Mechatronics Skripsie Proposal: Tip-thurst rotary aircraft

Mechatronic Project 478
Final Report

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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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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 for which during take off and landing, the aircraft derives their lift force directly from an open airscrew, where an airscrew is any actuator disc which has air as its working fluid. These type of aircraft have the ability to 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 concept 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 air-crews 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 had 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 ($lift\ \alpha\ air\ speed^2$). 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 incoming

air, thus 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 the text below.
There were two main points which 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 as 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 the 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 which 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 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 changing in 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

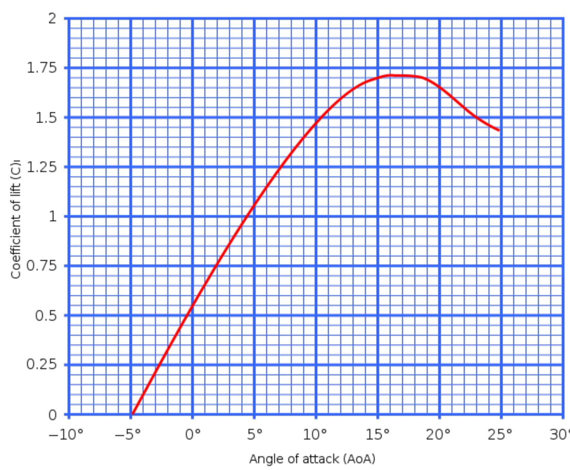


Figure 3.2: Lift vs Angle of Attack (SKYbary)

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 helicopter use as swashplate to achieve this control.

A swashplate consists of two plates connected to each other 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).)

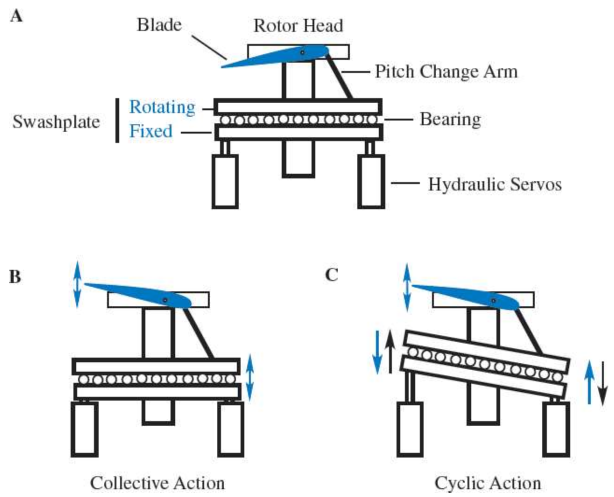


Figure 3.3: Lift vs Angle of Attack (Anderson and Eberhardt (2010))

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 a nozzle at the tip of the rotor blade. The temperature of the operating fluid splits the 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 which burns a mixture of compressed air and fuel, creating a 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 a 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 air flow, was installed at the back. Unfortunatly, although the concept was very promising, it was never constructed (Head, 1981).

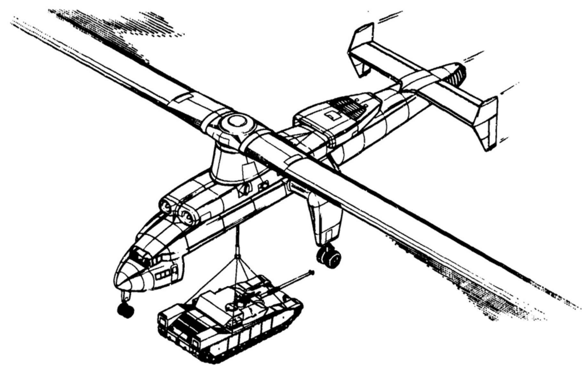


Figure 3.4: VHLF with a XM-1 Main Battle Tank payload

The ATRO-X tip-jet helicopter is an example of a fully constructed jet-tipped helicopter which also makes use of a hot-cycle to provide propulsion. The gas generator is situated on top of the rotor and is connected to flexible tube to the rotor. The operating fluid travels through the hollow rotors to the tips, where the fluid was 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 about what concepts work and which have fundamental issues and should be avoided.

Chapter 4

Planned Activities and Risks

4.1 Planned activities

The aim of this section is to outline the activities that will be done in order 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 use 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 decisions 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 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 preformed to see how the chosen propulsion method can influence the pitch of the rotor. Aspects such as feathering and flapping of the rotor needs 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 system should be investigated here. Determine whether the system can be used with just a PID controller, whether it needs as 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 receive the sensor data needs to decided one. A method for the way the controller receives user inputs and implement 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 for if the system would require to be wireless, alternativley 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 component 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 projected 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 risk 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 proper design of the system and 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 planing to ensure an accurate budget has been created. By minimizing the technical risk, as mentioned previously, this will prevent components or equipment 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 time schedule. Unexpected delays could have catastrophic effects on the project and could potentially cause it to become incomplete. To prevent this from occurring, a detail 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 work shop should be done in far enough advance such that if there are any unexpected delays, it will not crucially affect the projects schedule. It can also be reduced by choosing components which 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.

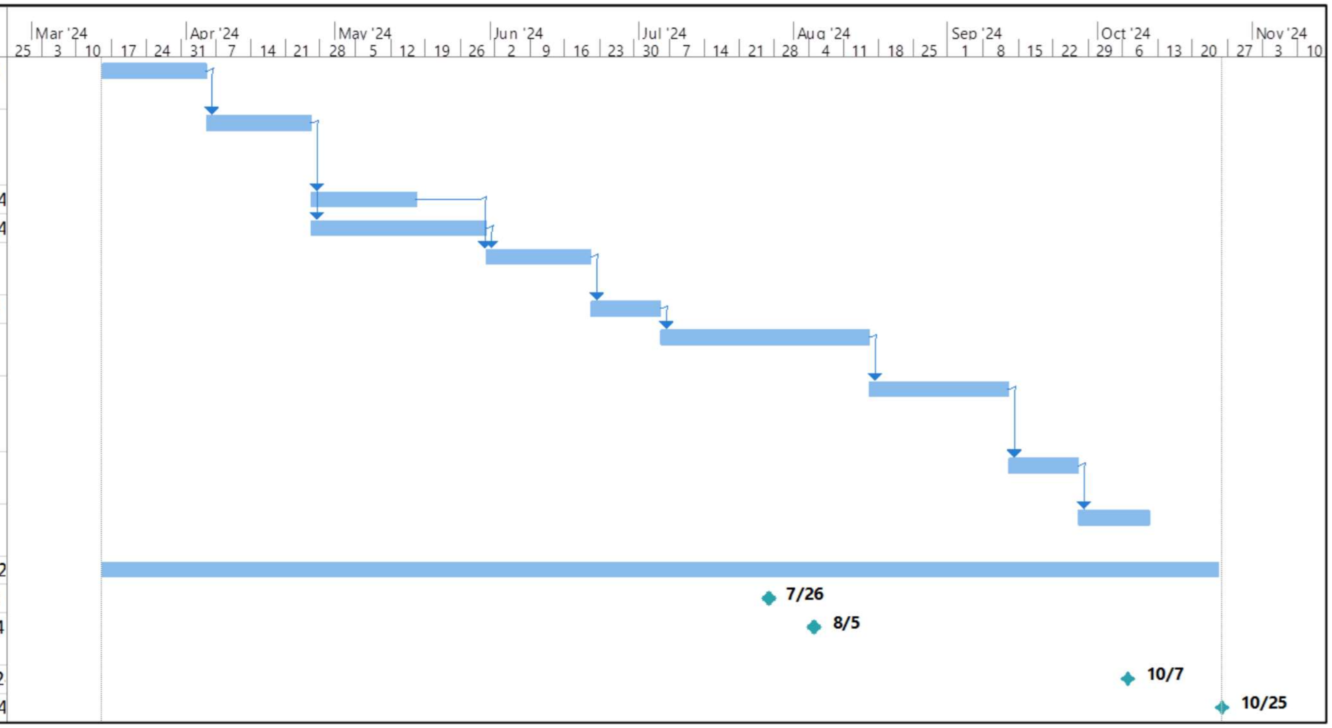
Appendix A

Gantt Chart and budget

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

Gantt Chart

Task Name	Duration	Start	Finish
Decide on the type of propulsion	3 wks	Fri 3/15/24	Thu 4/4/24
Transfer of potential energy to the rotor tips	3 wks	Fri 4/5/24	Thu 4/25/24
Pitch control	3 wks	Fri 4/26/24	Thu 5/16/24
Pitch control syster	5 wks	Fri 4/26/24	Thu 5/30/24
Pitch and rotor position sensing	3 wks	Fri 5/31/24	Thu 6/20/24
Computations	2 wks	Fri 6/21/24	Thu 7/4/24
Rotor and aircraft design	6 wks	Fri 7/5/24	Thu 8/15/24
Build the tip propelled rotary aircraft	4 wks	Fri 8/16/24	Thu 9/12/24
Test the directional thrust	2 wks	Fri 9/13/24	Thu 9/26/24
Evaluation and repetition	2 wks	Fri 9/27/24	Thu 10/10/24
Report writitng	160 days?	Fri 3/15/24	Thu 10/24/2
Progress Report	0 days	Fri 7/26/24	Fri 7/26/24
Project progress presentation	0 days	Mon 8/5/24	Mon 8/5/24
Draft final report	0 days	Mon 10/7/2	Mon 10/7/2
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 Labour		MMW Material	Total
	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**

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