Mechatronics Skripsie Progress Report: Tip-thurst rotary aircraft

Mechatronic Project 478
Final Report

Author: Rayde Krüger
24723061

Supervisor: Dr. A Gill

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Department of Mechanical and Mechatronic Engineering
Stellenbosch University
Private Bag X1, Matieland 7602, South Africa.

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Executive summary

Title of Project
Tip-thurst rotary aircraft
Objectives
The main objective is to design, build and test a prototype of a tip-thrust rotary aircraft with controllable pitch to create directional thrust.
What is current practice and what are its limitations?
Current thrust-tipped rotary aircraft either use traditional methods for pitch control, such as a swashplate, or use a fixed pitch rotor with additional methods for propulsion to control direction.
What is new in this project?
This project investiges the use of a variation of tip-thrust to control the pitch of the rotor.
If the project is successful, how will it make a difference?
The controling pitch using a variation of thrust will decrease the mechanical complexity of rotary aircraft, making then easier to produce, lighter and cheaper.
What are the risks to the project being a success? Why is it expected to be successful?
There is a risk that the pitch cannot change by a large enough amount or fast enough to allow for directional thrust. This risk is redduced through the correct selection and sizing of the components.
What contributions have/will other students made/make?
Previous student have studied drones, including the thrust produced by the rotors, which will assist in choosing a propulsion method.
Which aspects of the project will carry on after completion and why?
The control system and optimization of the design can be made to the finished prototype after the project is complete to improve efficiency.
What arrangements have been/will be made to expedite continuation?
By documenting the procedure, steps followed, including what each component does and how they interact with each other will assist any future further contribution.

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Constants

$\rho =$	air density $1.225\,\mathrm{kg/m^3}$	

Variables

C_L	Coefficient of lift	[ ]
C_{L_0}	Lift coefficient offset	[ ]
C_{L_α}	Lift coefficient gradient	[ ]
C_D	Coefficient of drag	[ ]
V_0	Axial component of air flow velocity	[m/s]
V_1	Resultant flow velocity	[m/s]
V_2	Radial component of air flow velocity	[m/s]
V_∞	Free-stream velocity	[m/s]
V_ω	Far wake velocity	[m/s]
α	Angle of attack	[Deg]
θ	Pitch	[rad]
ϕ	Angle made from thrust and lift	[Deg]
R	Blade length	[m]
c	Blade chord	[m]
T	Thrust	[N]
Q	Torque	[N·m]
L	Drag	[N]
b	Tip loss coefficient	[ ]
C_T	Thrust coefficient	[ ]
B	Number of blades	[ ]
ω	Angular velocity	[rads/s]
A	Area	[$\mathrm{m^2}$]
ζ	Damping ratio	[ ]
I	Current	[A]

Subscripts

$rotor$	Rotor
$Prop$	Propeller
$motor$	Tip-thrust brushless motors
n	Natural frequency

Abbreviations

AOA	Angle of Attack
ESC	Electronic Speed Controller

Chapter 1

Introduction

Helicopters are said to be the only aircraft that, since their conception, has saved more lives than they have taken (Anderson and Eberhardt (2010)). Their high level of mobility, vertical take off and landings and their ability to hover give helicopters great versatility. Helicopters are the most common example of a rotary aircraft and are used in environments ranging from rocky, mountains to stormy seas. With such high stakes it is vital to minimize points of potential failure. One of these failure points is the helicopter's tail rotor. It is required to counter the toque produced by the engine which rotates the main rotor to produce lift. If the tail rotor were to stop working, the helicopter would lose its controllability and would have to land immediately. A tip thrust rotary aircraft places the propulsion on the tips of the aircraft's rotor and thus does not produce any toque that needs to be canceled, eliminating the need of a tail rotor. As the tail rotor is connected to the same engine that operates the rotor, transmission of the rotation to the tail rotor increases complexity of the helicopter. By using a larger rotor, better efficiencies can be obtained compared to the efficiencies of current quadcopters drones, and by using tip thrust there would be no need for mechanical complexity of traditional rotary aircraft.

This project will research, design, construct and test a jet-tipped rotary aircraft which will actuate the pitch of the rotor through the use of propulsion situated at the tip of the blades. Traditional rotary wing aircraft change the rotor's pitch for portions of its rotation, this creates an unbalanced distribution of lift force, causing the aircraft to move in the desired direction. Different methods for directional thrust will investigate varying from traditional methods to using the propulsion force itself to control the direction of the aircraft. This project, which is prepared for Mechanical Project 448 and prepared by Mr RA Krüger, was proposed by the student after devising the concept with Dr A Gill. The research and results from this project hopes to further the development of tip-propelled rotary aircraft, which currently is a relatively unresearched field. Stated below include the projects scope, objectives, literature review, motivation and planning of the project are outlined.

Chapter 2

Project Definition

2.1 Problem statement

As previously mentioned this project will go through the research, design, build and test of a tip-propelled rotary aircraft. This project's aims is to create a tip-thrust rotary aircraft for which the rotor is responsible for directional movement. This should occur by varying the pitch of the rotor blade to create directional thrust. An investigation will be made to identify whether traditional methods, such as a swhashplate must be used or whether the variation of thrust can be used. To achieve directional thrust due to variation of propulsion, the tip-thrust should vary the pitch of the rotor such that at lower propulsion, the rotor will have a higher pitch, there by increasing the lift generated. As propulsion is increased, the pitch lessens, decreasing the lift produced, but also decreasing the drag generated by the rotor.

2.2 Scope and limitations

The final design should prove controllability, but does not need to achieve sustained flight, and thus showing that the aircraft can produce lift in the desired direction will suffice. While a basic understanding of rotor design can be applied to the aircraft's main rotor, it is not the focus of the project and thus no computational fluid dynamics are required either. While the most common method of propulsion for tip-propelled rotary aircraft is using an operating fluid in either a hot or cold cycle, this method will not be investigated due to the required large scale of these methods.

2.3 Objectives

The objectives of this project are as follows:

1. Design a prototype to achieve the desired aim

2. Construct a working prototype of the created design
3. Implement a method to produce directional thrust
4. Implement a control system for the tip-propulsion
5. Test and analyze the prototype

2.4 Research questions

2.4.1 Can the aircraft be fully controlled using the tip propulsion alone?

An investigation should be done to test the viability of different methods to introduce the control of the direction of the rotary aircraft through the use of a variation of thrust alone.

2.4.2 How much thrust can the aircraft produce?

The maximum amount of thrust should be determined to determine how effective the rotor is compared to the tip-propelled alone.

2.4.3 What is the efficiency of the aircraft?

The efficiency of the rotary aircraft can be evaluated by comparing the total lift it can produce vs the power it consumes

2.4.4 Which control system method works best?

An investigation of the different control system, including PID, lead/lag compensator and state space control, should be looked into to determine which method is the most effective.

2.4.5 How stable is the system?

Rotary aircraft are inherently unstable. The system needs t o be checked to determine how stable the implemented control system is.

2.5 Motivation

As previously mentioned, tip-propelled rotary aircraft remove the need for a tail rotor as they do not produce a torque which needs to be canceled. This decrease the complexity of the aircraft and reduces its wright as there is no longer a need for large transmission shafts and gearboxes. However, many current designs use this method of propulsion for autogyros aircraft designs. These use the main rotor to produce lift and have other methods for directional thrust. This adds in another system to the aircraft which could introduce unrealability and increase complexity. By making the aircraft controllable with the rotor, it will decease the complexity of the aircraft and decrease the weight, allowing for larger payload to be carried. Decreasing the weight can also increase the flight time of the aircraft. With the decreased weight and a larger rotor than conventional quad-copters, the efficiency of the aircraft will be increased, this will increase the potential flight time of the aircraft and reduce the mechanical complexity that is present with traditional helicopter, allowing the creating of small scale aircraft with longer flight time a possibility.

Chapter 3

Literature Review

3.1 Introduction

A rotary-wing aircraft is defined as a configuration in which during take-off and landing, the aircraft derives its lift force directly from an open airscrew, where an airscrew is any actuator disc that has air as its working fluid. These types of aircraft can hover and have vertical lift-off and landing (VTOL) capabilities. Rotary aircraft's airscrews have been given the name of 'Rotor' and are characterized by a low disc loading. Disc loading is defined as the average change in pressure across an airscrew. For a rotary aircraft, it is the ratio of the rotor disk area to the total weight of the aircraft (Stepniewski and Keys (1984)). The most common example of a rotary aircraft is a helicopter. Over the years helicopters have evolved and have gone through many concepts. Tip-propulsion is one of these changes and will be the focus of this literary review.

3.2 Historical development

One of the earliest concepts of a rotary aircraft can be traced back to Leonardo da Vinci, who came up with the idea of a flying machine based on the Archimedes screw. The Archimedes screw can be thought of as the precursor to the aircrews we have today. While Leonardo's design theoretically worked, it would have been too impractical to build a full-sized version, it did, however inspire people to create vertical flight machines. Stepniewski and Keys (1984)

The second factor hindering the development of the helicopter was a lack of understanding of basic aerodynamics. Helicopters are inherently unstable and have a tendency to flip over when in forward flight, this was later discovered to be due to an asymmetrical distribution of lift across the rotor. This is caused by the fact that the lift produced is directly proportional to the incoming air speed squared (lift α air speed^2). When in forward flight one side of the rotor will be moving opposite to the direction of airflow and thus its relative air velocity is higher than the rotor moving in the same direction of the incoming air, one side having increased lift and the other a decreased lift, causing the asymmetry of the forces (Anderson and Eberhardt (2010)). This was corrected using a swashplate as well as articulating the blade with flapping and feathering hinges, which will be discussed further in the text below.

There were two main points that made the helicopter such a difficult task to accomplish. The first was a lack of an efficient power source. Before the combustion engine, the only power source was the steam engine, which would not produce enough lift for its weight to make it a viable power source. Even with the combustion engine, it was only after World War I when they began using aluminum that a power-to-weight ratio became large enough to sustain flight. (Stepniewski and Keys (1984))

Figure 3.1: WNF 342 V4 (Linenbaum (2020))

The first concept of a tip-thrust helicopter can be traced back to the start of World War II, developed by a junior engineer at Wiener Neustädter Flugzeugwerke (WNF), Friedrich von Doblhoff. He proposed that to place ramjets on the tip of the rotor and after a short-lived proof of concept managed to impress officials, Friedrich obtained the necessary funding for his first Jet-tipped aircraft. In total four prototypes were constructed, namely WNF 342 V1, V2, V3 and V4, with each design improving on the previous. WNF 342 V4, seen in Figure 3.1, used a supercharged engine modified as a compressor to provide air to the rotors and to provide thrust at the back with a pusher propeller. The final design noted that using the jet-tip was inefficient and was used for vertical take-off and landings, when in forward flight, the compressor was switched off, and it operated as an autogyro. Autogyros have freely rotating rotors that spin due to the force of incoming air, this in turn generates lift. This design used a mechanism similar to a swash plate to control the cyclic pitch of the rotor and used the air pressure, along with torsional springs, to change the collective pitch (these concepts are further explained in Section 3.3). The development of tip-thrust was stopped when the test facility was taken by the Allied forces, however, Mr. von Doblhoff would go on to work in America and work on compound helicopters, helicopters which are a hybrid between the rotary-wing and fixed-wing aircraft.

3.3 Helicopter control

Helicopter control relies on the pitch of each blade. The change in pitch causes a change in the angle of attack (AOA). The AOA is directly related to the lift coefficient through

$$C_L = C_{L_0} + C_{L_\alpha} \cdot \alpha$$

where C_L is the coefficient of lift, C_{L_0} is the offset, C_{L_α} is how much the lift coefficient changes due to AOA, and α is the angle of attack, this is illustrated in Figure 3.2(Gudmundsson (2022)). Thus increasing the angle of attack increases the lift coefficient, which increases the lift produced.

Helicopters use collective and cyclic control to control the helicopter. The

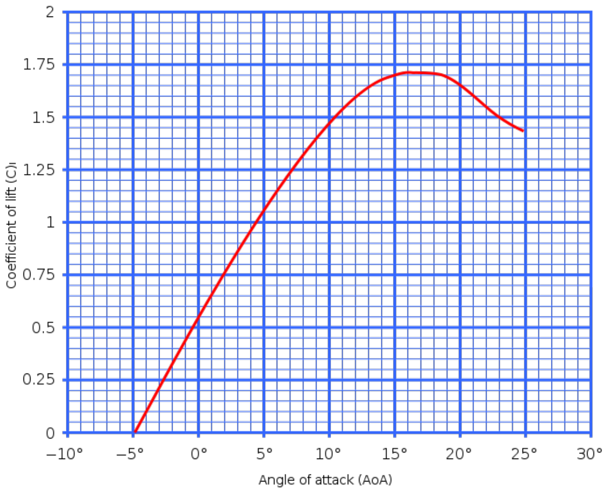


Figure 3.2: Lift vs Angle of Attack (SKYbary)

collective control adjusts the pitch of all the blades by the same amount, this creates more or less lift overall, allowing the helicopter to rise or fall. The cyclic control varies the pitch depending on where the rotor is in its rotation. Traditional helicopters use swashplates to achieve this control.

A swashplate consists of two plates connected with bearings. This allows the top plate to rotate and the bottom plate to remain fixed. The top plate is connected to the edge of each blade of the rotor by a pitch change arm. This allows control over the pitch by varying the height an angle of the swashplate as can be seen in Figure 3.3 (Anderson and Eberhardt (2010).)

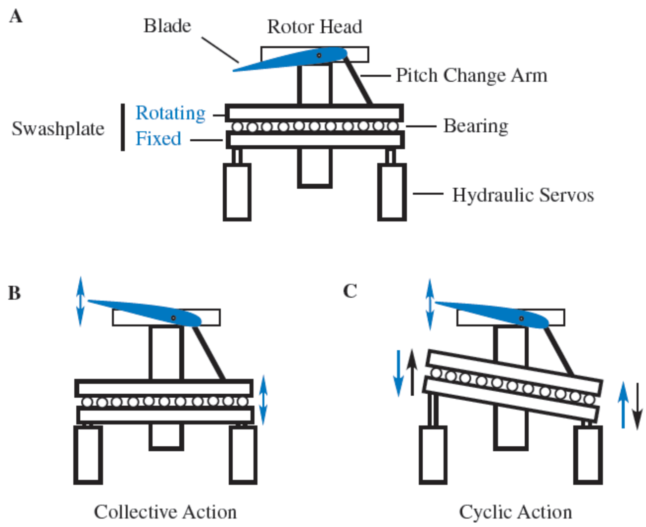


Figure 3.3: Lift vs Angle of Attack (Anderson and Eberhardt (2010))

3.4 Current state of the art

The concept of tip-thrust is an unresearched area of development, however, there a still many applications of this technique, all of which have been applied in different ways. The commonality between all the designs is the method used for propulsion. While some methods make use of ramjets or liquid rockets attached to the tip, it was found during the student's investigation that many designs have been built to create thrust by ejecting an operating fluid out of a nozzle at the tip of the rotor blade. The temperature of the operating fluid splits into two subcategories, cold-cycle and a hot-cycle. Cold-cycles use compressors and utilize compressed air as the operating fluid. Whereas a hot-cycle uses a gas generator that burns a mixture of compressed air and fuel, creating combustion of products (at temperatures greater than 700°C) which are used as the operating fluid (Elmahmodi *et al.*, 2014).

NASA designed a very heavy-lift helicopter (VHLH) using the hot-cycle technique. This was designed as a solution to the weight constraints of shaft-drive helicopters. It was designed such that it could lift an XM-1 Main Battle Tank, which has a total weight of 60 tons, shown in Figure 3.4. The helicopter has a fixed pitch rotor, which is used to generate lift, allowing for VTOL. To control the movement of this helicopter, as the pitch is fixed and cannot use conventional methods, a tail fan with a controllable pitch and controllable louvers, which direct the airflow, was installed at the back. Unfortunately, although the concept was very promising, it was never constructed (Head, 1981).

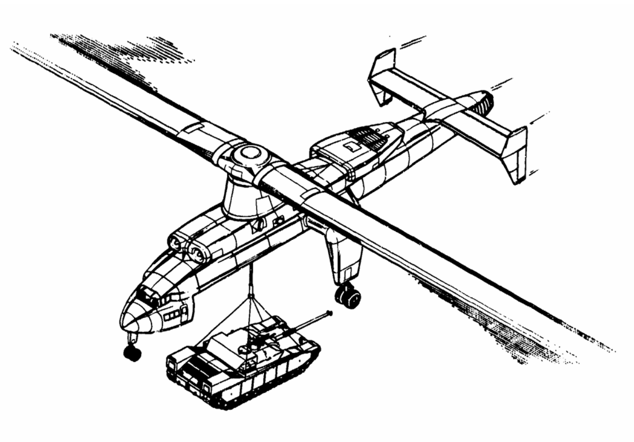


Figure 3.4: VHLF with a XM-1 Main Battle Tank payload

The ATRO-X tip-jet helicopter is an example of a fully constructed jet-tipped helicopter that also makes use of a hot-cycle to provide propulsion. The gas generator is situated on top of the rotor and is connected to a flexible tube to the rotor. The operating fluid travels through the hollow rotors to the tips, where the fluid is expelled. This helicopter only has the main rotor, greatly simplifying the complexity of the helicopter, however, a study by Kolarević *et al.* (2020) showed that it was not as efficient as a conventional helicopter. This was partly due to the significant pressure drop of the operating fluid in the rotor channels. It was also stated that the efficacy could be increased by making the rotor larger, however this causes a larger pressure drop. To try to rectify this issue a study by Elmahmodi *et al.* (2014) tried using the centrifugal force of the rotor as a radial compressor and proved the viability of this concept.

The issues that each of the above concepts encountered will be used to guide all designs regarding the current prototype. The current designs have provided very useful insight into what concepts work and which have fundamental issues and should be avoided.

3.5 Blade Element Theory

This method is used to predict the performance of a blade, such as a rotor or a propeller as explained by Aerodynamics for Students (2024). The method achieves this by dividing the blade into multiple independent sections along the length of the blade as shown in Figure 3.5. A force balance is applied to each 2D section to obtain the lift and drag as well as the torque and thrust produced over the section. These values can be summed to predict the total thrust and torque produced by the rotor.
As this theory considers the 2D segments, it does not take 3D effects into account, such as flow velocities induced on the blade by the shed tip vortex or the radial component created by the angular acceleration due to the rotation

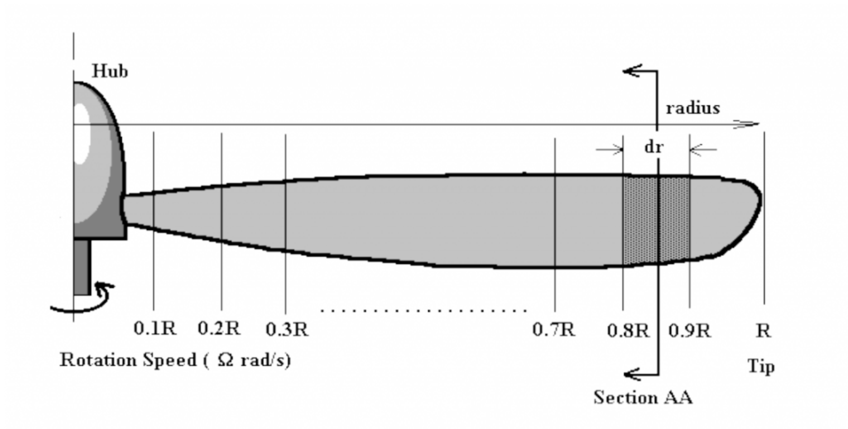


Figure 3.5: Diagram showing the blade split into segments (Aerodynamics for Students, 2024)

of the rotor. This results in the model overpredicting the thrust produced and underpredicting the torque, resulting in a theoretical efficiency that is between 5% to 10% larger than the measured efficiency. One of the flow assumptions made is that the flow on the blade is not stalled, which needs to be kept in mind for when designing the system.
As shown in Figure 3.5, the blade can be subdivided to make multiple discrete sections. For this analysis, only the axial and angular components, V_0 and V_2 respectively, as labeled in Figure 3.6, of the velocity and the induced flow is negligible. V_1 is the summation of these two velocities.

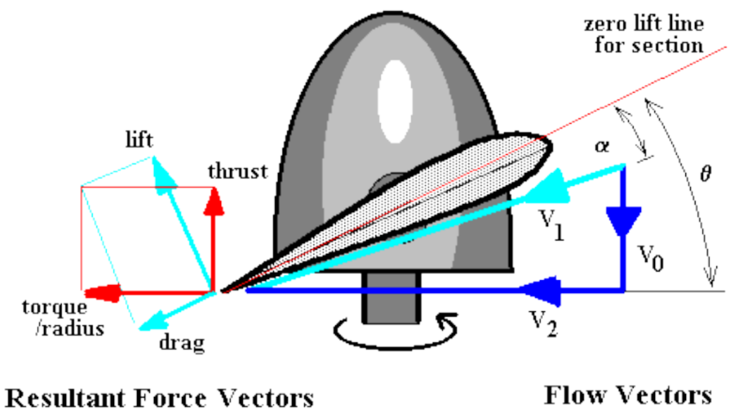


Figure 3.6: Forces acting on the 2D section AA of Figure 3.5 (Aerodynamics for Students, 2024)

Theta, θ, shown in Figure 3.6 is the geometric pitch of the blade. The angle created between the flow velocity vector (V_1) and θ creates the angle of attack (α). The lift and drag components are normal and parallel to the blade disk and can be calculated, using Eq. 3.1 and Eq. 3.2, to find the thrust and torque of the blade.

$$\Delta L = C_L \frac{1}{2} \rho V_1^2 c.dR \tag{3.1}$$

$$\Delta D = C_D \frac{1}{2} \rho V_1^2 c.dR \tag{3.2}$$

where C_L and C_D are for a given α
ρ is the air density
c is the blade chord

The difference in angle between thrust and lift can be defined as

$$\varphi = \theta - \alpha$$

and thus thrust and torque can be found as

$$\Delta T = \Delta L \cos(\varphi) - \Delta D \sin(\varphi) \tag{3.3}$$

$$\frac{\Delta Q}{R} = \Delta D \cos(\varphi) + \Delta L \sin(\varphi) \tag{3.4}$$

Combining Eq. 3.1 and Eq. 3.2 with Eq. 3.3 and Eq. 3.4 yields

$$\Delta T = \frac{1}{2} \rho V_1^2 c (C_L \cos(\varphi) - C_D \sin(\varphi)) B.dR \tag{3.5}$$

$$\Delta D = \frac{1}{2} \rho V_1^2 c (C_D \cos(\varphi) + C_L \sin(\varphi)) B.R.dR \tag{3.6}$$

where B is the number of blades

3.6 Momentum theory

Momentum theory simplifies the rotor of the helicopter's rotor by viewing it as a disc that air flows through and energy is imparted on it by the rotor as stated in Gessow and Garry C. Myers (1985). As shown in Figure 3.7, velocity increases from V_0 to V_3, and it is assumed that the air follows the streamlines, indicated in the figure. From conservation equation, we know that the $\dot{m} = \rho S_d V$, through the rotor, thus $\rho_1 S_1 V_1 = \rho_2 S_2 V_2 = \rho_3 S_3 V_3 = \rho_4 S_4 V_4 =$ constant, therefore the thrust can be given by

$$T = \rho S_2 V_1 (V_4 - V_2) \tag{3.7}$$

Thrust can also be found as the difference of pressure, $T = S_2(P_2 - P_3)$. Applying Bernoulli's equation which states that the static and dynamic pressure at P_1 be equal to that at P_2, similarly for P_3 and P_4, as $V_2 = V_3$.

$$P_1 + \frac{1}{2} \rho V_1^2 = P_2 + \frac{1}{2} \rho V_2^2$$

$$P_3 + \frac{1}{2} \rho V_3^2 = P_4 + \frac{1}{2} \rho V_4^2$$

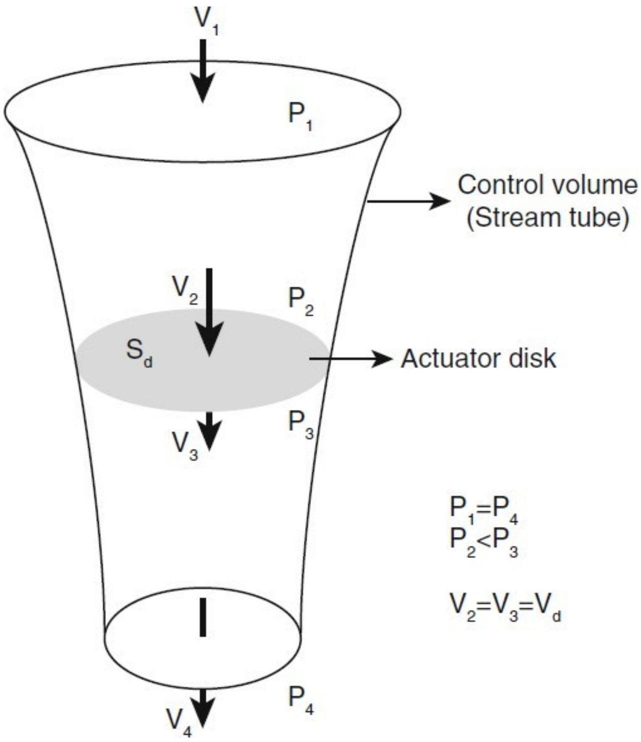


Figure 3.7: Momentum theory airstream velocities

These can be rearranged to give

$$P_3 - P_2 = \frac{1}{2}\rho(V_4^2 - V_1^2)$$
$$\Rightarrow T = \frac{1}{2}\rho S(V_4^2 - V_1^2) \tag{3.8}$$

Making Eq. 3.7 equal to Eq. 3.8 we get

$$\rho S_2 V_0 (V_4 - V_1) = \frac{1}{2}\rho S(V_4^2 - V_1^2)$$

which simplifies to

$$\frac{1}{2}(V_4 + V_1) = V_2 = V_3 \tag{3.9}$$

Chapter 4

Planned Activities and Risks

4.1 Planned activities

This section aims to outline the activities that will be done to ultimately achieve the aim of the project. These activities will be listed in the order of which they will be done.

4.1.1 Decide on the type of propulsion

As has already been mentioned in Section 3.4 the common propulsion method used in most tip-propelled aircraft uses compressed air as the working fluid in either a hot or cold cycle. As mentioned in the project's scope, this will not be considered, however using compressed air could be a potential means of propulsion. The other option is to mount electric motors to the tip and make use of propellers to provide the required thrust. The advantages and disadvantages of each will need to be investigated before a final decision can be made.

4.1.2 Transfer of potential energy to the rotor tips

No matter which means of propulsion is chosen, potential energy, in the form of compressed air or electrical energy, needs to be transported to the tips of the rotor. The fact that the rotor is constantly rotating provides a complicated problem that would need to be overcome to create a system in which each tip can have a user-defined amount of thrust at any time.

4.1.3 Pitch control

The method for how the pitch of the blades needs to be decided. Tests can be performed to see how the chosen propulsion method can influence the pitch of the rotor. Aspects such as feathering and flapping of the rotor need to be taken into account to decide on how the pitch of the rotor can be controlled to achieve directional thrust.

4.1.4 Pitch control system

As the pitch will be a parameter that can be influenced by the user, a control system will be required to achieve stability and directional thrust. The types of control systems should be investigated here. Determine whether the system can be used with just a PID controller, whether it needs a lag/lead compensator or if state space is a possibility. If possible a mathematical model should be derived for the prototype to aid with the creation of these control systems.

4.1.5 Pitch and rotor position sensing

The system needs to be able to detect the position of the rotor to supply the control system with the correct information, this will be needed to implement directional control as the pitch for directional control needs to vary depending on the position of the rotor's revolution. This will need to be fast and accurate as the rotation will need to be high enough to produce lift and the exact position needs to be known so that directional thrust can be in any direction.

4.1.6 Computations

A method for implementing the system controls and receiving the sensor data needs to be decided one. A method for the way the controller receives user inputs and implements the control system needs to be decided on as this could influence the choice of controller. Options like an ESP32 or a Raspberry Pi would be better if the system is required to be wireless, alternatively, a PLC would more reliable and lighter if it did not need to be wireless.

4.1.7 Rotor and aircraft design

As mentioned in the scope, an in-depth rotor design is not required, but research into basic rotor design should be done. A rotor should be designed using all the parameters decided from the above activities to ensure it can produce enough lift and that the method of pitch control can be implemented. The interface of the rotor to the rest of the system should also be considered. The rest of the aircraft will be built around the rotor which incorporates the tip thrust and all the components required to implement the control system.

4.1.8 Build the tip propelled rotary aircraft

The design should be complete and can be constructed. The design should be constructed using the resources in the mechanical department.

4.1.9 Test the directional thrust

The finished design can be placed on the testing rig. The system will be tested by instructing it to move in different directions. The data will be recorded for analysis.

4.1.10 Evaluation and repetition

Using the data retrieved from the previous activity, the aim of the project can be evaluated. This process can be used to gain information about the system and using this information activities 4.1.8 (building) to 4.1.10 (evaluation) can be repeated to optimize the design until the control system, directional thrust, and pitch control has become satisfactory.

4.1.11 Report writing

Once the final prototype has been designed, built and tested, the report can be finalized. This will be continuously worked on and updated throughout the planned activities and will be the last activity of the project.

4.2 Risks

4.2.1 Safety

This project deals with fast-spinning props and live electricity. Caution must be taken when the prototype is switched on and whenever the wires are being handheld. To minimize this risk, when working with the prototype the power source should be disconnected, this will prevent accidental activations as well as electrocution.

4.2.2 Technical Risks

These risks pertain to the risk of equipment or component failure. If equipment malfunction or component failure occurs this could cause harm to either the user or the prototype. To minimize this risk, thorough testing of the equipment and components should be done to ensure they are operating how to be expected. Another potential technical risk is whether the thrust and control system would be able to be operated with enough accuracy and speed to allow for directional thrust. This risk can be reduced through the proper design of the system and the correct selection of components.

4.2.3 Financial Risks

Financial risks include going over budget or standing more than expected. This risk can be minimized through proper budget planning to ensure an accurate budget has been created. Minimizing the technical risk, as mentioned previously, will prevent components or equipment from needing to be replaced.

4.2.4 Scheduling risk

There is a limited amount of time to complete this project and as such there is a very tight schedule. Unexpected delays could have catastrophic effects on the project and could potentially cause it to become incomplete. To prevent this from occurring, a detailed plan should be devised, and the student should follow it as closely as possible.

4.2.5 Resources risk

This risk relates closely to the previous risk, scheduling risk, as a delay in resources can cause a delay in the entire project. Ordering components or sending designs to be created at the workshop should be done in far enough advance such that if there are any unexpected delays, it will not crucially affect the project's schedule. It can also be reduced by choosing components that are readily available and easy to obtain.

Chapter 5

Project Scheduled Plan and ECSA Requirements

5.1 End-of-life strategy

Engineers need to ensure each of their projects have an end of life strategy to help ensure sustainable development. For this project a prototype will be developed. Before the design will be made, a list of potential items that could be used for the project will be created. This list could include actuators, power sources, microcontrollers, sensors and building materials. This list will be used during the design phase and a prototype that uses as many items from previous projects will be created, provided it does not affect its performance. While in the design phase, each piece will be created with the intentions of being able to disassembly the prototype. For all items that must be bought and cannot be reused, an active effort will be made to use recyclable materials and in the event of using a recyclable material, a disposal plan will be created, stating the precautions and necessary steps that were training to ensure a safe and sustainable development.

5.2 ECSA Requirements

Table 5.1: ECSA Requirements

Nr	**ECSA Graduate Attribute (GA)**	**Activity addressing attribute**	**Reasoning**
GA1	**Problem-solving**	4.1.2,4.1.3,4.1.5	The planned activities mentioned all have clear objectives and obstacles that need to be overcome to achieve them. These will require creative solutions to achieve the objective.
GA2	**Application of scientific and engineering knowledge**	4.1.4, 4.1.5, 4.1.8	These actives include creating a mathematical model of the system to then create a control system to be implemented. The building and design process will incorporate workshop trainings and learned from practicals
GA3	**Engineering design**	4.1.1, 4.1.7	Each of these activities requires the student to create a solution to the problem by designing a part which will integrate into the system as a whole.
GA4	**Engineering methods, skills and tools, including Information Technology**	4.1.2, 4.1.5, 4.1.6	These activities all require skills gained throughout the Engineering course to be able to understand the system and to implement the appropriate solution.
GA5	**Professional and technical communication**	4.1.11	Professional report writing to explain the results and how the objectives were met will ensure all the student's information has been conveyed correctly.
GA6	**Individual, team and multi-disciplinary working**	4.1.8, 4.1.10	Throughout the build process, the student will need to work with technicians to help build the system. Effectively working with the technicians will ensure that the component will be created to the student's specification. The whole project will have the student's demonstrating their individual work.
GA7	**Independent learning ability**	4.1.1, 4.1.2	As the student is a Mechatronic engineer, the more advanced fluid mechanics, such as rotor design, will require self work to research and understand how the rotor can be designed effectively.

Chapter 6

Modelling the System on MATLAB

To aid in creating the first design, a mathematical model is required to determine the metrics of the system. This allows for rapid testing and optimization of parameters.

6.1 Modelling the rotor

To model the rotor, Bade Element Theory analysis was applied. The rotor was divided into segments and the lift and drag for each segment were calculated. This gives the profile of the thrust and torque along the rotor as can be seen in Figure 6.1 and Figure 6.2, respectively. The sum of each segment will result in the total thrust and torque produced by the rotor. The thrust and torque produced by each segment is an iterative process as the incoming flow velocity is unknown. In the first iteration, it is assumed to be zero, and thus the angle of attack is equal to the pitch of the rotor. The incoming air can be calculated using the first approximation of thrust using Newton's First Law:

$$F = ma$$
$$T = \frac{d(ma)}{dt}$$

Assuming air above the rotor is stationary

$$T = \dot{m}V$$
$$T = \rho V_2 A V$$

This gives the thrust in terms of the air velocity and velocity at the disk. As stated by momentum theory and by Gessow and Garry C. Myers (1985), the far wake velocity is half that of the air velocity at the disk. Thus, for hover, assuming the free stream velocity is zero, the axial velocity at the disk can be given by

$$T = (\rho \pi R^2 V_2) 2V_2$$
$$V_0 = \sqrt{\frac{T}{2\rho\pi R^2}}$$

Using this and the angular rotation of the rotor, the angle of attack can be found as

$$\alpha = \theta - \arctan\left(\frac{V_0}{\frac{2}{3}R\omega_{Rotor}}\right)$$

Two-thirds of the blade's length is used as the speed of the blade is not constant along its radius, so the speed of the centroid was used to try to approximate the average angle of attack along the blade. It was seen that the thrust and torque converge after 25 iterations. Resulting in the profiles as seen in Figure 6.1 and Figure 6.2.

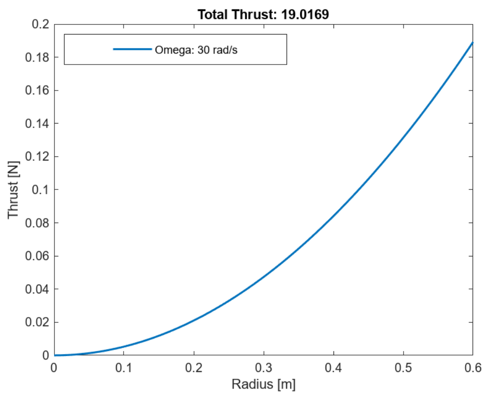


Figure 6.1: Thrust predicted over the length of the rotor

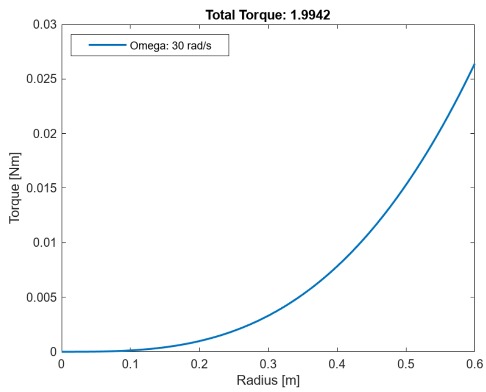


Figure 6.2: Torque predicted over the length of the rotor

Using these results, the number of segments can be found which minimizes the computational cost, while having sufficient accuracy. Figure 6.3 shows the predicted torque and thrust for the number of segments the rotor is split into. It can be seen that both graphs plateau and that after a certain amount of segments, the increase in accuracy is not beneficial for the computational power. The elbow of both of the predictions is around three hundred segments, which results in predictions that are 0.5% different from the value obtained using five thousand segments. It was decided that it was sufficient accuracy for the computational cost and thus three hundred segments were used for the model.

As mentioned previously, this analysis has assumptions to simplify the model, however, it results in underpredicting the torque and overpredicting the thrust produced. One of the assumptions neglects the tip vortices which will produce decreased thrust. To compensate for the decreased thrust, the predicted thrust can be multiplied by a tip-loss factor b. Gessow and Garry C. Myers (1985)

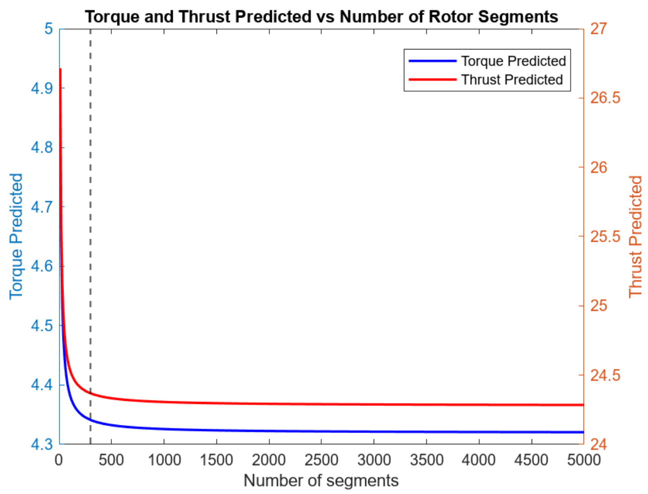


Figure 6.3: Predicted torque and thrust vs the number of segments

describe the tip-loss factor as a coefficient that is multiplied by the radius of the rotor for the thrust calculations. This assumes that from bR of the rotor, it will produce zero lift but still have drag. It is defined as

$$b = 1 - \frac{\sqrt{2C_T}}{B} \tag{6.1}$$

where B is the number of blades
C_T is the rotor thrust coefficient

The thrust coefficient is the thrust per unit blade span and can be defined as

$$C_T = \frac{T}{\pi R^2 \rho(\omega_{Rotor} R).^2} \tag{6.2}$$

The above gives the lift profile along each blade of the rotor, but finding the total thrust for different angular velocities is more vital for designing the initial prototype. To do this the thrust and torque values were calculated for a range of angular velocities and their values were stored. An exponential function is then fitted onto these equations, as can be seen in Figure 6.4 and Figure 6.5, resulting in two equations that can be used to predict the amount of thrust and torque produced for a given angular velocity, Eq. 6.3 and Eq. 6.4, respectively.

$$T = 0.01805\omega_{Rotor}^2 \tag{6.3}$$
$$Q = 0.002216\omega_{Rotor}^2 \tag{6.4}$$

6.2 Modelling the propeller

Modeling the propellers for the tip-thurst used a similar approach as for the rotor except that the propellers are smaller, and the accuracy is not as crucial

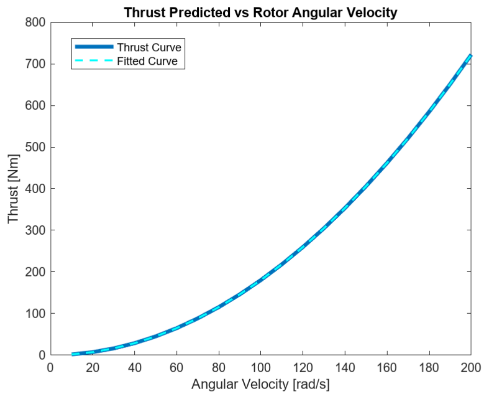


Figure 6.4: Thrust predicted vs angular velocities and the fitted exponential equation

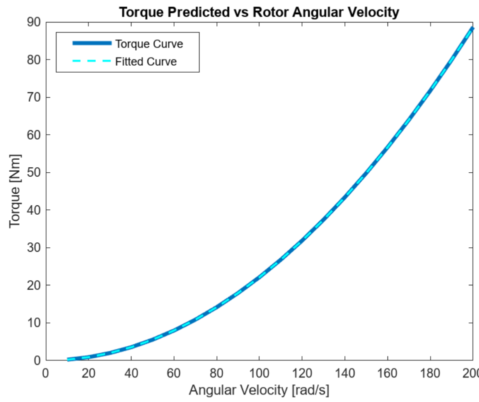


Figure 6.5: Torque predicted vs angular velocities and the fitted exponential equation

for designing the prototype. The thrust and torque produced were calculated using one section with the radius being two-thirds of the blade length as this was shown to give an accurate value with one section when compared to multiple sections.
The propeller's pitch is described by the distance the propeller moves forward per rotation and thus to find the average angle of the pitch it can be found as

$$\theta_{prop} = \arctan\left(\frac{\text{Pitch}}{\pi d}\right)$$

The incoming airflow of each propeller can be found by multiplying the angular velocity of the rotor by the position along the rotor blade of the propellers. The high velocities of the inflowing air will decrease the angle of attack. This requires the propellers to have high angular velocities to ensure an angle of attack that produces thrust. Choosing a propeller with a high pitch can ensure that the incoming air meets the blade at a more effective angle of attack.
As the incoming air velocity is dependent on the angular velocity, this results in a thrust and torque versus the angular velocity of the propellers to have a different shape depending on the angular velocity which can be seen in Figure 6.6 and Figure 6.7.
Each graph for the thrust, however, can be fitted by a parabolic graph, but with different coefficients depending on the rotor's angular velocity. The solution for this was to find a relationship between the coefficients and the rotor's angular velocity. The change of these coefficients can be seen in Figure 6.8,6.9 and 6.10, in which

$$T_{prop} = P_1\omega_{prop}^2 + P_2\omega_{prop} + P_3$$

From these graphs, clear relationships can be seen with all three coefficients and the angular velocity. Fitting curves to each coefficient result in the Eq. 6.5,

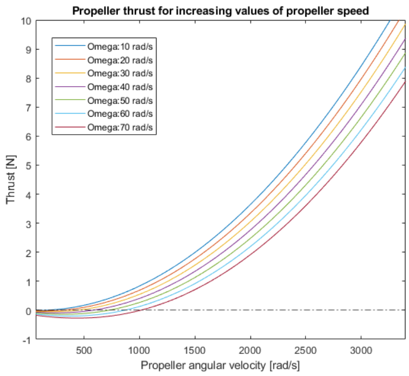


Figure 6.6: Propeller thrust versus its speed for different values of rotor angular velocity

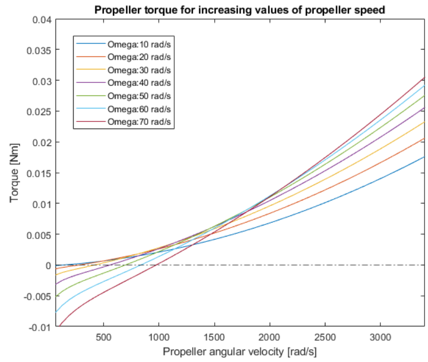


Figure 6.7: Propeller torque versus its speed for different values of rotor angular velocity

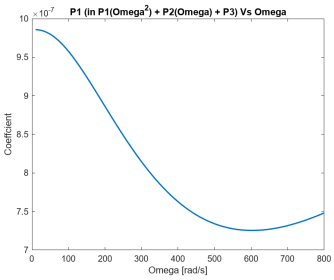


Figure 6.8: Coefficient P1

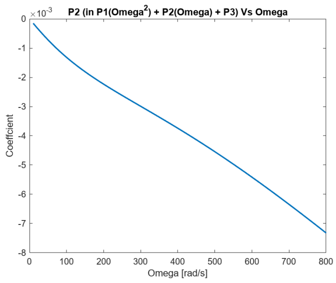


Figure 6.9: Coefficient P2

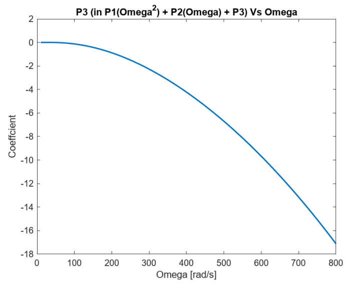


Figure 6.10: Coefficient P3

which fully describes the thrust produced by tip-thrust.

$$\begin{aligned} T_{prop} = &\big((-2.500\times10^{-16})\omega_{rotor}^3 + (1.517\times10^{-12})\omega_{rotor}^2 + (-1.314\times10^{-9})\omega_{rotor} \\ &+(1.037\times10^{-6})\big)\,\omega_{prop}^2 + \big((-7.806\times10^{-12})\omega_{rotor}^2 + (7.144\times10^{-9})\omega_{rotor}^2 \\ &+(-1.301\times10^{-5})\omega_{rotor} - 0.0003\big)\,\omega_{prop} + \big((-4.593\times10^{-5})\omega_{rotor}^2 \\ &+(-1.006\times10^{-3})\omega_{rotor} + 0.2227\big) \end{aligned} \tag{6.5}$$

6.3 Optimization of tip thrust positions

As previously mentioned the incoming airflow for the tip thrust is equal to the position of the tip thrust multiplied by the rotor's angular velocity. Having the propulsion at the end of the rotor will maximize the torque produced, however, it will have a higher incoming airflow and require higher rotation from the tip-thrust motors to produce thrust.
The optimum point of the tip-thrust motors would be where the torque is minimized, and the thrust produced is maximized. To find the optimum point the rotor angular velocity and tip thrust angular velocity were kept constant at an expected operating value. The thrust produced by the motors as well as the thrust that would be required to produce the torque were calculated for

each percentage length along the rotor as seen in Figure 6.11. This took the hub diameter into account, thus at 0% of the rotor (i.e. the base of the rotor), the torque does not tend to infinity.

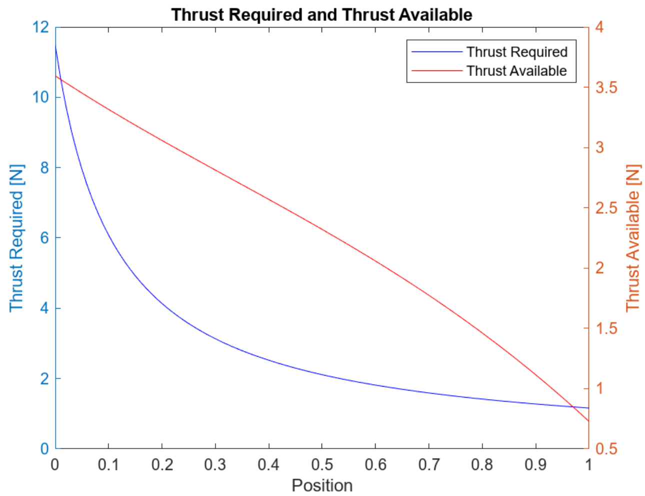


Figure 6.11: Thrust available and the thrust required for a position along the rotor

The thrust required and thrust available were standardized, so they could be compared. The two standardized sets of values were subtracted from each other and the turning point of the resulting graph was used as the optimized position along the rotor. As can be seen in Figure 6.12, this is around 32.5% along the rotor blade. While this does vary slightly depending on the motor's angular velocity, at the expected velocity a postilion of 32.5% of the rotor is optimum and is close to the mean for the position that incorporates the range of motor speed.

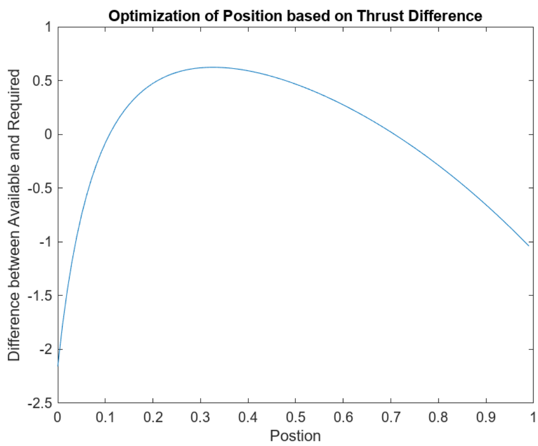


Figure 6.12: Optimization curve

6.4 Combined model

Using the models created above, the system can take the amount of thrust required and will output the torque produced, required thrust and speed of the tip thrusts.

$$\omega_{rotor} = \sqrt{55.4 T_{rotor}} \tag{6.6}$$
$$Q_{Rotor} = 0.1228 T_{rotor} \tag{6.7}$$

6.5 Pitch model

To estimate the amount of torque required to change the pitch of the rotor a rotational mass-spring-damper model was created. This models the system which assumes there will be natural damping, so no artificial damping will be introduced, and the system will be rotating on a low friction bushing, thus the effects of friction have been neglected. The model assumes a value for the moment of inertia based on a Cad model of the airfoil.
Two models have been created, one for a step input to achieve a fixed pitch change and a second one to achieve a varying pitch to create sinusoidal output which can be seen in Figure 6.13. This will create a differential amount of thrust that will induce forward movement. For these two models, the control of the steady state of the system was the objective, and thus the rise time and overshoot was a lower priority.

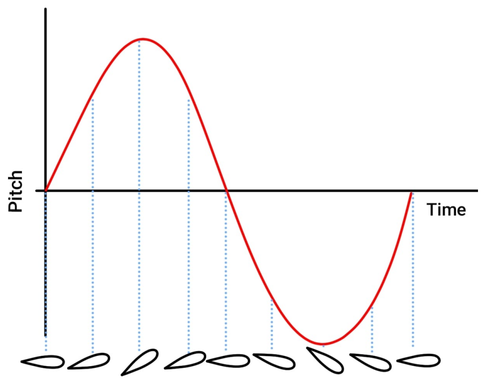


Figure 6.13: Pitch change sinusoidally

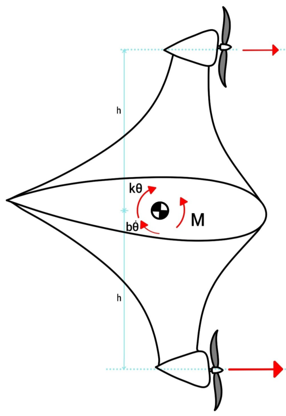


Figure 6.14: Free body diagram of tip thrust

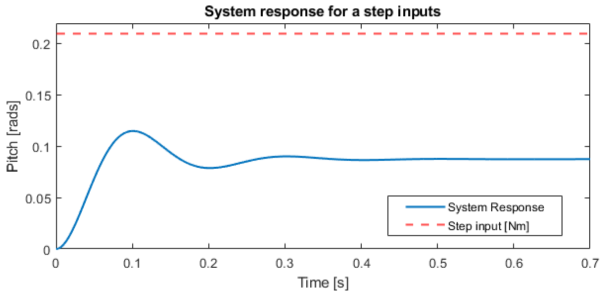


Figure 6.15: System response to a step input

6.5.1 Step input

From Figure 6.14, a differential equation can be derived for a step input to give Eq. 6.8.

$$\ddot{\theta} + 2\omega_n\zeta\dot{\theta} + \omega_n^2\theta = \frac{M_{required}}{I_{airfoil}} \tag{6.8}$$

As no artificial damping will be added to the system, it was assumed to be an under-damped system and an arbitrary dampening coefficient has been used until a more accurate can be found using experimental data, and it is assumed it is starting where θ and $\dot{\theta}$ is zero. Using this information, the solution to Eq. 6.8 given by Eq. 6.9.

$$\theta(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \phi) + \frac{M_{required}}{k} \tag{6.9}$$

where $A = \frac{-\frac{M_{required}}{k}}{\sin(\phi)}$

$M_{required} = \theta_{required}k$

$\theta_{required}$ is the pitch that is wanted

Figure 6.15 shows the system response to an applied moment that results in a steady state of 0.0873 rads (5°). It can be seen that the response from the system has some oscillation, however its settling time is reasonably fast and would suffice for the prototype.

6.5.2 Sinusoidal input

For a sinusoidal input the differential equation is given by Eq. 6.10

$$\ddot{\theta} + 2\omega_n\zeta\dot{\theta} + \omega_n^2\theta = \frac{M_{required}}{I_{airfoil}}\cos(\omega_{rotor}t) \tag{6.10}$$

The same dampening coefficient which was used for the step input was used for the sinusoidal input. This differential equation can be solved by Eq. 6.11

$$\omega(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \phi) + X\cos(\omega_{rotor} - \beta) \tag{6.11}$$

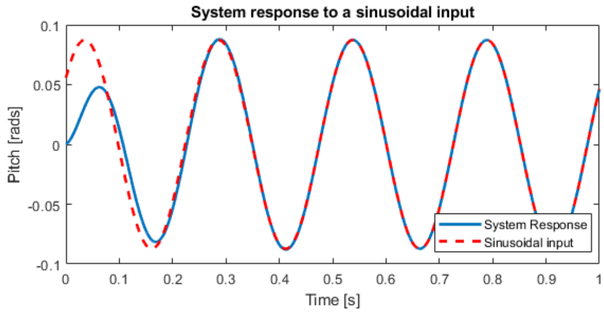


Figure 6.16: System response to a sinusoidal input

To find the torque required for a given steady state, first X must be determined. It can be seen that the exponential term will tend to zero as time tends to infinity, thus $X = \theta_{required}$. Knowing this, the moment can be given by

$$M_{required} = X I_{airfoil} \sqrt{(\omega_n^2 - \omega_{rotor}^2)^2 + (2\zeta\omega_n\omega_{rotor})^2}$$

This produces the graph as seen in Figure 6.16. To find the optimum spring stiffness and damping coefficient which will produces the smallest required torque, these two parameters were changed, and the torque required was plotted vs these parameters resulting in the graph as shown in Figure 6.17. With reference to the damping coefficient, it can be seen that the lower the coefficient, the lower the torque, however, this will affect how much the system's natural frequency influences the output. For the spring constant, it can be seen that there is a value for which the torque is minimized. After further inspection, it can be seen that choosing a spring constant which is results in the natural frequency being close to ω_{rotor} will require the lowest amount of torque to control.

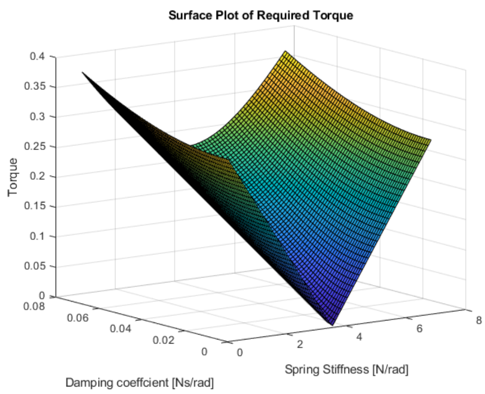


Figure 6.17: Surface graph showing of torque versus damping coefficient and spring stiffness

Chapter 7

Design

Using the values obtained from the mathematical models, the rotary aircraft can be designed. The two main components to design are the rotors and the hub. These need to have an interface together as well as with the microcontroller and other electronics.

7.1 Rotor

7.1.1 Airfoil

The airfoil of the rotor is the cross-sectional area of the rotor blade. It determines how much lift and drag is produced for a certain value of the angle of attack. Originally the NACA0012 airfoil, shown in Figure 7.1, however, this did not give enough lift at lower rotational speeds and had high drag coefficients at high angle of attacks. Figure 7.1 also shows the NACA4415, this airfoil has a higher lift coefficient and a lower drag coefficient, which allows the rotor to go at lower speeds to obtain the same amount of thrust.

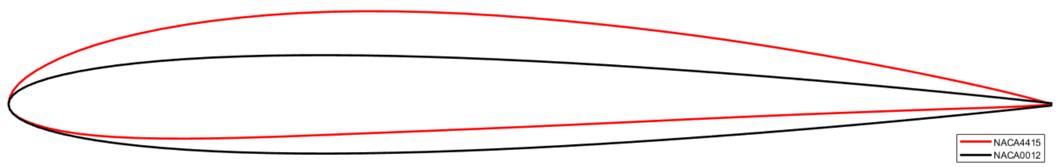


Figure 7.1: NACA profiles

To make the rotor this profile was extruded to the length of 600 mm. It was seen that making the rotor this length, allows it to produce the required thrust without having high rotational speeds.

7.1.2 Tip thrust

As mentioned before the thrust will be positioned 32.5% along the rotor blade. This reduces the incoming air speed that the tip-thrust propellers experience, however, it will require more thrust to produce the required torque. To assist with the high incoming airflow, a propeller with a high pitch will decrease the speed at which the tip-thrust motors must rotate to produce thrust by ensuring the angle of attack does not correlate with a negative coefficient of lift, but if the angle is larger than around 16° then the blades tend to stall and should also be avoided. The propellers that are currently being considered are HQ Prop 2.9X2.9X4 seen in Figure 7.2. These have a diameter of 73.66 mm with a pitch of 73.66 mm. This four-blade propeller can generate sufficient thrust

Figure 7.2: HQ 2.9X2.9X4 Props (Flying Robot, 2024)

without requiring the motors to operate at excessively high speeds. To produce 3 N of torque when the rotor is spinning at 70 rad/s, the motor will need to rotate at 24 000 RPM and will require a torque of 0.018 Nm. An option for the motor that meets these requirements is the Flash 1303.5 5500KV Motor, which is the brushless motor in Figure 7.3. To estimate the amount of torque produced, it can be found using the following equation

$$Q_{motor} = \left(KV \times \frac{\pi}{30}\right)^{-1} \times I$$

Figure 7.3: HQ 2.9X2.9X4 Props (FPV Fanatic, 2024)

For the motor in Figure 7.3, which has a KV of 5500, and a 12 A max current draw according to the datasheet, it can produce 0.02 Nm, which is enough torque to operate the propellers. It was stated to be able to produce a maximum of 297 g of thrust at 34489 RPM using a 76.2 mm diameter prop with 2 blades, and so can produce close to the required thrust with a two-bladed prop, and should with a 4-blade prop.

7.1.3 Interface

The rotor connects to the hub with a ⌀5 by 25 mm shaft, seen in Figure 7.4. The tip of the shaft is threaded and is used to connect the shaft to the rotor. The shaft rotates in a bushing to reduce friction, this is located by a circlip on the rotor side and a shoulder that connects the shaft to the hub. In between the circlip and the rotor are the torsional springs which will keep the rotor in a default pitch. A 1×1×2 mm raised feature will be milled out of the end shaft which will interface with a potentiometer. This will allow the controller to detect the pitch of the rotor. An issue with this design is that the interface

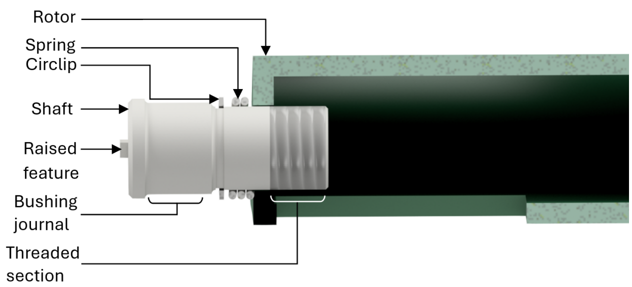


Figure 7.4: Labeled view of rotor connection

between the rotor shaft and the hub is too narrow. This causes high reaction forces to counter the moment caused by the rotor's weight and lift. While the shaft has been designed for these forces, the hub, which will be 3D printed may not. Future designs will increase the length of the shaft in the hub to help spread the load as well as in the rotor to help support the rotor.

7.2 Rotor hub

7.2.1 Electronics components

The hub of the aircraft connects the rotors to the main body of the aircraft. It houses the electronics where the speed is minimal and won't experience high forces. The hub needs to transmit data from the rotating rotor to the stationary microcontroller. To achieve this a slip ring, seen in Figure 7.5 will be used. This will allow a data connection that is rated to have a continuous rotation at 300 RPM, it may go above this speed but will decrease the part's life span.

This slip ring is rated to handle 240 V and up to 2 A. This causes an issue as the motors require 12 A each. While slip rings are rated up to 30 A exist, they only have four wires, compared to the twelve seen in Figure 7.5. To solve this issue, the decision to use two batteries was made. Using two three-cell Li-Po batteries helps balance the rotor, this can be seen in Figure 7.6, extends the flight time and does not require a battery that outputs 48 A.

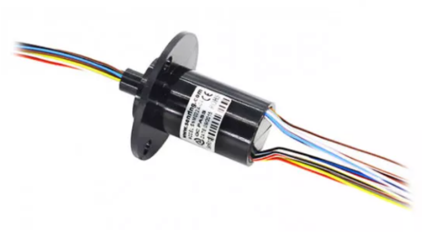


Figure 7.5: Slip ring (Micro Robotics, 2024)

To control the speed of the brushless motors each requires an ESC (electronics speed controller). Each will have two wires connected to the battery and three wires connected to the microcontroller via the slip ring to send it the commands. Three wires will come out of the ESC and go to each brushless motor.

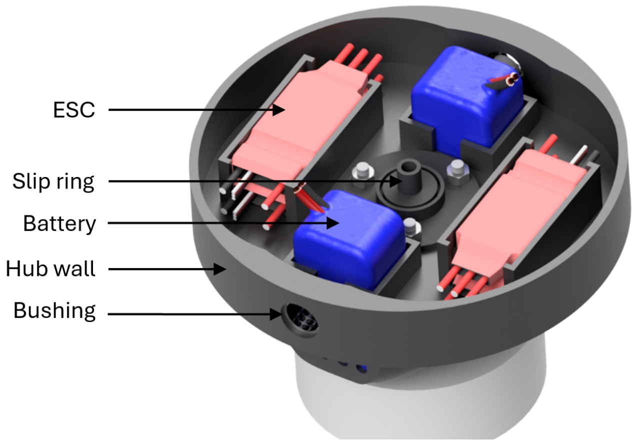


Figure 7.6: Rotor hub with electronic components

7.2.2 Interface

The hub needs to be connected to the nonrotating body. This is done with a hollow shaft. The shaft needs to have an inner diameter larger than ⌀22 mm as it needs to fit around the enclosure of the slip ring. It is flange mounted to the hub, using the same bolts used to fix the slip ring into place, seen in Figure 7.6. The shaft's diameter then decreases to ⌀25 mm, this acts as a shoulder that locates the top ⌀20 mm thrust bearing. This top bearing supports the weight of the hub and rotor before the thrust produced equals the weight of the rotor-hub assembly. The shaft at the end is threaded to allow a lock nut to be tightened onto it. This lock nut is used to locate the bottom bearing, which will support the thrust produced by the rotor and transmit it to the main body.

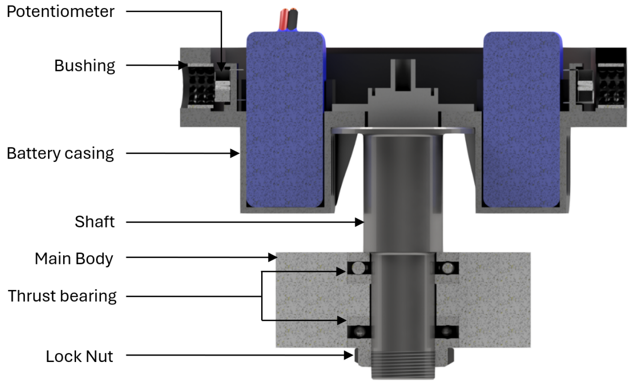


Figure 7.7: Sectioned view of hub showing the interface to the main body

7.3 First design and future development

Combining the two assemblies results in the model seen in Figure 7.8. In terms of further development, the first issue that will be addressed will be the rotors. An interface between the tip-thrust motor pylon and the rotor needs to be implemented such that they can be interchanged to allow iteration of the height without the need to reprint the rotor blade. The rotor blade will need to be split into two parts to allow it to be printed. The shaft used to interface the rotor with the hub will be made longer to help support the rotor and help with the connection of the rotor. Where the two rotor pieces connect, another pin will be added to ensure the parts properly align. Finally, the main body will need to be designed which will house some electronics, such as the microcontroller.

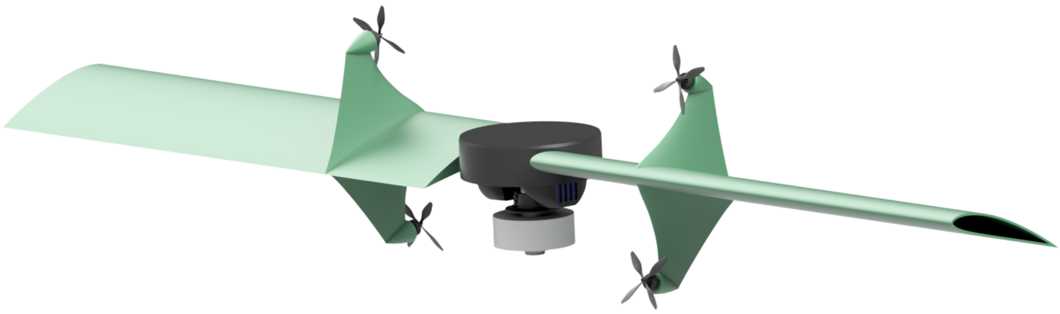


Figure 7.8: First design iteration

Appendix A

Gantt Chart and budget

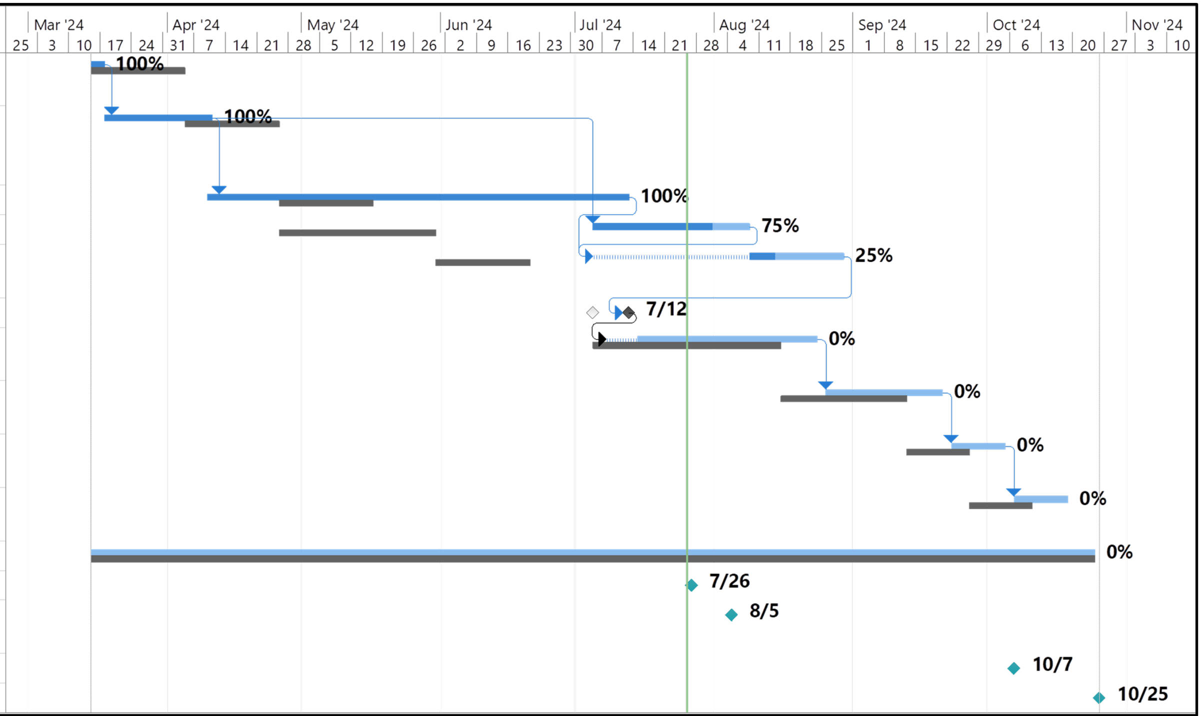
Please see below for the budget and Gantt chart proposed for this project.

A.1 Progress report

The Gantt chart that the student has followed shows that most of the planned activities that are required to be completed have been, however, there are some discrepancies, namely with the pitch control system and pitch and rotor position sensing. Currently, the student hasn't had the opportunity to test the different seeing methods for the position, while potential methods have been selected and incorporated into the design, an evaluation of their effectiveness and output has not been done as of writing. Without knowing the method for which the systems states are in, the control system of the pitch cannot be further.

Gantt Chart

Task Name	Duration	Start	Finish	Predecessors
Decide on the type of propulsion	0.2 wks	Fri 3/15/24 8:00 AM	Sun 3/17/24 5:00 PM	
Transfer of potential energy to the rotor tips	3.6 wks	Sun 3/17/24 5:00 PM	Wed 4/10/24 5:00 PM	1
Pitch control	13.6 wks	Wed 4/10/24	Fri 7/12/24 5	2
Pitch control system	5 wks	Fri 7/5/24 8:(	Thu 8/8/24 5	2
Pitch and rotor position sensing	3 wks	Fri 7/5/24 8:00 AM	Thu 8/29/24 5:00 PM	3,4
Computations	0 wks	Wed 4/3/24 8	Fri 7/12/24 5	5
Rotor and aircraft design	6 wks	Mon 7/8/24 8:00 AM	Fri 8/23/24 5:00 PM	6
Build the tip propelled rotary aircraft	4 wks	Mon 8/26/24	Fri 9/20/24 5:00 PM	7
Test the directional thrust	2 wks	Mon 9/23/24	Fri 10/4/24 5:00 PM	8
Evaluation and repetition	2 wks	Mon 10/7/24	Fri 10/18/24 5:00 PM	9
Report writitng	160 days?	Fri 3/15/24 8	Thu 10/24/24	
Progress Report	0 days	Fri 7/26/24 5	Fri 7/26/24 5	
Project progress presentation	0 days	Mon 8/5/24 8:00 AM	Mon 8/5/24 8:00 AM	
Draft final report	0 days	Mon 10/7/24	Mon 10/7/24	
Electronic Hand in	0 days	Fri 10/25/24	Fri 10/25/24	



Gantt Chart for project

Budget

Table A.1: Proposed budget for project

Activity	**Engineering Time**		**Running Costs**	**Facility Use**	**Capital Costs**	**MMW**			**Total**
						Labour		**Material**	
	hr	**R**	**R**	**R**	**R**	**hr**	**R**	**R**	**R**
Decide on the type of propulsion	25	10000	150	-	-	-	-	-	**10150**
Transfer of potential energy to the rotor tips	25	10000	300	-	-	-	-	-	**10300**
Pitch control	25	10000	-	-	-	-	-	-	**10000**
Pitch control system	60	24000	-	-	-	-	-	-	**24000**
Pitch and rotor position sensing	25	10000	100	150	-	-	-	-	**10250**
Computations	25	10000	250	-	-	-	-	-	**10250**
Rotor and aircraft design	100	40000	-	200	-	5	1500	250	**41950**
Build the tip propelled rotary aircraft	70	28000	-	-	-	20	6000	1500	**35500**
Test the directional thrust	15	6000	600	250	-	-	-	-	**6850**
Evaluation and repetition	15	6000	-	250	-	-	-	-	**6250**
Report writing	100	40000	-	-	-	-	-	-	**40000**
Total	**485**	**194000**	**1400**	**850**	**0**	**25**	**7500**	**1750**	**205500**

Table A.2: Proposed bill of materials

Item	**Vender**	**Quantity**	**Price**
Slip Ring	Micro Robotics	1	R 268
ESC	Communica	4	R 200
Flash 1303.5 5500KV Motor	FPV Fanatic	4	R 285
Thrust bearings	Bearings online SA	2	R 52
Bushes	Bearings online SA	2	R 9
2.9X2.9X4 propeller	Flying Robot	1	R 69
11.1V 1100MAH LIPO battery	Battery Experts	2	R 310
⌀12 mm Aluminium shaft	Stellenbosch University	0.05 m	R 21.6/m
⌀45 mm bright mild steel shaft	Stellenbosch University	0.015	R 209.19/m

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