>
<td>507.804</td>
</tr>
</tbody>
</table>

Flight calculations, which can be seen in Table 4.1.4-6, were done with both power supplies. Calculations included power loading, thrust loading, and disk loading, lift, solidity, tip velocity and coefficient of thrust [18, 19, 20]. These calculations were done assuming hover conditions. Additionally, calculations were done to find the optimum radius for the rotors. From this data, it is clear that both options would provide ample power to the aircraft. The final selection made for the power supply will be discussed in subsequent sections.

Table 4.1.4-6: Summary of calculations in hover

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>KDF Direct</th>
<th>Metric</th>
<th>Radial Compact</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loading</td>
<td>$PL = \frac{p}{A}$</td>
<td>318.612 W/m²</td>
<td>1851.810 W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrust Loading</td>
<td>$T = \frac{6.6359PL}{\omega - 0.3197}$</td>
<td>1.449 W/m²</td>
<td>0.839 W/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift for 1 engine</td>
<td>$L = \frac{T \omega}{LP}$</td>
<td>8251.730 kg</td>
<td>27758.796 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Lift</td>
<td>$L_{\text{rot}} = L_{\text{no rot}}$</td>
<td>33006.920 kg</td>
<td>27758.796 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solidity</td>
<td>$\alpha = \frac{A_{\text{blade}}/A_{\text{disk}}}$</td>
<td>1.750</td>
<td>1.750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{\text{tip}}$</td>
<td>$V_{\text{tip}} = \alpha R$</td>
<td>6.096 m/s</td>
<td>23.876 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disk Loading</td>
<td>$DL = \frac{W_{\text{gross}}}{A}$</td>
<td>24.366 kg/m²</td>
<td>25.911 kg/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_T$</td>
<td>$C_T = \frac{W_{\text{pAV}}}{V_{\text{tip}}^2}$</td>
<td>0.656</td>
<td>0.045</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tot. Radius Opt</td>
<td>$R = \sqrt{\frac{W_{\text{gross}}DL}{2\rho \pi R}}$</td>
<td>2.385 m</td>
<td>2.385 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For 4 Rotors</td>
<td>$R = \frac{0.596 R}{4}$</td>
<td>0.596 m</td>
<td>0.596 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1.5 Materials

As with all aircraft design, a major concern is weight. The goal is to minimize the weight of the aircraft, being that the actual amount of lift that will be produced from the aerial screws is unknown. There are two primary components on the rotors to consider for material selection. The first is the internal structure, which would most likely involve filling the rotor area with a thermoplastic or foam, or creating a system of spars and ribs. The second is the skin. Several materials were considered, including some experimental materials, some commonly used materials, and some uncommon materials which offer potential trade-offs.

For the external structure (the skin), the primary consideration was an experimental metal recently discovered by scientist Nick Birbillis and the research teams at the University of New South Wales and Monash University. The new material is a magnesium-lithium alloy with a density of only 1.4 g/cm$^3$, which is 30% less dense than magnesium and 50% less dense than aluminum. Previously, engineers strayed away from magnesium because it corrodes easily and quickly. This team of researchers has manipulated the new alloy to be corrosion resistant, giving it vast new potential. Scientists and engineers are already discussing the possibility of this material revolutionizing fields like the automotive and aeronautics industries. Scientists believe this material will be cost effective, as it is relatively easy to produce and is composed of common materials. However, this material is not readily available for purchase.

Other materials considered include some aeronautic standards like aluminum 7075-T6 and carbon fiber. Aluminum 7075-T6 is one of the lighter and more cost effective materials used in the aeronautic industry. It has a density of 2.81 g/cm$^3$ and is only $4.19/kg. Carbon fiber, on the other hand, has a lower density of only 1.55 g/cm$^3$, but comes at a much higher price of
$140/kg. In this case, while carbon fiber is lighter, its trade-offs include durability and cost effectiveness.

Lastly, kevlar was considered as a skin material. Kevlar has a slightly lower density than that of carbon fiber, may be more durable, and comes at a significantly lower price tag. However, the aerodynamic properties are a concern with this material. There may be more skin friction drag present than with either of the other materials.

Ultimately, calculations for the skin were done with the magnesium-lithium alloy, the aluminum, and the kevlar. The results are shown in the table 4.1.5-3 below. Upon further analysis and modeling these options will be narrowed down further until one is chosen.

For the internal structure, two options were considered; a material filling the volume of the rotor blade, and a rib framework. Both options provide structural support for the rotor blades.

For filler material, there are two experimental materials that were examined. The first is 3D graphene. Recently, a team of scientists from MIT began experimenting with 2D graphene, wondering if there was a way to make the material more useful. What they created was a sponge-like 3D model that boasted a density of only 5% that of steel and was 10 times as strong. It turns out, while the results were astounding, they were also applicable to materials better suited to specific purposes. The strength of the structure had more to do with geometry than the actual material being used [21]. One of the final rotor blade options did include the use of this structure simply for its low density and high strength. This material would be difficult to use as it has to be 3D printed, due to the complexity of the structure.

The other experimental material examined was metallic microlattice. This material was found to be the world’s lightest material, with a density of 0.9 mg/cm³, which is less than any
aerogel or ultralight foam to date. This structure is 99% air, and yet exhibits extraordinary strength and energy absorption [22]. One concern is that this material is able to compress to half of its volume, which could be an unwanted characteristic as a structural support in the rotor blades. Finally, although this material is currently being used by both Boeing and GM, it is not currently available for purchase by the public, eliminating it as a viable option at this time.

Another design alternative was considered for the internal structure, one with an internal skeletal system, or ribbing. For this design structure, given that each rotor blade will have a solidity greater than 1, ribs will be included in increments of 0.25. For example, a rotor blade with a solidity of 1.5 will contain 5 ribs (this excludes the start and end points). For initial sizing purposes, the ribs are estimated to be hollow rods with a radius of 13 mm and a thickness of 6 mm. The rods will extend from the shaft to the leading edge of the rotor wing, which will be roughly 610 mm. Many of the same materials considered for the skin were considered for the ribs, including the magnesium-lithium alloy and the aluminum. In addition, Titanium 6AL-4V was considered.

Titanium is slightly heavier than aluminum. However, it is much stronger than its counterpart. It also comes at a much higher price tag. Calculations for the ribs were done for all three materials in this case. Tables 4.1.5-1 and 4.1.5-2 below show the densities, weights, and costs of each material discussed in this section. In addition Table 4.1.5-3 shows the comparisons between certain combinations of materials that were considered.
Table 4.1.5-1: Material densities and weights

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Mass Density (g/cm³)</th>
<th>Mass Density (g/cm³)</th>
<th>Skin Weight (lb)</th>
<th>Skin Weight (lb)</th>
<th>Rib Weight (lb)</th>
<th>Rib Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Graphene</td>
<td>Internal</td>
<td>0.0071</td>
<td>0.0071</td>
<td>6.822</td>
<td>6.822</td>
<td>3.015</td>
<td>3.015</td>
</tr>
<tr>
<td>Metallic Microbatte</td>
<td>Internal</td>
<td>0.006</td>
<td>0.006</td>
<td>5.945</td>
<td>5.945</td>
<td>2.015</td>
<td>2.015</td>
</tr>
<tr>
<td>Magnesium Lithium Alloy</td>
<td>Internal</td>
<td>0.0312</td>
<td>0.0312</td>
<td>68.422</td>
<td>68.422</td>
<td>21.055</td>
<td>21.055</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>External</td>
<td>0.0056</td>
<td>0.0056</td>
<td>12.399</td>
<td>12.399</td>
<td>22.115</td>
<td>22.115</td>
</tr>
<tr>
<td>Aluminum 7075-T6; T651</td>
<td>Internal</td>
<td>0.301</td>
<td>0.301</td>
<td>99.155</td>
<td>99.155</td>
<td>12.399</td>
<td>12.399</td>
</tr>
<tr>
<td>Titanium 6AL-4V</td>
<td>Internal</td>
<td>0.261</td>
<td>0.261</td>
<td>146.642</td>
<td>146.642</td>
<td>16.565</td>
<td>16.565</td>
</tr>
<tr>
<td>Kevlar</td>
<td>Internal</td>
<td>0.051</td>
<td>0.051</td>
<td>4.572</td>
<td>4.572</td>
<td>51.605</td>
<td>51.605</td>
</tr>
</tbody>
</table>

Table 4.1.5-2: Material costs

<table>
<thead>
<tr>
<th>Material</th>
<th>Use</th>
<th>Avg. Cost/ε</th>
<th>Total Skin Cost</th>
<th>Total Vol. Cost</th>
<th>Total Rib Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Graphene</td>
<td>Internal</td>
<td>$50.00</td>
<td>$150.42</td>
<td>$1,908.66</td>
<td>N/A</td>
</tr>
<tr>
<td>Metallic Microbatte</td>
<td>Internal</td>
<td>Unknown</td>
<td>$41,111.11</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Magnesium Lithium Alloy</td>
<td>External</td>
<td>$2.40</td>
<td>$59.54</td>
<td>$649.63</td>
<td>$7.78</td>
</tr>
<tr>
<td>Carbon Fiber</td>
<td>External</td>
<td>$140.00</td>
<td>$3,264.01</td>
<td>$343,378.52</td>
<td>$502.68</td>
</tr>
<tr>
<td>Aluminum 7075-T6; T651</td>
<td>External</td>
<td>$4.19</td>
<td>$177.87</td>
<td>$2,244.92</td>
<td>$27.77</td>
</tr>
<tr>
<td>Titanium 6AL-4V</td>
<td>Spars</td>
<td>$21.03</td>
<td>$1,409.93</td>
<td>$17,759.13</td>
<td>$213.78</td>
</tr>
<tr>
<td>Kevlar</td>
<td>External</td>
<td>$26.46</td>
<td>$573.02</td>
<td>$2,263.60</td>
<td>$88.25</td>
</tr>
</tbody>
</table>

Table 4.1.5-3: Cost and weight analysis for specified material selections

<table>
<thead>
<tr>
<th>Case</th>
<th>External Material</th>
<th>Internal Material</th>
<th>Rib</th>
<th>Total Weight (lb)</th>
<th>Total Cost</th>
<th>TW; ALL ROTORS</th>
<th>TC; ALL ROTORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>Mag. 3rd. Alloy</td>
<td>3D Graphene</td>
<td>Mag. 3rd. Alloy</td>
<td>42.95</td>
<td>$1,916.46</td>
<td>73.79</td>
<td>$7,065.82</td>
</tr>
<tr>
<td>Typical</td>
<td>Aluminum</td>
<td>N/A</td>
<td>Titanium</td>
<td>32.39</td>
<td>$245.69</td>
<td>49.42</td>
<td>$974.75</td>
</tr>
<tr>
<td>Other</td>
<td>Kevlar</td>
<td>N/A</td>
<td>Aluminum</td>
<td>7.72</td>
<td>$43.21</td>
<td>10.88</td>
<td>$173.24</td>
</tr>
</tbody>
</table>

4.1.6 TOPSIS Analysis:

TOPSIS analysis was used to analyze various combinations of materials and power supplies. TOPSIS Analysis is a Multi Criteria Decision Making Analysis (MCDM) tool which evaluates criteria in order to specify an “Ideal” solution. The criteria used to formulate the decision matrix includes components and aspects of those components which play a role in the performance of the helicopter. For this particular project, weight, cost, and performance play a major role in the selections of materials used. Below in Table 4.1.6-1 the initial criteria matrix is shown showing the combinations analyzed and the criteria by which they are compared.
Table 4.1.6-1: Initial Criteria Matrix

<table>
<thead>
<tr>
<th>Power Supply &amp; Rotor Material Combination</th>
<th>Motor Cost (USD)</th>
<th>Power to Weight Ratio</th>
<th>Motor Weight (kg)</th>
<th>Angular Velocity (RPM)</th>
<th>Ribs Mass Density (g/cm³)</th>
<th>External Mass Density (g/cm³)</th>
<th>Total Weight All Rotors (kg)</th>
<th>Total Cost All Rotors (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KDE Direct Material Scenario 1</td>
<td>2387.80</td>
<td>2.42</td>
<td>3.38</td>
<td>5790</td>
<td>4.45</td>
<td>2.81</td>
<td>57.105</td>
<td>1006.93</td>
</tr>
<tr>
<td>KDE Direct Material Scenario 2</td>
<td>2387.80</td>
<td>2.42</td>
<td>3.38</td>
<td>5790</td>
<td>2.401</td>
<td>2.44</td>
<td>54.825</td>
<td>277.38</td>
</tr>
<tr>
<td>Compact Radial Material Scenario 1</td>
<td>5560.00</td>
<td>1.07</td>
<td>51</td>
<td>4700</td>
<td>4.45</td>
<td>2.81</td>
<td>57.105</td>
<td>1006.93</td>
</tr>
<tr>
<td>Compact Radial Material Scenario 2</td>
<td>5560.00</td>
<td>1.07</td>
<td>51</td>
<td>4700</td>
<td>2.801</td>
<td>1.44</td>
<td>34.823</td>
<td>277.38</td>
</tr>
</tbody>
</table>

The weightage for each category was determined based on this project's design specifically, and illustrates which categories the team believes will most impact the helicopter designs success.

The material scenarios in the left side of the table is further detailed below.

**Material Scenario 1**
- Aluminum Skin/External
- Titanium Ribs

**Material Scenario 2:**
- Kevlar Skin/External
- Aluminum Ribs

Below are the equations required for formulating the Normalized Matrix and the Weighted Normalized Matrix. Tables 4.1.6-2, 4.1.6-3, and 4.1.6-4 are shown below with the correlating equations from which the matrix was programmed.

(Eq. 4.1.6-1)

$$
\bar{X}_{y} = \frac{X_{y}}{\sqrt{\sum_{i=1}^{n} X_{y}^{2}}}
$$
### Table 4.1.6-2: Normalized Matrix

<table>
<thead>
<tr>
<th>Normalized Matrix</th>
<th>Motor Cost (USD)</th>
<th>Power to Weight Ratio</th>
<th>Motor Weight (kg)</th>
<th>Angular Velocity (RPM)</th>
<th>Rib Mass Density (g/cm³)</th>
<th>External Mass Density (g/cm³)</th>
<th>Total Weight All Rotors (kg)</th>
<th>Total Cost All Rotors (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KDE Direct Material Scenrio 1</td>
<td>0.2790039071</td>
<td>0.04671211369</td>
<td>0.0766432264</td>
<td>0.5480564385</td>
<td>0.337661773</td>
<td>0.62921931951</td>
<td>0.6037115408</td>
<td>0.6817140179</td>
</tr>
<tr>
<td>KDE Direct Material Scenrio 2</td>
<td>0.2790039071</td>
<td>0.04671211369</td>
<td>0.0766432264</td>
<td>0.5480564385</td>
<td>0.337661773</td>
<td>0.62921931951</td>
<td>0.6037115408</td>
<td>0.6817140179</td>
</tr>
<tr>
<td>Compact Radial Material Scenrio 1</td>
<td>0.64977245869</td>
<td>0.2889429782</td>
<td>0.7028408338</td>
<td>0.4456464408</td>
<td>0.537661773</td>
<td>0.62921931951</td>
<td>0.6037115408</td>
<td>0.6817140179</td>
</tr>
<tr>
<td>Compact Radial Material Scenrio 2</td>
<td>0.64977245869</td>
<td>0.2889429782</td>
<td>0.7028408338</td>
<td>0.4456464408</td>
<td>0.537661773</td>
<td>0.62921931951</td>
<td>0.6037115408</td>
<td>0.6817140179</td>
</tr>
</tbody>
</table>

### Table 4.1.6-3: WeightedNormalized Matrix

<table>
<thead>
<tr>
<th>Weighted Normalized Matrix</th>
<th>Motor Cost (USD)</th>
<th>Power to Weight Ratio</th>
<th>Motor Weight (kg)</th>
<th>Angular Velocity (RPM)</th>
<th>Rib Mass Density (g/cm³)</th>
<th>External Mass Density (g/cm³)</th>
<th>Total Weight All Rotors (kg)</th>
<th>Total Cost All Rotors (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KDE Direct Material Scenrio 1</td>
<td>0.05580618141</td>
<td>0.12932424313</td>
<td>0.013328164528</td>
<td>0.05489884385</td>
<td>0.02988303858</td>
<td>0.03146444599</td>
<td>0.062921931951</td>
<td>0.06537115408</td>
</tr>
<tr>
<td>KDE Direct Material Scenrio 2</td>
<td>0.05580618141</td>
<td>0.12932424313</td>
<td>0.013328164528</td>
<td>0.05489884385</td>
<td>0.02988303858</td>
<td>0.03146444599</td>
<td>0.062921931951</td>
<td>0.06537115408</td>
</tr>
<tr>
<td>Compact Radial Material Scenrio 1</td>
<td>0.1299448734</td>
<td>0.05718859559</td>
<td>0.1405881668</td>
<td>0.0456464409</td>
<td>0.02988303858</td>
<td>0.03146444599</td>
<td>0.062921931951</td>
<td>0.06537115408</td>
</tr>
<tr>
<td>Compact Radial Material Scenrio 2</td>
<td>0.1299448734</td>
<td>0.05718859559</td>
<td>0.1405881668</td>
<td>0.0456464409</td>
<td>0.02988303858</td>
<td>0.03146444599</td>
<td>0.062921931951</td>
<td>0.06537115408</td>
</tr>
</tbody>
</table>

### Table 4.1.6-4: Ideal Best/ Ideal Worst Matrix

| Ideal Best: V+ | 0.05580618141 | 0.12932424313 | 0.013328164528 | 0.0456464409 | 0.02988303858 | 0.03146444599 | 0.062921931951 | 0.06537115408 |
| Ideal Worst: V− | 0.1299448734 | 0.05718859559 | 0.1405881668 | 0.0456464409 | 0.02988303858 | 0.03146444599 | 0.062921931951 | 0.06537115408 |

(Eq 4.1.6-2)

**Calculating the Performance Score**

\[ P_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \]
From the results of the TOPSIS analysis, it has been concluded that according to the Ideal criteria, the KDE Direct Electric Motors paired and the Material Scenario 2 best fit the teams goal criteria. The performance score was .936, with the nearest competitive option being the KDE Direct Electric Motors with Material Scenario 1 having a performance score of .7279. Based on these results the team can know what power supply and materials for the rotor best fit the teams design for a successful helicopter.
4.2 Calculations

4.2.1 Weight Calculations

Before diving into flight calculations, the gross weight of the rotorcraft was calculated. While this has been briefly mentioned in the preceding sections, this section will provide a more thorough walkthrough of the process by which the gross weight was obtained.

Initially, the team had to decide on the size, shape and material of the rotor, as previously discussed. Once those components had been finalized, by finding the surface area of the rotor blade and the cross-sectional areas where the ribs would be placed the weight for each component was calculated. The surface and cross-sectional areas were provided by SolidWorks from the created model, however these could have been found using the standard calculus equations for area and surface area if other resources had not been available. These areas were multiplied by the corresponding material weights and summed together to obtain a gross weight for a single rotor. The value obtained was then multiplied by four to account for all rotors in the system.

In addition to the weight of the four rotor structures, the weight for the fuselage, motors, batteries, controls, and payload were summed together to obtain the gross weight.

4.2.2 Hover Calculations

The calculations done for this rotorcraft design were based on the specifications previously discussed and will be summarized in subsequent sections. From these specifications and the gross weight previously found, a series of calculations were done to assess the
performance in hover conditions. To ensure accuracy, all calculations were initially done by hand then redone using Excel.

The first of these calculations found the total power available from the motors. The total power was found by multiplying the power output specification given by KDE Direct by the number of rotors \( n \) the design contained. This value was then multiplied by 0.8 to account for any power losses. This is shown as Equation 4.2.2-1 below.

\[
P_{\text{avail}} = P_{\text{spec}}(n)(0.8)
\]

KDE Direct also provided a document of recorded motor performance data. Within this document was a compilation of thrust values given for specific aircraft parameters. From this source, it was determined that the maximum amount of thrust that the rotorcraft could produce would be 723.32 kg [17]. Using this value and the value obtained for gross weight, the thrust to weight ratio was calculated. This is a crucial calculation as for helicopters, a thrust to weight ratio greater than one indicates the ability to hover.

From the provided motor specifications the value for angular velocity \( \Omega \) was obtained. By multiplying this value by the radius of the rotors \( R \), the maximum tip velocity was determined. This calculation was done using Equation 4.2.2-2 below.

\[
V_{\text{tip}} = \Omega * R
\]
From the power available \((P_{\text{avail}})\) and the total area of all rotors \((A_{\text{allRot}})\), the power loading \((PL)\) for each rotor was found. The equation for power loading is given by Equation 4.2.2-3 below [19].

\[
PL = \frac{P_{\text{avail}}}{A_{\text{allRot}}}
\]

(Eq. 4.2.2-3)

A simple next step was to find the thrust loading \((TL)\). The relationship between power loading and thrust loading is shown in Equation 4.2.2-4 below [19].

\[
TL = 8.6859 \times PL^{-0.3107}
\]

(Eq. 4.2.2-4)

Using the values obtained from Equation 4.2.2-4 for thrust loading and Equation 4.2.2-1 for power available the lift generated by each rotor was calculated. This value was then multiplied by the number of rotors to yield the total amount of lift \((L)\) generated by the rotorcraft. The equation used to find this value is shown in Equation 4.2.2-5 below [19].

\[
L = TL \times P_{\text{avail}} \times n
\]

(Eq. 4.2.2-5)
Equation 4.2.2-6 below shows the calculation done to find the disk loading (DL). The disk loading is defined to be the ratio of thrust to the area of all rotors. In hover, thrust is equal to weight, thus for this calculation the gross weight was used in place of the thrust [9].

\[ DL = \frac{T}{A_{allRot}} = \frac{W_{gross}}{A_{allRot}} \]  

(Eq. 4.2.2-6)

Calculations were then done to find both the coefficient of thrust \( (C_T) \) and the coefficient of power \( (C_p) \). The equations used for these calculations are given by Equation 4.2.2-7 and Equation 4.2.2-8 [9].

\[ C_T = \frac{W}{\rho AV_{tip}^2} \]  

(Eq. 4.2.2-7)

\[ C_p = \frac{C_T^{3/2}}{\sqrt{2}} \]  

(Eq. 4.2.2-8)
The figure of merit (FM) was calculated to assess the efficiency of the rotors and is the ratio of ideal power to actual power. The equation used to calculate this value is given by Equation 4.2.2-9 below [9].

\[
FM = \frac{P_{\text{ideal}}}{P_{\text{actual}}}
\]  

(Eq. 4.2.2-9)

The induced velocity \( (v_i) \) in hover was calculated using Equation 4.2.2-10 below [9]. For this equation standard density at sea level was used as the rotorcraft will only fly at extremely low altitudes per its mission profile.

\[
v_i = \sqrt{\frac{T}{2\rho A_{\text{allRot}}}}
\]  

(Eq. 4.2.2-10)

A logical step from the induced velocity was to find the power required to hover, or ideal power \( (P_{\text{ideal}}) \). The ideal power can be found by simply multiplying the induced velocity by the thrust. This relationship is shown in Equation 4.2.2-11 below [9].

\[
P_{\text{ideal}} = T \times v_i
\]  

(Eq. 4.2.2-11)
Additionally, from the induced velocity, the induced inflow ratio ($\lambda_h$) was calculated by simply dividing the induced velocity by the tip speed. Equation 4.2.2-12 below was used for this calculation [21].

(Eq. 4.2.2-12)

$$\lambda_h = \frac{v_i}{V_{tip}}$$

Lastly, the maximum rate of climb ($V_{climb}$) was determined. This is calculated by dividing the excess lift by the gross weight. For this design, there is a significant amount of excess lift so it is expected that the maximum climb rate would be very high. The equation used to determine this value is shown in Equation 4.2.2-13 below.
This concluded the calculations done prior to selecting an airfoil. Further calculations based on airfoil selection are discussed in a subsequent section.

4.2.3 Forward Flight Calculations

The following calculations are an estimate of the expected behavior of the aircraft. For forward flight calculations a freestream velocity of 4.500 m/s was chosen and the angle of attack was measured to be 4.6 degrees. Using this information the advance ratio (μ) was calculated using Equation 4.2.3-1 below [9].

\[ \mu = V_{\infty} \cdot \cos \left( \frac{\alpha}{V_{\text{tip}}} \right) \]  

(Eq. 4.2.3-1)

Using the induced velocity found for hover conditions and the angle of attack the induced velocity for forward flight was calculated. This calculation was done using Equation 4.2.3-2 below. In this equation \( v_i \) is the induced velocity for forward flight and \( v_h \) is the induced velocity for hover [9].

\[ v_i = \frac{v_h^2}{\sqrt{(V_{\infty} \cos \alpha)^2 + (V_{\infty} \sin \alpha + v_h)^2}} \]

(Eq. 4.2.3-2)
Using the freestream velocity, angle of attack, induced velocity, and tip speed the inflow ratio ($\lambda$) was calculated. Equation 4.2.3-3 was used for this calculation [9].

\[
\lambda = \frac{V_{\infty} \cos(\alpha + v_i)}{V_{tip}}
\]

Having a value for the forward flight induced velocity also enabled the ability to calculate thrust. Using Equation 4.2.3-4 below, a value for thrust in forward flight was obtained [9].

\[
T = 2\rho Av_i \sqrt{(V_{\infty} \cos \alpha)^2 + (V_{\infty} \sin \alpha + v_i)^2}
\]

Finally, from the thrust, freestream velocity, angle of attack, and induced velocity, the power required for forward flight was calculated. The equation used is given by Equation 4.2.3-5 below [9].

\[
P = TV_{\infty} \sin \alpha + Tv_i
\]

It is important to note that due to the experimental nature of the helical rotor and the data required, the forward flight calculations were considered unreliable for the rotorcraft. It would be difficult, if not impossible, to gather all data components without a physical model as those values are typically found empirically through historical data or wind tunnel testing.

Additionally, these calculations were intended to apply to multi-blade systems with a much lower solidity with blades that share the same plane of motion. The team also attempted
the use of equations for coaxial rotors to predict behavior, however, these also proved to be unreliable. The fact that the experimental rotor is a single, continuous spiral, led to unexpected interactions with the air. Its behavior combined actions where the rotor was chopping through air or alternately capturing and funneling the air downwards. An alternative approach to finding other variables would be to use quadcopter physics to explain forward flight dynamics. This paper will not discuss quadcopter physics, but there are many good resources publically available for those that wish to know more [25].

4.2.4 Airfoil Calculations

The following calculations were done with the rotors modeled with the NACA 0006 airfoil. For a specific airfoil, my parameters are obtained through historical data, such as the coefficients of lift and drag, the lift to drag ratio. In order to accurately estimate any values from the graphs which depict the historical data however, the reynold’s number (Re) had to be computed. This was done using equation 4.2.4-1 below. In this equation, \( \nu \) represents the kinematic viscosity of air which is \( 1.48 \times 10^{-5} \) m\(^2\)/s.

\[
Re = \frac{Vc}{\nu}
\]

(Eq. 4.2.4-1)

The values obtained from historical data allowed further calculations to be done. Using the coefficient of drag \( C_d \), the drag (D) was calculated using Equation 4.2.4-2 below.

(Eq. 4.2.4-2)
\[ D = \frac{1}{2} \rho A V^2 C_d \]

Using equation 4.2.4-3 below, the profile power \( (P_0) \) was calculated. The following is a list identifying the new variables in this equation: \( N_b \) is the number of blades, \( c \) is the chord, and \( C_{d0} \) is the zero drag lift coefficient. All other variables have been previously identified.

\[ P_0 = \frac{1}{8} \rho N_b \Omega^2 c C_{d0} R^4 \]

Equations 4.2.4-4 and 4.2.4-5 below show the equations used to find the profile power coefficient \( (C_{p0}) \) and induced power coefficient \( (C_{pi}) \) respectively [9].

\[ C_{p0} = \frac{1}{8} \sigma C_{d0} \]

\[ C_{pi} = C_p - C_{p0} \]

The final calculation done with the airfoil data was the induced power factor \( (\kappa) \). The equation used is shown in Equation 4.2.4-6 below [9].

\[ \kappa = \frac{C_{pi} \sqrt{2}}{C_{T}^{2/3}} \]

4.2.5 Propulsion Calculations

Much of the information used was obtained from the KDE Direct website as they not only provide the specifications for their motors, but they also provide performance data for a
wide range of rotor parameters. This left the team with little to do in the realm of propulsion, however, calculations were performed to ensure that the data being used was correct.

Using the motor velocity constant (Kv), the resistance (R), and the voltage supplied by the chosen battery (V), and the maximum continuous current (I) the maximum angular velocity was determined. Equation 4.2.5-1 below shows the equation used for this calculation [26].

\[
\Omega = Kv(V - IR)
\]

(Eq. 4.2.5-1)

The torque was calculated using the motor torque constant (Kt), the current at the desired throttle position, and the no load current. The calculation was done using equation 4.2.5-2 below.

\[
Q = Kt(I - I_0)
\]

(Eq. 4.2.5-2)

The relationship between Kv and Kt was also confirmed. There is an established relationship between these two parameters such that their product should be equal to 1352. This relationship is shown in equation 4.2.5-3 below. In this equation Kt is measured in RPM/volt and Kv is measured in in-oz.

\[
KvKt = 1352
\]

(Eq. 4.2.5-3)

Finally the motor efficiency (\(\eta\)) was found using equation 4.2.5-4 below. Recall here that \(C_T\) is the coefficient of thrust and \(\mu\) is the advance ratio previously calculated.

\[
\eta = \frac{2}{1 + \sqrt{1 + \frac{8C_T}{\pi\mu}}}
\]

(Eq. 4.2.5-4)
4.3 Modeling

4.3.1 Quadcopter Assembly

Following the reduction in rotor size, the quadcopter assembly’s frame reduced considerably in size, as seen in Figure 4.3.1-1 below. Cyclic and collective pitch controls were selected as the main pilot control components and added to the assembly. These controls can be applied to both traditional helicopter maneuverability and electrical system controls. Internal mechanisms for the controls, any electrical wiring, and the aircraft’s power sources are housed in the rectangular section of the body located directly below the seat.

![Assembly size reduction: before (left) and after (right)](image)

Figure 4.3.1-1: Assembly size reduction: before (left) and after (right)

The initial design included cowlings around each rotor. However, after sufficient calculation and CFD analysis of the rotors, it was found that they were capable of producing sufficient thrust without the addition of the cowling. Seeing that each cowling added an extra 30 kg of weight and additional thrust was not necessary, they were removed from the design.
KDE Direct’s web page for the KDE8218XF-120 [17] provided a scale model of the motor (shown in Figure 4.3.1-2), which was implemented under each rotor in the assembly. The motor model’s material was adjusted so that its overall mass reflected the 845 g listed on its specifications (which includes estimations for the wiring).

4.3.2 Assembly Weight

Figure 4.3.2-1: Calculated Assembly Mass
The material of each component was selected to match the materials chosen in the design calculations. The body, landing rails, controller shafts, rotor shaft, and rotor ribs were input as 7075-T6 Aluminum alloy. For the sake of weight reduction, the seat was input as a lightweight ABS plastic.

This brought the assembly’s overall mass to approximately 422 kg (shown in Figure 4.3.2-1), which is within 2 kg of the estimated aircraft mass of 420.184 kg found in the hand calculations. After adding the 60 kg passenger mass requirement and converting to kilo-Newton, the overall flight weight was found to be 4.71 kN, which is well below the 8.96 kN overall lift found in the hand calculations. This surplus of available thrust verifies the current aircraft model is capable of both vertical and forward flight.

Also worth noting is the calculated center of mass found in the assembly is centered just below the seat. With the addition of the passenger, it will shift upwards and slightly to the back of the aircraft. This final center of mass location provides balance, and with proper controls in place the quadcopter will be capable of stable, maneuverable flight.
Chapter 5

5.1 Results and Discussion

5.1.1 Final Component Selections

Materials Selection

As previously discussed, a substantial amount of time went into materials research. Experimental and uncommon materials as well as standard aircraft materials were analyzed. Ultimately, the team decided to use a kevlar skin and aircraft grade aluminum for the internal support structures such as ribs and struts. A few of the many criteria considered included availability, cost, and weight. Other preliminary factors were considered such as the strength of the material, however all options selected for further analysis were capable of withstanding the stress of flight.

Upon analysis, the experimental materials were too hard to obtain, came at a very steep price, and ultimately added unnecessary weight. While aluminum is a standard skin material used in aircraft, it was significantly heavier than the kevlar, and in combination with the titanium ribs and spars came out to be much more expensive than the kevlar aluminum combination. The strength of the rotors ended up being a less important aspect as the mission profile for this rotorcraft is limited to extremely short, low altitude flights at low speeds where damage is unlikely to occur.
The overall weight of the kevlar and aluminum combination came to 30.886 kg and cost $173.24. The comparisons to other materials was shown in Tables 4.1.4-1, 4.1.4-2, and 4.1.4-3 previously.

**Table 5.1.1-1: Total weight and cost estimates for final material selections**

<table>
<thead>
<tr>
<th>Case</th>
<th>External Material</th>
<th>Ribs</th>
<th>Weight/rotor (kg)</th>
<th>Cost/Rotor</th>
<th>Total Weight</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 3</td>
<td>Kevlar</td>
<td>Aluminum</td>
<td>7.722</td>
<td>$43.31</td>
<td>30.886</td>
<td>$173.24</td>
</tr>
</tbody>
</table>

Power Supply Selection

The two power supply options discussed were the Compact Radial MZ201 and the KDE8218XF-120. While both of these options provided more than enough power as discussed previously, the team decided to use the four electric motors instead of the gas engine. The power output from the gas engine was much greater than that of the four combined electric motors, which already provided more than enough power. In addition, the Compact Radial MZ201 added a significant amount of weight to the design and provided little benefit for that addition. The comparison between the two power supply options was previously shown in Table 4.1.3-3.
Airfoil Selection

After several iterations and modeling, the team decided to implement a modified NACA 0006 airfoil for the rotor. A plot of the airfoil can be seen in Figure 5.1.1-1. Compared to asymmetrical (cambered) airfoils, symmetrical airfoils are less complicated in design while still generating acceptable performance under a wide range of attack angles and airspeeds [7]. Moreover, design simplicity lowers manufacturing cost. A drawback of symmetrical airfoils is their lower lift production, but due to the multirotor configuration and substantial powerhouse capabilities of the final design, this was not an issue. Undesirable stall characteristics at certain speeds was another con of symmetrical airfoils, but again not an issue here. The thickness of this NACA airfoil provided enough interior room for ribs and spars once the chord length was modified to match the desired rotor diameter. This was achieved with nominal increase in rotor surface area.

![Plot of NACA 0006 airfoil](image)

*Figure 5.1.1-1: Plot of NACA 0006 airfoil*

5.1.2 Results of Analytical Calculations

Final Size and Weight Calculations

After extensive analysis through both calculations and simulations, the size and weight values were determined. The rotor was selected to have a radius of 0.305 meters with a rotor
shaft of 0.013 meters at the center. A solidity of 1.500 was also selected. This yielded a blade area of 17.206 square meters per rotor. The ribs and spars were found to have an overall volume of 0.001 cubic meters per rotor. Table 5.1.2-1 below shows a summary of the final basic sizing calculations.

Table 5.1.2-1: Final sizing calculations

<table>
<thead>
<tr>
<th>Estimated/Calculated Data</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Radius</td>
<td>12.000</td>
<td>0.305</td>
</tr>
<tr>
<td>Rotor Shaft Radius</td>
<td>0.500</td>
<td>0.013</td>
</tr>
<tr>
<td>Solidity</td>
<td>1.500</td>
<td>1.500</td>
</tr>
<tr>
<td>Rotor Blade Area</td>
<td>677.406</td>
<td>17.206</td>
</tr>
<tr>
<td>No. Rotors</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Thickness of shell material</td>
<td>0.125</td>
<td>0.003</td>
</tr>
<tr>
<td>No. Ribs</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Rib Volume*</td>
<td>31.408</td>
<td>0.001</td>
</tr>
</tbody>
</table>

After sizing, material, and component selection was finalized, the weight was calculated. Included in the weight calculations were the weight of the rotors, fuselage, motors, batteries, control systems, and the required payload of 60 kilograms. The total weight was simply the summation of these components and came to 325.823 kilograms. Table 5.1.2-2 below shows the breakdown of the component weights followed by the total gross weight.

Table 5.1.2-2: Component weight breakdown and total gross weight.

<table>
<thead>
<tr>
<th>Weight Estimations</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotors</td>
<td>34.823</td>
</tr>
<tr>
<td>Fuselage</td>
<td>200.000</td>
</tr>
<tr>
<td>Crew</td>
<td>60.000</td>
</tr>
<tr>
<td>Motors (x4)</td>
<td>3.380</td>
</tr>
<tr>
<td>Battery (x4)</td>
<td>3.804</td>
</tr>
<tr>
<td>Controls</td>
<td>9.071</td>
</tr>
<tr>
<td>Total</td>
<td>311.078</td>
</tr>
</tbody>
</table>
Hover Calculations

Once the power source selection was finalized, along with the sizing, material and component selection previously mentioned, the hover condition calculations were performed. In this section the performance variables will be discussed as they relate rather than in order of how they were calculated as the process was discussed in a previous section.

One of the major performance variables focused on was power. From the motor specifications, the power available from the engine was found to be 6.531 kilowatts. This is the power output with the motor at 80% power. The power was adjusted to be utilized at 80% to account for any potential losses and to ensure that the rotorcraft would be capable of performing without the motor at its maximum capacity. It was also determined that the power required to hover, also referred to as ideal power, was 0.935 kilowatts.

Using values found for ideal and available power, the figure of merit for the rotorcraft was found to be 14.3%. This value is substantially lower than the average because much of the available power is not being used. While smaller motors could have been chosen, there was concern that the rotorcraft would not perform as expected due to its experimental nature and the fact that the equations being used were for standard helicopter configurations which are vastly different from this design. A figure of merit of 14.3% was deemed acceptable as the efficiency of the design was not the primary focus.

Several different load factors were computed for hover including power loading, thrust loading and disk loading. Their respective calculations resulted in values of 379.586 W/m², 1.372 W/m², and 4.520 kg/m². These values were all determined to be within an acceptable range.
The lift produced by a single rotor blade was determined to be 2.241 kN yielding a total lift for the system of 8.962 kN. This value was more than sufficient to perform the desired mission profile, however, there is some speculation as to whether or not this value is accurate as the simulation produced different results. These results will be discussed in a subsequent section, but it is important to mention that even though the simulation only produced roughly half the lift, it was still able to produce enough lift to perform the required tasks.

The maximum tip speed was found to be 29.362 m/s, however the simulated tip speed reached a maximum value of only about half this number. The simulated tip speed will be discussed in a subsequent section, but both tip speeds found were considered to fall within an appropriate range.

The coefficients of thrust and power were also calculated. These values were determined to be 0.021 and 0.002 respectively. It is evident that these values are much lower than they should be, however after going through calculations several times to optimize it, any realistic changes made led to values around these same numbers. It is also worth mentioning that using the simulated tip speed for the calculation produced higher values for the coefficients. These values were calculated at 0.084 for the coefficient of thrust and 0.017 for the coefficient of power. The team has theorized that equations for the tip speed and coefficients may be insufficient to accurately compute values for these parameters given the design differences presented by the use of aerial screws rather than rotors.

The other crucial performance variable that was determined was the thrust to weight ratio. From the performance data it was determined that the maximum amount of thrust that could be produced was 462.48 N. It was then found that for this rotorcraft the thrust to weight
ratio was 1.487. As previously stated, for a helicopter a thrust to weight value greater than one indicates the ability to hover, thus this value indicates that the rotorcraft is capable of sustained hover.

A few other minor performance variables were calculated including induced velocity, induced inflow ratio, and the maximum climb velocity. These values were determined to be 3.007 meters per second, 0.095, and 27.810 m/s respectively. These variables were primarily used to find other variables, but are important nonetheless. Additionally the value for maximum climb rate is very high given the mission profile, however, this was expected as there is a substantial amount of excess thrust. The climb velocity being used for the mission profile was set to be 2.32 meters per second.

Lastly, the rotor radius was optimized. The optimal value was found to be 0.293 meters, however, this was not the rotor radius selected because the output of the optimization equation would continually change as the other variables changed. The 0.305 meter radius was chosen as it and the optimization value were closest at this point. A summary of all variables, equations and results can be seen in Table 5.1.2-3 below.
Table 5.1.2-3: Summary of all variables, equations, and results for hover conditions

<table>
<thead>
<tr>
<th>Hover Calculations</th>
<th>Equation</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Available</td>
<td>$P_{avail} = power \ (in \ Watts)$</td>
<td>6531,200 W</td>
</tr>
<tr>
<td>Power Loading</td>
<td>$PL = power/4$</td>
<td>379,586 W/m²</td>
</tr>
<tr>
<td>Thrust Loading</td>
<td>$TL = 8.6559PL^{-0.3107}$</td>
<td>1.372 W/m²</td>
</tr>
<tr>
<td>Lift for 1 engine</td>
<td>$L = TL/power$</td>
<td>2240.538 N</td>
</tr>
<tr>
<td>Total Lift</td>
<td>$L_{tot} = L \times no. \ Rot.$</td>
<td>8962.230 N</td>
</tr>
<tr>
<td>Solidity</td>
<td>$a = a \ blade/a \ disk$</td>
<td>1.500</td>
</tr>
<tr>
<td>Tip speed</td>
<td>$V_{tip} = QR$</td>
<td>29.362 m/s</td>
</tr>
<tr>
<td>Disk Loading</td>
<td>$DL = W_{ gross} (4 \times No_Rot)$</td>
<td>4.520 kg/m²</td>
</tr>
<tr>
<td>Coefficient of Thrust</td>
<td>$C_I = W_{ipAV_{tip}}^p2$</td>
<td>0.021</td>
</tr>
<tr>
<td>Coefficient of Power</td>
<td>$C_P = (C_I \times 3/2) / SQRT(2)$</td>
<td>0.002</td>
</tr>
<tr>
<td>Figure of Merit</td>
<td>$FM = P_{ideal} / P_{actual}$</td>
<td>0.143</td>
</tr>
<tr>
<td>Induced Vel</td>
<td>$V_I = SQRT(T/2 \rho)$</td>
<td>3.007 m/s</td>
</tr>
<tr>
<td>Power Req. Hover/ideal Power</td>
<td>$P = T \times SQRT(2 \rho)$</td>
<td>392.92 m/s</td>
</tr>
<tr>
<td>Induced inflow ratio</td>
<td>$h_{ind} = v / QR$</td>
<td>0.095</td>
</tr>
<tr>
<td>Thrust/Weight ratio</td>
<td>$T/W = T_{max} / W_{gross}$</td>
<td>1.487</td>
</tr>
<tr>
<td>Max Thrust per Spec Sheet</td>
<td>$T_{max} = 115.62 \times no. \ Rot.$</td>
<td>462.48 N</td>
</tr>
<tr>
<td>Tot. Radius Optim.</td>
<td>$R = (SQRT(T_{w gross} DL \times 4 \times No_Rot)) / No_Rot$</td>
<td>0.293 m</td>
</tr>
<tr>
<td>Max Climb Rate</td>
<td>$V_{climb} = (W_{gross} / W_{gross})$</td>
<td>27.810 m/s</td>
</tr>
</tbody>
</table>

Forward Flight Calculations

For forward flight, it is important to note that the angle of attack of the rotors is 4.6 degrees and the rotorcraft is set to travel at a speed of 4.5 meters per second. Using this information the advance ratio was calculated at 4.445.

It was found that the power and thrust required to hover were 503.667 watts and 311.078 kg respectively. Both of these values are substantially lower than their respective available values indicating that the system would have enough power and thrust to sustain forward flight.

Other variables including the induced velocity and inflow ratio were also obtained. The values for these performance variables came out to be 6.091 meters per second and 0.146 respectively. The performance variables discussed in this section, along with their corresponding equations and results are summarized in Table 5.1.2-4 below.
Table 5.1.2-4: Summary of forward flight variables, equations, and results

<table>
<thead>
<tr>
<th>Forward Flight Calculations</th>
<th>Equation</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream Velocity</td>
<td>$V_{\infty}$</td>
<td>4.500 m/s</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>(\alpha)</td>
<td>4.600 deg</td>
</tr>
<tr>
<td>Advance Ratio</td>
<td>(m = V_{\infty} \cdot \cos(\alpha/V_{tip}))</td>
<td>4.445</td>
</tr>
<tr>
<td>Induced velocity</td>
<td>(ref\ [9] pg 95)</td>
<td>6.091 m/s</td>
</tr>
<tr>
<td>Thrust</td>
<td>(ref\ [9] pg 95)</td>
<td>311.078 N</td>
</tr>
<tr>
<td>Inflow ratio</td>
<td>(\lambda = V_{\infty} \cdot \sin(\alpha + V_i/V_{\infty}))</td>
<td>0.146</td>
</tr>
<tr>
<td>Power Required</td>
<td>(P = TV_{\infty} \cdot \sin(\alpha) + T \cdot V_i)</td>
<td>503.667 W</td>
</tr>
</tbody>
</table>

Airfoil Calculations

For calculations specific to the chosen airfoil, an angle of attack (\(\alpha\)) of 4.6 degrees was chosen and a Reynold’s number (Re) of 92675.676 was calculated. These values enabled the retrieval of historical airfoil data pertaining to the model. Figures 5.1.2-1 through 5.1.2-4 below show the graphs from which the airfoil data was pulled [27, 28].

Figure 5.1.2-1: Drag Polar

Figure 5.1.2-2: Lift coefficient vs angle of attack
With the selected angle of attack and calculated Reynold’s number, it was determined that the airfoil would most closely follow the orange plotted lines of the graphs. Using this information the values for the coefficients of lift and drag were obtained. Their values are estimated to be 0.53 and 0.025 respectively. The lift to drag ratio was estimated to be roughly 21, which when calculated from the estimated lift and drag ratios came out to be 21.2 proving the estimations were relatively accurate. The zero lift drag coefficient was also found to be 0.010.

Using the values obtained from the airfoil performance graphs, the drag coefficient was found to be 4.355. These values also permitted the team to determine the profile power and both the coefficient for profile power and induced power. The profile power was found to be 1.823 kilowatts, the profile power coefficient was found to be 0.002 and the induced power coefficient was found to be 0.001. This yielded an induced power factor of 0.019. The performance variables discussed in this section as well as their corresponding equations and results are summarized in Table 5.1.2-5 below [9].
Propulsion Calculations

The calculations done for the propulsion served as an audit for the performance data given by KDE Direct. Using the motor velocity constant (120 RPM/V), the motor torque constant (0.0796 Nm/A), the resistance (0.037 Ohms), and the voltage supplied by the battery (44.4 V), the maximum angular velocity was found to be 5199.24 RPM. This is slightly higher than the published maximum for similar conditions. It is theorized that the minor changes made to our system could have impacted this value slightly, but it still fell within an acceptable range to proceed.

The torque was found to be 2.173 Nm. This is quite a bit higher than the estimated maximum. After several attempts to rectify this without seeing any result, it was decided that while that is that maximum torque it was unlikely that the motors would ever experience this.
A check was done to ensure that the Kv and Kt values were accurate by comparing their product to the standard 1352 it should be. The calculated value came to 1352.677 yielding a percent error of only 0.05%.

Lastly, the efficiency of the motor was determined to be 49.97%. While this is slightly low, most motors are designed to perform anywhere between 50% and 100% efficiency, with many maxing out at only 75%. With 49.97% being so close to that range, it was determined that while low, this was an acceptable value as the efficiency was not a primary concern for this project. A summary of the performance variables and their corresponding equations and results can be seen in Figure 5.1.2-6 below.

**Table 5.1.2-6: Summary of variables, equations, and results for propulsion calculations**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Equation</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Velocity Constant</td>
<td>$K_v$ -- given</td>
<td>120 RPM/V</td>
</tr>
<tr>
<td>Motor Torque Constant</td>
<td>$K_t$ -- given</td>
<td>0.0796 Nm/A</td>
</tr>
<tr>
<td>Resistance</td>
<td>$\Omega$ -- given</td>
<td>0.037 $\Omega$</td>
</tr>
<tr>
<td>Applied Velocity</td>
<td>$V$ -- given</td>
<td>44.4 $V$</td>
</tr>
<tr>
<td>Angular Velocity (rpm)</td>
<td>$RPM = K_v(V - IR)$</td>
<td>5199.24 RPM</td>
</tr>
<tr>
<td>Torque</td>
<td>$Q = K_t(I - I_0)$</td>
<td>2.17308 Nm</td>
</tr>
<tr>
<td>KvKt</td>
<td>$K_v K_t (in-oz)$</td>
<td>1352.6772</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\eta = 2/[1 + \sqrt{(1 + 8C_{T/p} \mu \eta)}]$</td>
<td>49.97% N/A</td>
</tr>
</tbody>
</table>


Final Simulation Results

Having determined the sizing of the rotor, computational flow analysis was repeated for configurations of the model with varying angles of attack. The cut plot shown in Figure 5.1.2-5 shows the final configuration, which featured an effective angle of attack of 4.6 degrees, and an approximate mean chord length of 102 cm.

The trajectory lines illustrate a very symmetrical flow. A high velocity region is also shown in red just below the leading edge. This indicates that consistent lift is being generated near the top of the rotor. This is also shown in figure 5.1.2-6.

*Figures 5.1.2-5: Final rotor CFD analysis, side view*
**Figures 5.1.2-6: Final rotor CFD analysis, bottom view**

It must be noted that the nature of the simulation makes this red zone of lift appear asymmetrical across the rotors main axis. This is because the cut plots are of a single instant, not a continuous motion. Seeing that in practice the rotor will be rotating at a very high speed, this red lifting zone will create an even circle around the rotor’s main axis, and this implies stable, consistent lift. Additionally, when viewed from a top-down or bottom-up perspective, the lifting region does not intersect with the lower sections of the blade near the trailing edge. This implies that the downwash generated at the top of the rotor interacts minimally with the lower faces, further improving the overall lift capabilities.

An additional study was run simultaneously to the flow study which calculated the amount of vertical force being exerted on the blade surfaces, in order to find the instantaneous average lift. These results can be seen in the graph at the bottom of figure 5.1.2-8. They range as high as 6 kN, down to just 300 N. Hand calculations indicated a max lift of 2.24 kN per rotor.
Seeing that they are within the range of simulation, the simulations are found to be an acceptable form of experimental evidence.

Figures 5.1.2-7: Calculated Lift Force Plot

The rotor frame design was subjected to repeated stress analysis in order to determine its most critical locations and loads. It was found that the frame fails at 1.489 kN, at the connection of the shaft and the 3rd spar from the leading edge. This is shown in figure 5.1.2-8. With this information, it can be presumed that the frame is capable of producing 1.25 kN of force while maintaining a reasonable factor of safety (shown in figures 5.12-9). This results in a potential lift of 5 kN between the 4 rotors. Having found the calculated takeoff weight to be 3.05 kN, it was stated that the final assembly is capable of safely producing up to 1.95 kN of lift during flight operations.
Figures 5.1.2-8: Rotor frame stress plot at failure

Figures 5.1.2-9: Rotor frame stress plot at design load
Final Model Configuration

The final assembled model is shown in Figures 5.1.2-10. As previously stated, an X-style quadcopter configuration was selected for the body. Four rigid, fixed-pitch spiral rotors with a modified NACA 0006 airfoil were attached directly onto the motor shafts. Each pair of adjoining rotors are mirror images of each other, allowing them to rotate in opposite directions to cancel out torque.

The rotors were modeled by wrapping a NACA 0006 airfoil sketch around it’s shaft in a helical structure. The sketch can be viewed in Figure 5.1.2-11. The pilot seat was placed in the center of the body. Additional components include electrical systems such as the batteries. All electrical components (excluding the motors) are stowed away in a compartment below the seat, as shown in figure 5.1.2-12. Operation of the helicopter is executed via a cyclic and pitch control modified to operate with the electrical control interface. Finally, the design rotor assembly is shown in figure 5.1.2-13.

*Figure 5.1.2-10: Final aircraft assembly*
**Figure 5.1.2-11:** NACA 0006 airfoil wrapping process for modeling

**Figure 5.1.2-12:** Interior section view of final helicopter assembly base

**Figures 5.1.2-13:** Final design rotor assembly
5.2 Conclusions

The Blue Ninja Turtles team members have individually contributed countless hours of their time ensuring presented project material was innovative, had technical depth, and genuinely investigated the technical aspects of DaVinci’s aerial screw invention.

However, the project is far from perfect; If the team had more time and resources to expend on this project, or if another group wanted to continue this project, some subsequent work recommendations can be found below:

- Building a physical model of the helicopter for truly objective testing.
- Incorporating more safety components (seat belts, toe and knee guards for protection from rotors and debris, etc.).
- For future iterations, it would be rewarding to prepare the helicopter to the point it could be marketed as a kit helicopter. Preparation would include market research, a more extensive component selection in terms of flight controls and electrical components, physical testing in terms of structures, and airworthiness certification, among others.
- A future goal for this product would be to prepare the design to be marketable as a kit helicopter. Doing so would require further market research, a more extensive component selection process in terms of flight controls and electrical components, physical testing of structures, and obtaining an airworthiness certification.
References


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Appendices

Appendix A: Acknowledgements

As a team, we would like to express our gratitude to Dr. Adeel Khalid for the time and effort he has invested in each of us. Thank you, Dr. Khalid, for your contributions and guidance throughout our academic pursuits, including this project.

We would also like to extend our thanks to Professor Santana Roberts, whose continued direction and support was critical to our success throughout the solid modeling process.

Lastly, we would each like to express our overwhelming gratitude to our families for their endless support and encouragement throughout our academic career. We could not have done it without you.

Thank you!
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Appendix C: Reflections

Throughout this process, we were able to use valuable knowledge from each of our respective fields to bring a unique set of skills to this project. One of the challenges we faced was figuring out how to manage the project while displaying the unique abilities of each team member. We ended up dividing the work into three sub-areas which included calculations, computational analyses and modeling, and project management. Ultimately, this ended up working in our favor as the COVID-19 Pandemic hit.

The COVID-19 Pandemic forced each of us to isolate. While for many group projects, this would have been devastating, our compartmentalization at the beginning really helped us work through this issue. We would work individually for a week or so then reconvene to swap information and results. Using this method, we were able to successfully complete the tasks for this project.

This project has taught us a lot with respect to the difficulties of long term projects, time management, but it also showed us how much we have truly learned throughout our academic careers. It can often be daunting leaving school and trying to find a job. It is easy to focus on how unqualified you are or how much you do not know, but this project allowed us to pull knowledge from courses throughout our entire academic careers and challenged us to focus on what we do know.

Throughout the process we also gained new and equally valuable knowledge. Giving us more skills and projects to be proud of as we enter the workforce. As we reflect, we are thankful for the knowledge and skills we have learned and the challenges we have had to face because they made us into the engineers we are today.
Appendix D: Supporting Details and Documentation
Blade Solidity

\[ \lambda = \frac{V_{max}}{V_{tip}(AR)} \]

\[ V_{tip}(AR) = 75 \text{ mph} \]

\[ V_{tip}(AR) = 528 \text{ ft./min} \]

\[ \lambda = \frac{110 \text{ ft./sec}}{731.29 \text{ ft./sec}} = 0.150 \]

\[ \sigma = \frac{C_t}{BL} \]

\[ \frac{1}{\lambda} = \frac{V_{tip}(AR)}{V_{tip}(AR)} \]

\[ 110 \text{ ft./sec} \]

\[ \sigma = \frac{33.528 \text{ ft./sec}}{222.95 \text{ ft./sec}} \]

\[ \sigma = 0.150 \]

\[ \sigma = \text{Solidity} \]

\[ \frac{C_t}{BL} \]

\[ \text{from PDF} \]

\[ \text{Solidity} = \frac{\text{Blade area}}{\text{Disk area}} \]

\[ b = \# \text{ blades} \]

\[ C = \text{chord (longitudinal dimension of blade)} \]

\[ R = \text{radius of disk} \]

Assume that for a spiral blade, the chord is equal to the circumference of the disk.

\[ \sigma = \frac{bc}{\pi R} \]

\[ b = 1 \]

\[ C = 2\pi R \]

\[ R = R \text{ from (4)} \]

\[ \sigma = \frac{1(2\pi(2.75\pi))}{2(2.75\pi)} = 2 = \sigma \]

\[ \sigma \text{ from requirements; } \sigma \text{ has to be } 1 \text{ or greater. This means an} \]

\[ \text{chord must be at least } \frac{1}{2} \text{ the circumference of the disk.} \]

\[ \therefore \text{ our blade must consume } \frac{1}{2} \text{ of the disk area at minimum.} \]