DE-41 (DME)

NUST COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

DESIGN AND FABRICATION OF AN ORNITHOPTER

PROJECT REPORT

DE-41 (DME)

Submitted by

NC ABDUL REHMAN

NC DANIAL AHMAD

NC IJAZ AHMED

BACHELORS

IN

MECHANICAL ENGINEERING

YEAR

2023

PROJECT SUPERVISOR

DR. IMRAN AKHTAR

PROJECT CO-SUPERVISOR

DR. ZAFAR BANGASH

NUST COLLEGE OF
ELECTRICAL AND MECHANICAL ENGINEERING
PESHAWAR ROAD, RAWALPINDI

DECLARATION

We hereby declare that no portion of the work referred to in this Project Thesis has been submitted in support of an application for another degree or qualification of this of any other university or other institute of learning. If any act of plagiarism is found, we are fully responsible for every disciplinary action taken against us depending upon the seriousness of the proven offence, even the cancellation of our degree.

COPYRIGHT STATEMENT

ACKNOWLEDGEMENTS

Thanks to Allah Almighty for giving us the knowledge, strength, and patience to carry out all this work and making us able to follow our passion with ease. We would also like to thank our parents who have supported us throughout our education here and have motivated us whenever we needed it to move forward towards the completion of this project.

Furthermore, we would like to thank our supervisor Dr. Imran Akhtar and our co-supervisor Dr. Zafar Bangash for providing us with all the assistance and guidance when needed. We would also like to thank Dr. Mohsin Islam Tiwana, Sir Hamza Ahmed, Sir Usman Aslam, Dr. Taosif Iqbal, Dr. Anas Bin Aqeel, and Sir Rameez Raja and our degree mates Muhammad Rafay and Maaz Ali for their support in this project. We would also like to express our sincere gratitude to Usman Jahangir for his support in this project.

ABSTRACT

Nature has always inspired us to solve our problems in a different way. Quadcopters, one of the most common and commercially available unmanned aerial vehicles, are good for cinematic shots, spying and even various other things, but they cannot glide like the fixed wing planes. On the other hand, fixed wing planes lack the ability to hover when subjected to a confined space. Inspired by the complex flight dynamics of a hummingbird which is the only bird capable of hovering and generating thrust on both forward and backward stroke. And additionally, its weight is around 20g, which is why we decided to replicate the flight of a bird in a feasible manner. In this project, we present some cost and time-effective prototypes for such micro aerial vehicles. Because of the inter-dependence of power, cost, availability, and size of various components involved, their selection was a tedious process, and intensive research and literature review was done to ensure minimal financial loss. To realize a compact and reliable control mechanism, we made two prototypes based on an optimized string-based flapping mechanism and a gear-linkage based flapping mechanism. The completed prototype has a flapping frequency of 15 Hz and a full wingspan of 275mm.

This report covers the design process for both mechanical and electrical systems involved in making an ornithopter along with their component selection and a comparison of the similar projects conducted in the campus as well as some of the successful prototypes from all over the world.

TABLE OF CONTENTS

Chapter 1

INTRODUCTION

Chapter 2

REVIEW OF AERODYNAMICS

Chapter 3

LITERATURE REVIEW

Chapter 4

FLAPPING MECHANISM

Chapter 5

WING DESIGN

Chapter 6

CONTROL MECHANISM

Chapter 7

ON-BOARD AVIONICS AND COMPONENT SELECTION

Chapter 8

BODY DESIGN

Chapter 9

SIMULATOR AND OTHER ASSISTIVE TOOLS

Chapter 10

TESTING AND EVALUATION

Chapter 11:

CONCLUSIONS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

C_L Coefficient of lift

L Lift Force

C_D Coefficient of Drag

D Drag Force

T Thrust Force

W Weight

q_s Dynamic Pressure

Re Reynolds Number

ρ density

V Velocity

l characteristic length

μ dynamic viscosity

Φ Flapping Angular Speed

C(r) Spanwise chord distribution

C_L Lift coefficient

ρ_{air} density in kgm^{-3}

S Area of one wing

N Number of wings

R Half of wingspan

C_T Thrust coefficient for one wing

V_{ref} Reference speed

Chapter 1:
INTRODUCTION

Humans have long found inspiration in nature, leading to remarkable inventions that imitate natural beings. In recent years, biologists have conducted studies to model the complex aerodynamic mechanisms of bird flight, resulting in the development of ornithopter. Ornithopters, designed on the basis of the flapping mechanisms of birds, have given rise to various projects such as the Delfly from Delft University [1], Techjet by Georgia Tech [2] , Roboraven by the University of Maryland [3], Robobee from Harvard University[4] , Nano Hummingbird by Aerovironment [5] , Robotic Hummingbird by Texas A&M University [6], and Colibri by the Université Libre de Bruxelles [7].

However, it is important to note that these projects had certain limitations that hinder their performance as compared to their biological counterparts. For example, Roboraven lacked the ability to hover, instead relied on forward speed to stay aloft. The Delfly and Techjet differed significantly from their counterpart natural flyers, featuring four wings with external vanes and fins. Although the Robobee could hover, but it needed to be tethered to the ground due to its high voltage demand. Additionally, the Colibri experienced flapping frequency and flight autonomy issues, while the Nano Hummingbird was costly due to its mechanical complexity.

As ornithopters draw inspiration from nature, it is believed that their agility surpasses that of quadcopters and other types of drones. Thus, the focus of our project was to develop ornithopters based on the flapping mechanism of hummingbird and pigeon, aiming to gain insights into their aeromechanics, and flight dynamics. Our primary goal was to create remote-controlled ornithopters capable of controlling roll, pitch, yaw, and thrust.

One of the ornithopters was inspired by the clap and fling mechanism that is exhibited by a pigeon during take-off. The second ornithopter was inspired by the lemniscate-shaped flapping mechanism of a hummingbird and it additionally incorporated a flight control board. This ornithopter focused on mimicking the intricate wing movements and agility of hummingbirds while also incorporating advanced flight control capabilities. By integrating a flight control board, we aimed to achieve precise maneuverability and stability in flight, enabling greater control over roll, pitch, yaw, and thrust.

1.1 Unmanned Aerial Vehicles

Unmanned Aerial Vehicle (UAV), also known as drone, is an aircraft which does not have any human pilot on-board. It can be remote-controlled or can be autonomous. Initially it was made for military operations but now it is being widely used for video logging, experimentation, photography, inspecting crops and farms, for search and rescue operations during complex missions as well as exploring all type of terrains.

1.2 Classification of Unmanned Aerial Vehicles

Unmanned Aerial vehicles can be classified on the basis of:

- Size
- Maximum Take-off weight
- Operating Altitude
- Speed

We will just focus on the classification based on the size of UAVs, since all the other classifications are quite simple.

For the classification of UAVs according to their size, we have some criteria [8] shown in figure 1.1:

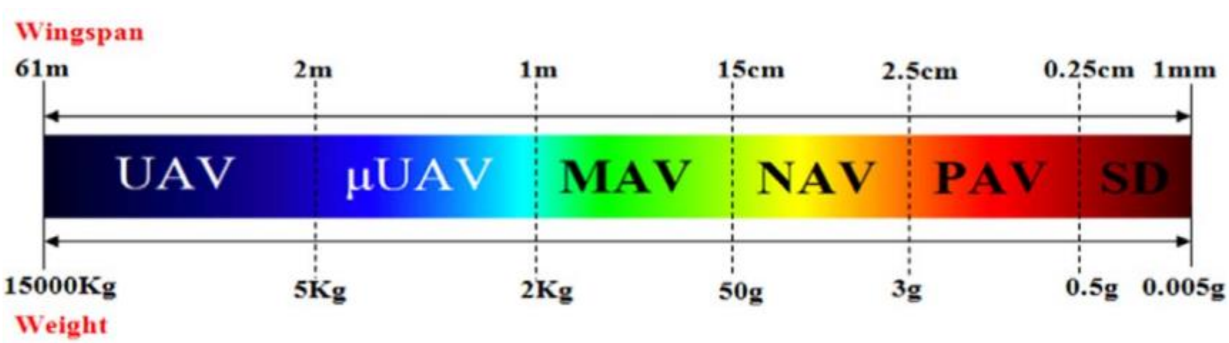

Figure 1.1: Spectrum of Drone Classification

1.3 Rationale for Micro Aerial Vehicles

Micro Aerial vehicles have gained a significant amount of attention in the recent years due to their potential benefits which bridges the gap between quadcopters and fixed wing aircrafts. Since the quadcopters are good at their ability to hover but their rotors can pose threat to human lives if they are flying in close proximity to human population. And on the other hand, fixed wing aerial vehicles lack the ability to hover. Therefore, they are not suitable for tasks which are in confined spaces. However, flapping wing vehicles are suitable for both tasks, involving hovering at a place and gliding over long distances.

1.4 Bird Flight

The flight of a bird can involve various phases like gliding, hovering, take-off, and landing. But not all birds are capable of hovering; only the hummingbird has made an exception to this trend. Contrary to that, most birds can glide except for the hummingbird. This section explores the different phases of bird flight and highlights the unique abilities of certain bird species.

1.5 Insect Flight

The flight of an insect [8] differs from that of a bird in many ways, and some of it is illustrated in figure 1.2.

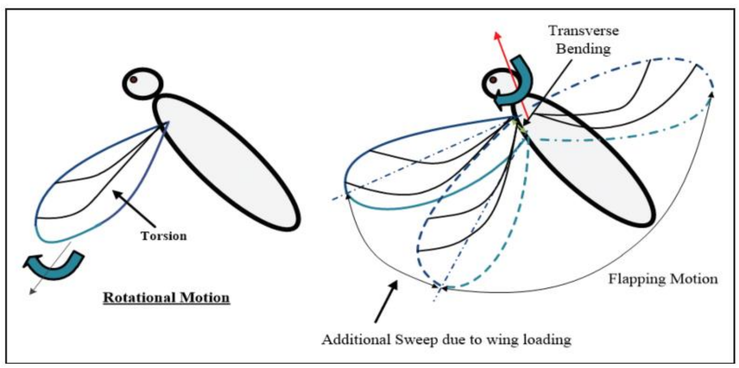

Figure 1.2: Schematic of flight of an insect

Considering the mechanics behind the flight of an insect [8] and comparing it to some of the approaches when designing the flapping mechanism for an insect-based micro aerial vehicle, we can first simplify its biological counterpart and then make a flapping mechanism using a rotary or a crank-slider mechanism as shown in figure 1.3

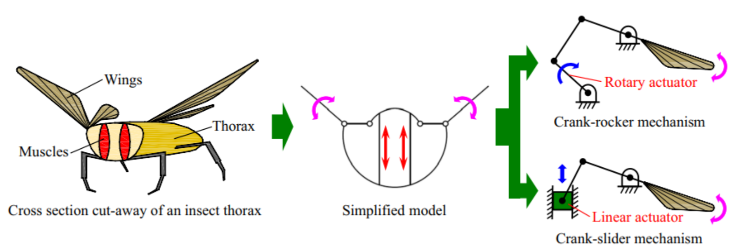

Figure 1.3:Illustration for understanding the flight of an insect

1.6 Hummingbird Flight

The flight of a hummingbird resembles more to an insect than to a bird. It has the ability to hover, a skill that all other birds lack. In addition, hummingbirds generate lift in both the forward and backward strokes, unlike all other birds, which generate lift only in the downward stroke. Figure 1.4 visually demonstrates the flight pattern of a hummingbird. This section delves into the similarities between hummingbird flight and insect flight and emphasizes the distinctive abilities of hummingbirds.

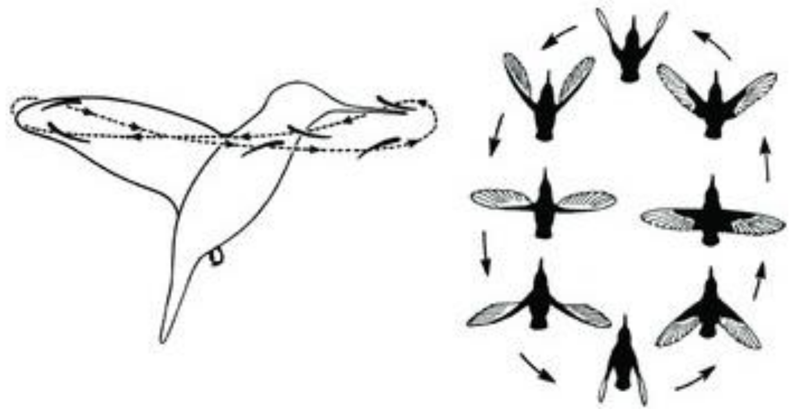

Figure 1.4: Flight of a hummingbird

1.7 Importance of Micro Aerial Vehicle

Micro aerial vehicles (MAVs) play a crucial role due to their lightweight nature and potential for energy-efficient flight. They have significant applications in surveillance as well as search-and-rescue operations. This section highlights the importance of MAVs and their advantages in various domains.

1.8 Recent Developments

Recent developments in MAV technology have focused on increasing flight endurance and seeking safe and energy-efficient alternatives to rotary and fixed-wing aerial vehicles. Researchers are exploring flapping wing mechanisms for micro aerial vehicles. This section discusses the latest advancements and innovations in the field of MAVs.

1.9 Limitations

Despite various research efforts, some projects face limitations, particularly those without sufficient funding. Non-funded research initiatives often encounter obstacles due to the lack of resources required for research, testing, equipment, and machining costs. This section addresses the limitations faced by such projects and the impact of inadequate funds on their progress.

Chapter 2:
REVIEW OF AERODYNAMICS

Since the dawn of the stone age, humanity has been captivated by the graceful flight of birds. Throughout history, humans have looked up at these feathered creatures, wondering with awe and curiosity, pondering the secrets behind their flight. A partial role in this curiosity has been the desire of humans to fly themselves as well.

Ever since many attempts have been made in the direction of flying like the birds in the sky. Balloons filled with hot air can fly but they are not very much maneuverable. Apart from balloons, kites were also one of the first things that humans were able to make fly. They were first used as signaling instruments by the Chinese which they used to send signals across long distances. Later, Sir George Cayley, a British aviator, who is also known as “The Father of Aerial Navigation” studied kites and discovered the most basic principles of flight which are the foundation of the modern science of aeronautics [8]. One of the illustrations for his works can be seen in figure 2.1.

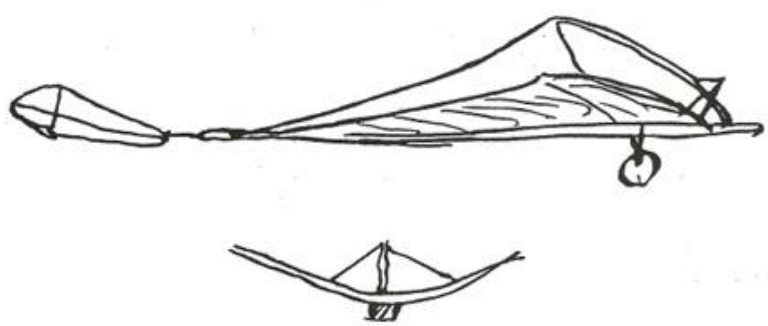

Figure 2.1: Cayley Glider

After the discoveries of Cayley, many new designs of flying machines were proposed by scientists. A big monoplane was designed by William Samuel in 1842 which was run on a steam engine enclosed in a fuselage. This proved to man that even heavy objects could be lifted using the principles of flight. This fact was also proved by Otto Lilienthal when he proved that manned flight in air is possible although man is heavier than air. This helped humanity realize the dream of powered flight which was fulfilled by the Wright brothers on 17th December 1903 who successfully attained the first ever powered, sustained and controlled airplane flight.

Before we can go ahead with the aerodynamic modeling of an ornithopter, it is essential to review the basic aerodynamic concepts which will help in better understanding of the more advanced concepts relating to unsteady aerodynamics. In this chapter first conventional fixed aerodynamics has been presented and then flapping wing aerodynamics has been focused upon. Fixed wing MAVs are largely governed by steady aerodynamics, whereas flapping wing aerodynamics is characterized by unsteadiness whose knowledge is still developing. For large birds with slow flapping rate, it is less unsteady but for small birds and insects, the aerodynamics are highly unsteady.

2.1 Fixed Wing Aerodynamics:

In aerial vehicles that rely upon fixed wings for their flight, there are four forces acting on the body of the flying aerial vehicle. These four forces can be seen in the figure 2.2:

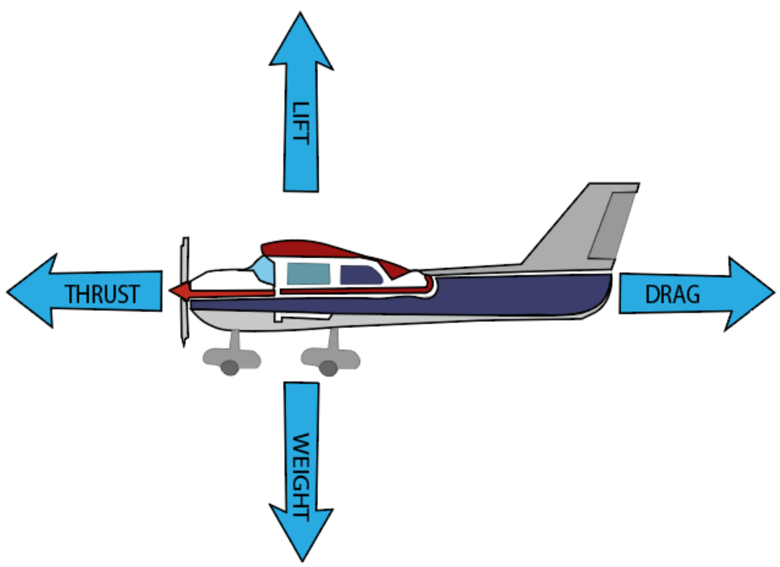

Figure 2.2: Forces on an aircraft

The four forces acting upon an aircraft are discussed below:

a. Weight: It is the total weight of the aircraft that is acting vertically downwards on the center of gravity of the aircraft.
b. Lift: It is the force generated by the aircraft to make it fly. This force acts perpendicular to wind direction.
c. Thrust: It is the force that propels the aircraft in the direction of motion. This force is generally generated by the propellers or the rotors on the aircraft. This force acts in

the direction opposite to drag to overcome it. Under normal cruise conditions this force acts along the longitudinal axis of the aircraft.

d. Drag: It is the force that is produced due to the movement of the aircraft through the air. This force acts in the direction parallel to the wind. This is the unwanted force on the aircraft and while designing aircraft efforts are made to minimize this force.

2.1.1 Aerodynamic Force on Airfoil:

All the fixed wing air vehicles depend upon the profile of their wings for the generation of lift. This specific profile or shape is called an airfoil. Aerodynamic force is produced by the interaction of the air flowing on the top and bottom surface of the airfoil. This interaction of air and the airfoil develops a pressure difference between the top and bottom surface of the airfoil that results in an aerodynamic force on the wing as can be seen in the figure 2.3:

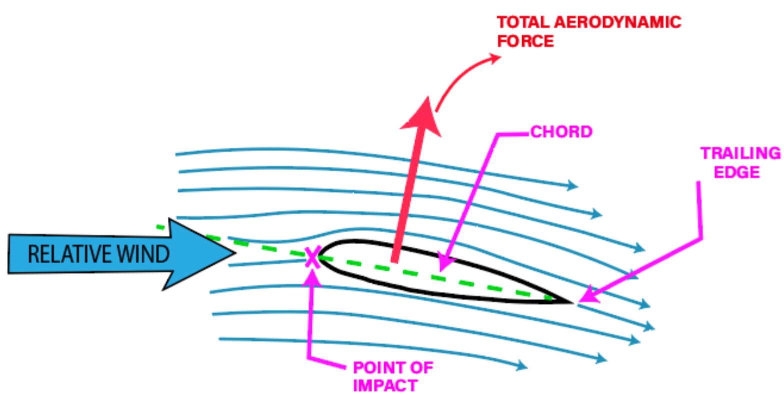

Figure 2.3: Aerodynamic Force on an airfoil

2.1.3 Terminologies related to airfoil:

Apart from the aerodynamic force, there are some other terminologies that can be associated with the airfoil. These terminologies are shown in figure 2.4 to aid in understanding them visually.

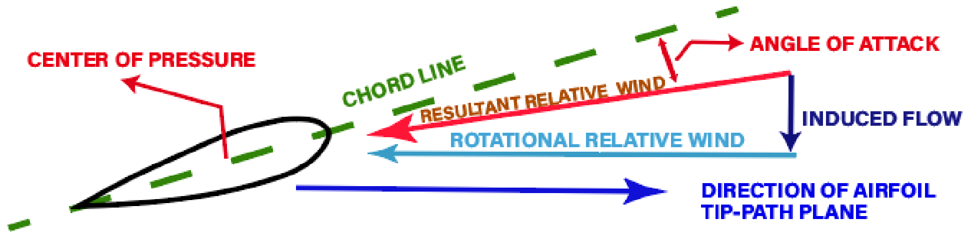

Figure 2.4: Angle of Attack, Induced Flow and Relative Wind

2.1.4 Lift and Drag Force:

The aerodynamic force acting on the airfoil can be resolved into two forces. One of these two forces will be perpendicular to the relative wind speed. This force by definition is the lift force. The other force is parallel to the relative wind speed. This is the drag force. The resolution of the aerodynamic force can be seen in figure 2.5:

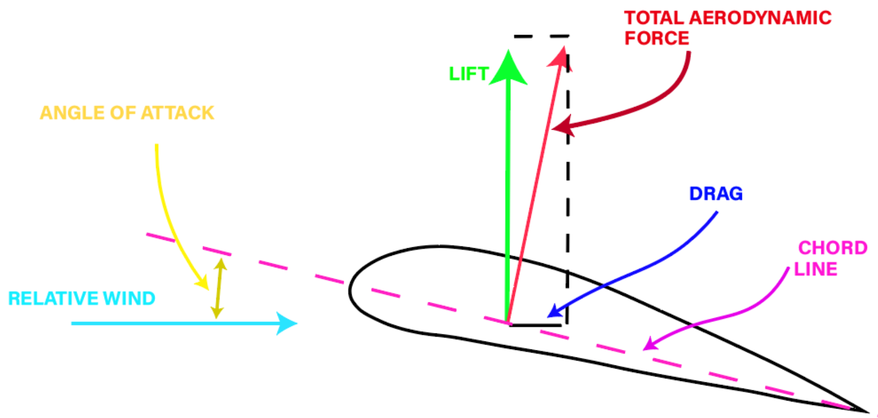

Figure 2.5: Lift and Drag Forces

2.1.5 Lift and Drag Coefficient:

Lift coefficient is a dimensionless quantity used to characterize the lift force.

Lift coefficient can be defined as the ratio of the lift force generated and the dynamic pressure.

$$C_L = \frac{L}{q_s} \qquad (1)$$

Drag coefficient is a dimensionless quantity used to characterize the drag force.

Drag coefficient can be defined as the ratio of the drag force generated and the dynamic pressure.

$$C_D = \frac{D}{q_s} \qquad (2)$$

The graph [9] for the values of lift and drag coefficient for a generic airfoil against the angle of attack can be seen in figure 2.6:

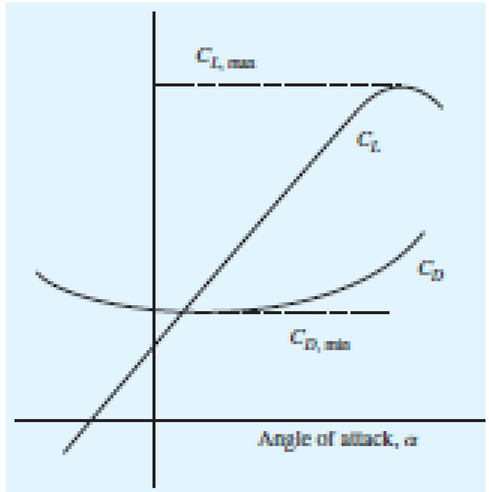

Figure 2.6: Lift and Drag coefficients versus Drag

2.1.6 Lift to Drag Ratio:

The lift-to-drag ratio (L/D ratio) is a measure of the efficiency of an aircraft, typically an airplane, in generating lift compared to the amount of drag it produces. It is an important parameter in aviation as it affects the overall performance, fuel efficiency, and range of an aircraft.

Mathematically, this quantity can be represented as $\frac{L}{D}$ or $\frac{C_L}{C_D}$.

The graph showing the lift-to-drag ratio [10] against the changing angle of attack can be seen in figure 2.7:

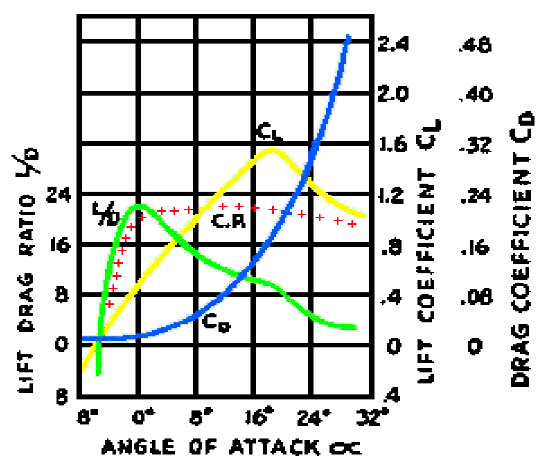

Figure 2.7: Lift Drag Ratio versus Angle of Attack

2.1.7 Reynolds Number:

Reynolds number is a dimensionless number used in fluid mechanics used to characterize the flow of fluids. It can be defined as the ratio of the inertial forces to the viscous forces within a fluid flow. The formula that can be used to calculate the Reynolds number is as follows:

$$Re = \frac{\rho * V * l}{\mu} \qquad (3)$$

The significance of Reynolds number lies in the fact that it can tell us about the type of flow. The value of Re tells us if the flow is laminar or turbulent.

Understanding the Reynolds number is crucial in designing efficient systems involving fluid flow, such as pipelines, aircraft wings, and cooling systems, as it helps determine the appropriate flow regime and optimize the performance and efficiency of these systems.

2.1.8 Vortex Shedding and its effects:

Vortex shedding is a phenomenon that occurs when a relative motion between a fluid and solid object takes place, such as flow past a circular cylinder or an airfoil, creating vortices in the wake of the solid body. The vortices are formed because of the intersection between the fluid flow and the object's geometry.

Some of the effects of vortex shedding on the various aerodynamic parameters are given below:

a. **Lift and Drag:** Vortex shedding can contribute to the lift and drag forces of an object. For example, in case of an airfoil passing through the air, vortex shedding generates lift by inducing a pressure difference between the upper and lower surface of the airfoil. However, on the other hand the same vortex shedding will also be causing an induced drag in the body which will contribute to the total drag of the body

b. **Vibrations and Oscillations:** Vortex shedding can cause resonance in structures. This happens when the frequency of vortex shedding becomes equal to the natural frequency of the structure.

c. **Flow Control:** Vortex shedding can be harnessed for flow control purposes. By manipulating the shedding process, the aerodynamic characteristics of an object can be modified. Engineers do this to change the lift and drag coefficients of objects, such as airfoil, to improve performance in certain operating conditions.

2.1.9 Aspect Ratio:

The Aspect ratio is a geometric parameter that describes the proportion between the wingspan squared and the total surface area of the wing. It can be calculated using equation 4.

$$Aspect\ Ratio = \frac{b^2}{S} \qquad (4)$$

2.2 Flapping Wing Aerodynamics:

Flapping wing aerodynamics refers to the study of the airflow and forces involved in the flight of organisms or engineered systems that employ flapping wings, such as birds, insects, and ornithopters. Understanding the aerodynamics of flapping wings is crucial for designing efficient flying mechanisms and optimizing flight performance.

Flapping wing aerodynamics is a complex and multidisciplinary field that combines fluid dynamics, biomechanics, and control theory. The study of these principles helps researchers and engineers in designing and optimizing flapping wing systems for a variety of applications, including bio-inspired unmanned aerial vehicles (UAVs), and micro and nano air vehicles.

2.2.1 Strouhal Number and its influence:

The Strouhal number is a dimensionless parameter that characterizes the unsteady flow behavior around objects. It is defined as the ratio of the characteristic length scale of the flapping motion to the characteristic time scale of the motion. Equation 6 can be used to calculate the Strouhal number.

$$St = \frac{f * l}{V} \qquad (6)$$

Strouhal Number plays a major role in determining the aerodynamic performance of a flapping air vehicle. Some of its key influences are discussed below:

a. **Thrust Generation:** The Strouhal number affects the ability of the ornithopter to generate thrust. At a low Strouhal number, the phenomenon of vortex shedding and flow separation from the boundary layer takes place which results in poor thrust generation. As the value of the Strouhal number increases, the efficiency of thrust generation increases. Generally, the ranges of Strouhal number which can be used to know if thrust will be produced or not are mentioned in Table 2.1.

Table 2.1 Table Representing range of Strouhal Number and the corresponding effects:

Strouhal Number St	Effect
St < 0.2	Drag will be produced
0.2 < St < 0.4	Neutral
St > 0.4	Thrust will be produced

b. **Efficiency:** Strouhal Number also influences the energy expenditure of an ornithopter. If the Strouhal number is too high or too low, this would result in reduced efficiency as an effective conversion of flapping motion into thrust would not occur.

2.2.2 Wing Kinematics:

The flapping wing can exhibit three distinct motions along different axes:

a. Flapping: This refers to the up and down motion of the wing, resembling a plunging movement. Flapping is responsible for generating the majority of the bird's power and offers the largest degree of freedom. Typically, it has a range of motion from forty degrees downward to ninety degrees upward. In most ornithopter designs, flapping is the primary mechanism used to generate lift and thrust.

b. Feathering: Feathering involves the variation of the wing's pitch angle. It can vary along the wing's span due to rotations in the bird's wing joints (shoulder, elbow, and hand) and the flexibility of feathers and bone structure.

c. Lead-lag: Lead-lag refers to the in-plane lateral rotation of the wing around the bird's vertical axis.

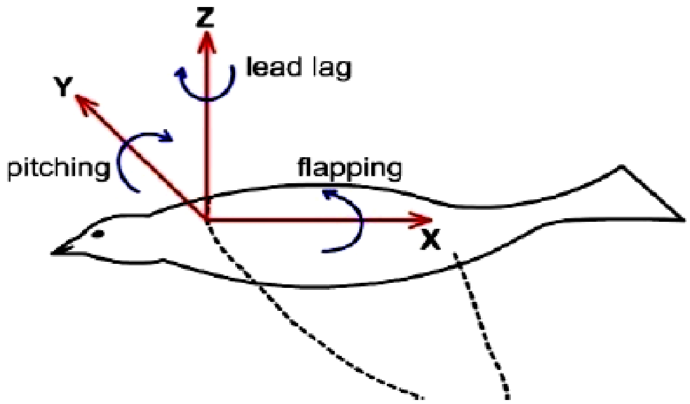

Figure 2.8: Angular movement of wing [8]

These three wing motions, shown in figure 2.8, play essential roles in the flight of birds and the design of ornithopters. Flapping generates lift and thrust, feathering provides flexibility and control, and lead-lag contributes to stability. Understanding and optimizing these wing kinematics is crucial for achieving efficient and biomimetic flight in ornithopter designs.

Chapter 3: LITERATURE REVIEW

Some of the common steps which are followed for the development of nano or micro aerial vehicles are shown below:

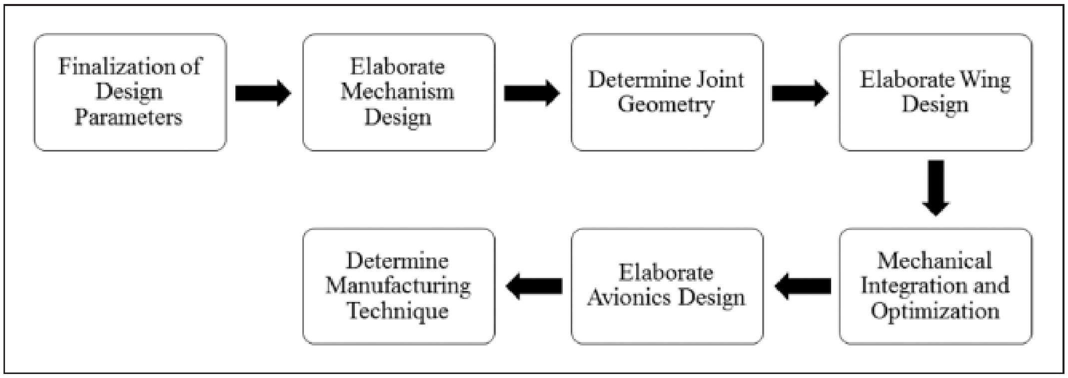

Figure 3.1: Different steps for MAV or NAV Development [12]

3.1 Types of Models

Different types of models have been developed by various institutions and they have been based on different biological flyers, some features of some biological flyers [12] are shown in table 3.1.

Table 3.1 : Important wing design parameters for some natural flyers

S. No.	Biological flyers	Aspect Ratio	mass(g)
1	Chalcid Wasp	4.24	2.6×10^{-7}
2	Fruit fly	6.12	9.6×10^{-04}
3	Honeybee	6.65	0.1
4	Hawkmoth	5.3	1.6
5	Rufous Hummingbird	9	3.4
6	Giant Hummingbird	6	20

And for the wingbeat frequencies, we have the following data for some of the flyers in table 3.2

Table 3.2 : Wingbeat frequencies of some natural flyers[12]

Flyer	Bats	Hummingbird	Dragonfly	Butterfly	Pigeon	Honeybee
Frequency (Hz)	12	50	38	13	7	220

3.2 Wing Materials and Arrangements

For the fabrication of flapping wings, initial material selection for the wing and wing arrangement is crucial to the flight.

The number of possible wing arrangements are:

- Monoplane

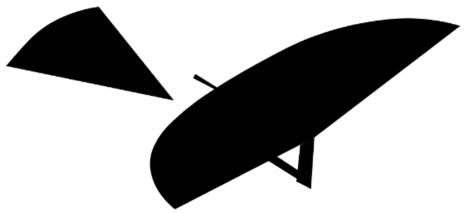

Figure 3.2: Monoplane configuration

One wing plane, and these(as in figure 3.2) have been popular since the 1930s for fixed wing aircrafts.

- Biplane

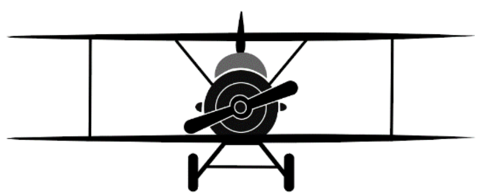

Figure 3.3: Biplane configuration

For biplane configuration, we have two wing planes of similar size, where the wings are stacked one above another as in figure 3.3.

- Tandem Wing

  This wing design has two wings where the wings are one behind the other as visible in figure 3.4.

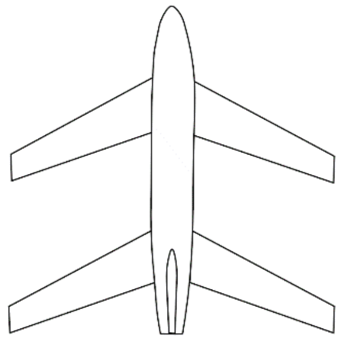

Figure 3.4: Tandem Arrangement

For the wing materials, we have the following options available:

- Mylar Film
- Polyimide (PI) Film
- Polyethylene (PE) Film
- Parylene Membrane
- Latex Rubber

3.3 Body Material

- Expanded-Polypropylene
- Styrofoam
- Balsa Wood

3.4 Control Method

- Wing Twist Modulation
- Wing Rotation Modulation
- Stroke Plane Modulation
- Flapping rate modulation
- Flapping amplitude modulation

For different researchers and their prototypes, we get the following control mechanisms as mentioned in Table 3.3.

Table 3.3 : Different Researchers and their prototypes

S. No.	Author	MAV	Control technique
1	Bejgerowski et al. [11]	-	Novel parallel crank-rocker mechanism
2	Finio et al [12]	-	Three perpendicular piezoelectric actuator
3	Fenelon et al. [18]	SF-3	Differential Steering
			Steering by altering prototype CG
4	Bergou et al. [19]	-	Torsional Hinge Limiter
5	Kevin et al [4]	RoboBee	split-cycle constant-period frequency
6	Keennon et al.[5]	Nano Hummingbird	Wing twist and Wing rotation modulation
8	Nguyen et al. [15]	FW-MAV	Passive wing pitch
			Servo controlled rudder and actuator

3.5 Linkage Mechanisms for Flapping:

When considering the linkage mechanisms for a flapping micro aerial vehicle, we have some of the possibilities as mentioned in Table 3.4 which we compiled from multiple sources.

Table 3.4 : Different international researches and their Linkage Mechanisms

S. No.	Author	Drive mechanism weight (g)	Linkage type
1	Galiński et al. [16]	-	2 Scotch Yokes and Universal Joint
2	Finio et al. [12]	-	Four-bar Linkage
3	Bejgerowski et al. [16]	1 .5	Four-bar Linkage
4	Fenelon [18]	-	Crank Slider mechanism
5	Keenon et al.[5]	2.47	Crank Rocker mechanism attached with Four-bar Linkage

6	Truong et al [17]	-	Combination of Scotch Yoke and Crank Slider mechanism
7	Phan & Park [18]	-	Stroke Plane Change (SPC) mechanism
8	Peng et al. [10]	1.34	Crank Slide Mechanism
9	Jang et al. [24]	-	Combination Of slider crank and three bar linkage mechanism

3.6 Actuators:

Different actuation mechanisms and their efficiencies [12] which were used by different researchers are compiled and mentioned as a summary in Table 3.5.

Table 3.5 : Different Actuation Mechanisms and their efficiency

Actuator	Operating principle	Efficiency (%)	Comments
Piezoelectric	Converse	10-30	A simple planar structure requiring high operating voltage
Motor	piezoelectric effect Coil rotation	-	
Electrostatic	Electrostatic force	>90	Operates on principle of electro-motive force (EMF) Operates on very high voltage Requires MEMS manufacturing process
Elastomer Thermal	deformation Thermal expansion	<5	Different geometries with wide material range Requires high energy density
SMA (Shape memory alloy)	Thermal phase change	<5	Requires high energy density

For the max deflection, max force and the actuation speed of the actuators, we have a general summary[12] compiled in table 3.6.

Table 3.6 : Different Actuation mechanisms and some of their features

Actuator	**Max deflection**	**Max force**	**Actuation speed**
Piezoelectric	High	Medium	Fast
Motor	3600	Medium	Very fast
Electrostatic	Low	Low	Very fast
Elastomer Thermal	Medium	Very High	Slow
SMA (Shape memory alloy)	High	Very High	Slow

Different types of actuators which were employed by different researchers are by compiling the data, we have a summary in table 3.7.

Table 3.7 : Different Researchers and their Actuation Specifications

S. No.	Author	Actuator specifications
1	Galiński et al. [21]	Rotary DC motor
2	Zdunich [22]	Astro flight 020 brushless motor
3	Finio BM et al. [17]	Piezoelectric actuator
4	Bejgerowski et al. [16]	DC pager motor
5	Baek et al. [26]	DC Electric Motor
6	Keennon et al. [5]	DC Electric Motor
7	George et al. [25]	Brushless DC Maxon Motor EC 40-1 18899 and 16-232241
8	Teoh & Wood [27]	Piezoelectric bimorph actuators

9	Truong et al. [22]	Electromagnetic Motor
10	Nguyen[20]	3.1 gram brushless motor AP-03, kv=7000

3.7 Flapping Frequencies:

Flapping frequency also plays a vital role in making flapping based micro aerial vehicles, and for that reason, we have compiled a data for flapping frequencies of various successful micro aerial vehicles in Table 3.8.

Table 3.8 : Different Micro Aerial Vehicles and their Flapping Frequencies

S. No	Author	MAV	Flapping frequency (Hz)
1	Galiński and Zbikowski [21]	-	20
2	Zdunich et al. [25]	Mentor	30
3	Finio et al. [17]	-	30
4	Bejgerowski et al. [16]	-	>71
5	Baek et al. [26]	Hummingbird Inspired MAV	18.8
6	Phillip and Knowles [32]	Flapperatus (Ground setup)	20
7	Keennon et al. [5]	Nano Hummingbird	30
8	Truong et al. [22]	-	38.5
9	Nguyen et al. [20]	Hybrid insect-inspired design	12.4
10	Peng et al. [10]	-	8.5
1 1	Karásek et al. [30]	Delft Inspired MAV	17
12	Jang & Yang [24]	Dragonfly Inspired MAV	15

For the kinematic specifications and material choices, we have compiled the data in table 3.9.

Table 3.9: Material Choice for various prototypes

S. No	Author	Material	Kinematics
1	Bejgerowski et al. [16]	HIVAL ABS HG6	Flapping Amplitude: 65°
2	Sreetharan [31]	Carbon fiber reinforced polymer	Flapping Amplitude: 100° Rotation Amplitude: 120°
3	Keennon et al. [5]	Aluminum PEEK	Flapping Amplitude: 180°
4	George et al. [27]	-	Rotation Amplitude: 180° Elevation Amplitude: 160° Feathering Amplitude: 360°
5	Truong et al. [22]	Carbon fiber sheet Delrin	Flapping Amplitude 111°
6	Nguyen et al. [20]	high gloss carbon fiber sheet	Flapping Amplitude: 125°

3.8 On-campus Projects at EME

Different attempts have been made even at the NUST College of EME Campus, but unfortunately none of those were capable enough to qualify for a successful flight due to several reasons. 6 graduation projects with their supervisors were compiled in Table 3.10:

Table 3.10: Final Year Projects in EME Campus related to micro aerial vehicles

Title	**Year/Degree**	**Supervisor**
Design, analysis and fabrication of a flapping wing micro aero vehicle (MAV)	2011/ME-29	Muhammad Saif Ullah Khalid
Bio inspired flapping wing model based on Corvus Splendens	2014/MTS-32	Dr. Khurram Kamal
Bio inspired flapping wing model based on Corvus Splendens	2015/MTS-33	Dr. Khurram Kamal
Corvus Splendens Based Flapping Wing UAV	2016/MTS-34	Dr. Khurram Kamal
Design and fabrication of micro air vehicle i.e. Ornithopter	2018/ME-36	Dr. Imran Shafi & Dr. Sadia Riaz
Flapping wing micro aerial vehicle	2022/MTS-40	Dr. Anas bin Aqeel, Dr. Uzair Khaleeq uz Zaman, Kanwal Naveed

The graduation projects from 2014 to 2016 in the Mechatronics Department were a continuation of the same project based on its biological counterpart of a crow. Therefore, after refining the table 3.10, we get Table 3.11.

Table 3.11: Projects related to MAVs in College of EME

Title	Active Years	Supervisor
Design, analysis and fabrication of a flapping wing micro aero vehicle (MAV)	2011	Muhammad Saif Ullah Khalid
Bio inspired flapping wing model based on Corvus Splendens	2014-2016	Dr. Khurram Kamal
Design and fabrication of micro air vehicle i.e. ornithopter	2018	Dr. Imran Shafi & Dr. Sadia Riaz
Flapping wing micro aerial vehicle	2022	Dr. Anas bin Aqeel, Dr. Uzair Khaleeq uz Zaman, Kanwal Naveed

We will go over various aspects of these projects to know more about them.

3.8.1 Biological Counterpart:

The biological counterparts for those projects are compiled in Table 3.12.

Table 3.12: Projects and their biological counterpart

Title	Biological Counterpart
Design, analysis and fabrication of a flapping wing micro aero vehicle	-
Bio inspired flapping wing model based on Corvus Splendens	House Crow
Design and fabrication of micro air vehicle i.e. Ornithopter	Dragonfly
Flapping wing micro aerial vehicle	Barn Owl

3.8.2 Weight Comparison:

The weight comparison for those projects can be seen in the table 3.13:

Table 3.13: Weight comparison of the projects

Title	**Year/Degree**	**Target Mass**	**Total Mass**
Flapping Wing MAV	2011/ME-29	-	29g (First prototype) 50g (Second Prototype)
Bio-inspired Flapping Wing Model (Corvus Splendens)	2014/MTS-32	<400g	-
Bio-inspired Flapping Wing Model (Corvus Splendens)	2015/MTS-33	<400g	149g for model weight
Corvus Splendens Based Flapping Wing UAV	2016/MTS-34	<400g	1kg
Design and Fabrication of Micro Air Vehicle (Ornithopter)	2018/ME-36	~300g	1kg
Flapping Wing Micro Aerial Vehicle	2022/MTS-40	500g	600g

3.8.3 Flapping Mechanism:

The flapping mechanisms for those projects are as mentioned in table 3.14.

Table 3.14: Projects and their flapping mechanism

Title	Flapping Mechanism
Design, analysis and fabrication of a flapping wing micro aero vehicle (MAV)	Scotch Yoke Mechanism
Bio inspired flapping wing model based on Corvus Splendens	20:441 Gear ratio with compound gear train
Design and fabrication of micro air vehicle i.e. ornithopter	Pinion-based mechanism
Flapping wing micro aerial vehicle	Linear Gear Mechanism

3.8.4 Control Mechanism:

Control Mechanism for those projects can be seen in table 3.15.

Table 3.15: Projects and their control mechanism

Title	Control Mechanism
Design, analysis and fabrication of a flapping wing micro aero vehicle (MAV)	Gyroscopic Rings
Bio inspired flapping wing model based on Corvus Splendens	20:441 Gear ratio with compound gear train
Design and fabrication of micro air vehicle i.e. ornithopter	Pinion-based mechanism
Flapping wing micro aerial vehicle	2 Servos on Tail

3.8.5 Wingspan and Length:

Going towards the wingspan and length for those projects, we get table 3.16.

Table 3.16: Projects with their wingspan and Length

Title	Wingspan	Length
Design, analysis and fabrication of a flapping wing micro aero vehicle (MAV)	280mm, 290mm	609.6mm
Bio inspired flapping wing model based on corvus splendens	800mm	333mm
Design and fabrication of micro air vehicle i.e. ornithopter	800mm	254mm
Flapping wing micro aerial vehicle	920mm	700mm

3.9 Key Findings and Insights

After going through the existing research, we came to know about a lot of important aspect of design and fabrication of the micro aerial vehicles, and it is apparent that weight of a micro aerial vehicle is of utmost importance when it comes to a successful flight along with the wing material and body material choice.

Chapter 4:
FLAPPING MECHANISM

The flapping mechanism is a crucial component in the manufacturing of an ornithopter. This chapter focuses on the intricate design and engineering principles involved in developing efficient and effective flapping mechanisms. The objective of this chapter is to explore the various considerations and challenges faced in creating flapping mechanisms that can mimic the natural wing movements of birds while ensuring stability, maneuverability, and aerodynamic performance. By delving into the fundamental concepts and design approaches, this chapter aims to shed light on the key elements that enable the successful manufacturing of flapping mechanisms for ornithopters.

Two different flapping mechanism have been designed, one for each of the ornithopter.:

1. Linkage Based Clap and Fling Mechanism
2. String Based Flapping Mechanism

4.1 Gear Terminologies:

One common thing in both these flapping mechanisms is the use of gear train to reduce the speed of the motor and to increase the torque. So, first of all, some important terminologies related to gears are discussed below:

4.1.1 Gears:

Gears are the mechanical components with teeth that are used to transmit torque and rotational motion by interlocking their teeth with each other. They are used in various machines to change speed, direction and torque of various transmitted motions.

4.1.2 Pitch Circle:

The imaginary circle passing through the point where the two gears will mesh. If one sees at two meshing gears and their pitch circles are somehow visible, then the two pitch circles of the meshing gears would be tangent to each other.

4.1.3 Pitch Diameter:

Pitch diameter is the diameter of the pitch circle.

4.1.4 Module:

This is a standardized measure of the gear size and tooth spacing. This provides the ratio between pitch diameter and the number of teeth.

$$Module = \frac{Pitch\ Diameter}{Number\ of\ teeth} \quad (7)$$

4.1.5 Pressure Angle:

The angle between the line of action, which is actually the tangent line to the pitch circles at the point of meeting and the line perpendicular to the tooth profile at the point of contact is called the pressure angle.

4.1.6 Addendum:

It is the distance from the pitch circle to the top of the gear teeth. Addendum diameter can be defined as the diameter of the whole gear up to the top of the teeth. This diameter can be calculated using the formula:

$$Addendum\ Diameter = Pitch\ diameter + (2)(Module) \quad (8)$$

4.1.7 Dedendum:

It is the distance between the pitch circle and the bottom of the teeth. Dedendum diameter is the diameter of the gear excluding the teeth of the gear. This diameter can be calculated using the formula:

$$Dedendum\ Diameter = Pitch\ Diameter - (2.5)(Module) \quad (9)$$

4.1.8 Clearance:

It is the space between the top land and bottom land of two meshing gears. This clearance is left so that the teeth of the meshing gears do not collide with the body of each other during operation. Clearance diameter can be found using the formula:

$$Clearance\ Diameter = Pitch\ Diameter - (2)(Module) \quad (10)$$

4.1.9 Base Circle:

The base circle of a gear is a fundamental concept in gear design and refers to the theoretical circle from which the gear tooth profiles are derived. It is a hypothetical circle that is used as a reference for determining various parameters and dimensions of the gear teeth.

4.1.10 Gear Ratio:

Gear ratio is the ratio of the number of teeth of the two meshing gears. This ratio provides information about how much will the rotational speed and torque change.

4.2 CAD Modelling of a Gear:

Designing a gear in any CAD software such as the SolidWorks is a very technical task. This is because the teeth of the gear must be designed such that they should mesh with the teeth of the other gear. For the sake of gear design in Solid Works, the following steps were taken by us:

- First of all, five circles were drawn. These five circles were:
    a. Addendum circle
    b. Dedendum circle
    c. Pitch circle
    d. Clearance circle
    e. Base circle
- After drawing the five circles, we went into the equations section of Solid Works and over there we specified the number of teeth, module of the gear and the pressure angle.
- The next step was to specify the equations for the calculation of the diameter of the five circles specified above.
- After specifying the basic parameters of the gear, the involute profile of the gear is sketched. The involute profile is the general profile that is used for the teeth of the gear. Such a profile of the teeth of the gears is necessary for the smooth transmission of power between gears especially at very high speeds.
- After the involute profile is made, the profile can be extruded to form a single tooth of the gear.
- A circular pattern of this single tooth is then made to make the total number of teeth.
- After that, the extrusion for the middle part of the gear can be made.

The one thing that is required to be kept in mind is to keep the module equal for the meshing gears. If this one requirement is not fulfilled, then the two gears would not mesh properly.
It is crucial to ensure that the module is consistent for the meshing gears. This uniform module is essential to achieve proper gear meshing and ensure smooth transmission between gears.

By following the steps mentioned above and maintaining a consistent module, we can design accurate gears that would mesh perfectly with each other.

Now that we have discussed the designing of the gears, we can dive right in to designing the mechanism.

4.3 Linkage Based Clap and Fling Mechanism:

The linkage-based clap and fling mechanism is a mechanical system that mimics the motion of a hand clapping and flicking gesture.

4.3.1 Two position synthesis:

The clap and fling mechanism is based on links and the design of any linkage mechanism begins with a position synthesis. The target while performing the position synthesis was to get the output rocker, the one to which the wings will be attached, to flap by an angle of 40 degrees. The link length of the output rocker is kept at 7 mm. The two position synthesis was performed which is shown in the figure 4.1.

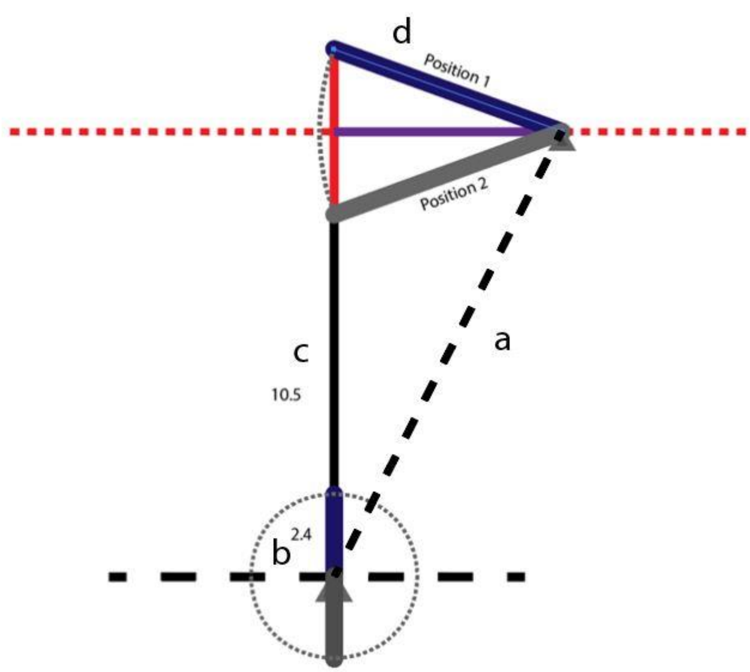

Figure 4.1: Rocker Illustration

The two position synthesis gave us the lengths of the four links that constitute this mechanism. These lengths are shown in the table 4.1.

Table 4.1: Links and their lengths

Link	Length (mm)
a	11.4
b	2.4
c	10.5
d	7

The two-position synthesis gave us a four bar mechanism, as shown in Figure 4.2, which was only for a single wing. The exact mechanism was mirror copied for the second wing as well. The next thing that we did was to extend the two output rockers such that each of them can hold two wings. This would mean that the whole mechanism will have a total of four wings which would help in generating more thrust.

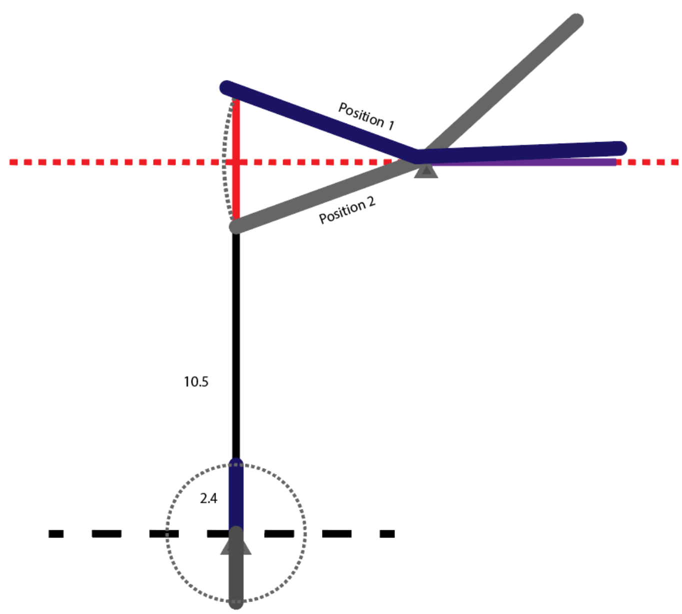

Figure 4.2: Rocker Illustration for two position synthesis

The proposed design above suggests incorporating two motors to run this mechanism. However, this approach would have inevitably led to the increase of weight of the whole mechanism. Additionally, another issue that would have arisen by adopting the dual motor strategy is the synchronization of the two wings, as the mechanism controlling each wing would be working independently.

To address the aforementioned challenges, an alternative solution was implemented, using a single motor and incorporating gears for the sake of synchronization of the two mechanisms which otherwise would have been working independently. By using a single motor, the weight of the mechanism was decreased considerably. By introducing gears into this mechanism, a mechanical contact was established between the two mechanisms, one for each side of the ornithopter. This allowed the transmission from the side which was run by the motor to the other side, as visible in Figure 4.3.

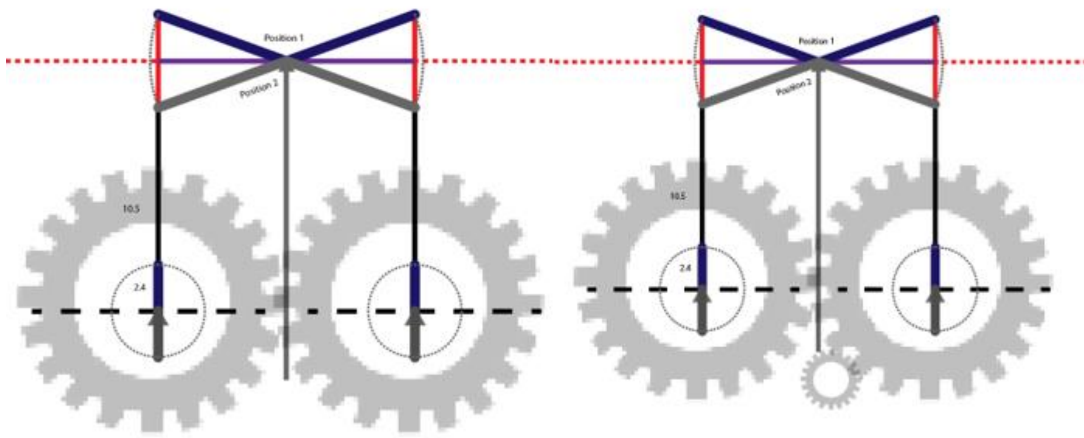

Figure 4.3: Gear and Rocker

4.3.2 CAD Modelling:

The links have been labeled in the figure. These links were designed in SolidWorks, the details of which are given below:

a. **Gear for Link b:** The first part that was designed was the gear which will effectively be the link b in the mechanism. This part, apart from being the link b, would also be responsible for transmitting the rotation from the side that is run directly by the motor to the other side.

   The gear is designed such that the pitch diameter of the gear is 11.8 mm and there are 40 teeth on the gear. Apart from the aperture of the gear, another hole was made in the gear which was at a distance of 2.4 mm which is the effective length of link b. This hole is where the joint for the next link will be made.

b. **Link c:** This part was simply a rocker between the input and the output of the mechanism. The effective length of this link was supposed to be 10.5 mm. This is why after designing a single rocker two holes were made in that at a distance of 10.5 mm. These holes are where the joints for this link will be made.

c. **Link d:** This is the output link of the mechanism. Two holes are made in this link at a distance of 7 mm. One of these holes is to keep this link attached to the ground. The next hole is to form a joint with link c. Apart from these two holes, two slots are also made in this part on the two extremes of this link for the purpose of holding the carbon fiber rods on which the wings will be mounted.

   An important aspect to consider at this point is that all the parts designed till this point will require duplicating. In simpler words, two of each component designed till now will be required.

d. **Compound Gear:** The next part that was designed was a compound gear. This compound gear is comprised of a small gear and a large gear. The large gear was the one meshed to the gear mounted on the motor. The small gear was the one that was meshed with the gear of the mechanism.

   The compound gear was not exactly in the center. It was a little bit offset so that it would mesh only with one of the two gears of the mechanism. If it had meshed with both gears, then the whole mechanism would not be operational as it would have locked up the whole mechanism.

   The larger gear of the compound gear had 40 teeth and a pitch diameter of 11.8 mm. The smaller gear of the compound gear was designed to have 9 teeth and a pitch diameter of 2.6 mm.

e. **Gear Mounted on the Motor Shaft:** The last gear that was designed was a very small gear that was mounted on the motor to transmit the rotational energy from the motor to the mechanism.

   The pitch diameter of the gear was 2 mm and the number of teeth on this gear was 7. The aperture of this gear was 0.8 mm which was also the diameter of the motor shaft on which this gear was supposed to be mounted.

   An important thing to note down is that the module of all the gears designed was kept constant because that is one of the requirements for the proper meshing of teeth. The module kept for the gears of this mechanism was 0.295. We can see the CAD model for different parts in figure 4.4.

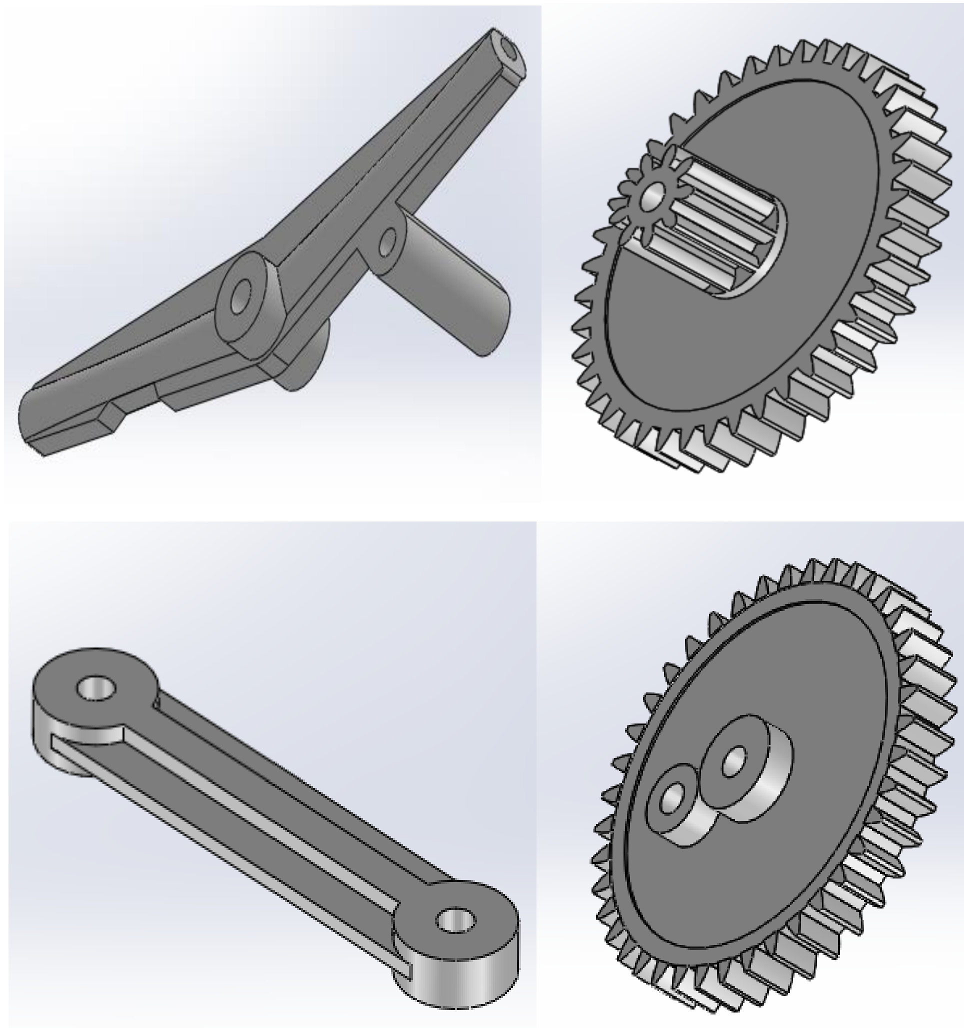

Figure 4.4: Effective links of clap and fling mechanism

f. **Gear Ratio:** The clap and fling mechanism uses a compound gear train to transmit power from the motor to the mechanism. In this section, the total gear ratio of the gear train used in this mechanism is calculated using the formula:

$$Gear\ ratio = \frac{Number\ of\ teeth\ in\ second\ gear}{Number\ of\ teeth\ in\ first\ gear} \qquad (11)$$

The first gear ratio calculated is between the gear mounted on the motor and the larger gear of the compound gear:

$$(Gear\ ratio)_1 = \frac{40}{7} = 5.71 \qquad (12)$$

The second gear ratio calculated is between the smaller gear of the compound gear and the gear of the mechanism:

$(Gear\ ratio)_2 = \frac{40}{9} = 4.44$ (13)

The total gear ratio of the gear train can be calculated as:

$Total\ Gear\ Ratio = (Gear\ ratio)_1 * (Gear\ ratio)_2$ (14)

$Total\ Gear\ Ratio = 5.71 * 4.44 = 25.4{:}1$

The gear ratio of 25.4 reduces output gear speed by a factor of 25.4 while increasing motor torque by the same factor.

g. **Base:** The base was the initial component designed for this mechanism serving as the foundation. However, its development progressed alongside the designing phase, adapting to the specific requirements of all the other parts. Before designing the base, we knew that this base was supposed to hold the two gears of the mechanism. This base also needed to hold a compound gear which would transmit the power from the motor to the gear of the mechanism. Another thing that this base was required to hold was the motor which would be actuating the whole mechanism. This base would also be responsible for holding a carbon fiber rod which acted as separation for the two wings. An initial design was made for the base, making the holes for the gears for them to be mounted in those. The distance between the two holes made for the gears of the mechanism had a distance of 11.8 mm between them and that is from where the pitch diameter of the mechanism's gears was decided as the pitch circles of the two gears are required to be tangent to each other for proper meshing of the gears.

While designing the base, the hole for the compound gear was placed lower than the holes for the other two gears of the mechanism. This was because the smaller gear of the compound gear was supposed to be meshing with the gears of the mechanism. This is why it was needed to place the larger gear of the compound gear below the gears of the mechanism. This hole was also made at an offset from the center because the smaller gear was supposed to mesh with only one of the two gears of the mechanism.

A holding was made in this base for the motor. The distance between the hole of the compound gear and this holding helped us decide the pitch diameter of the gear mounted on the motor.

Another holding was made for the carbon fiber rod on which the wings were supposed to be mounted. Right above this holding a stopper was made as well. This stopper was made to hold the wings on their spot. The holding for the motor base is visible in figure 4.5.

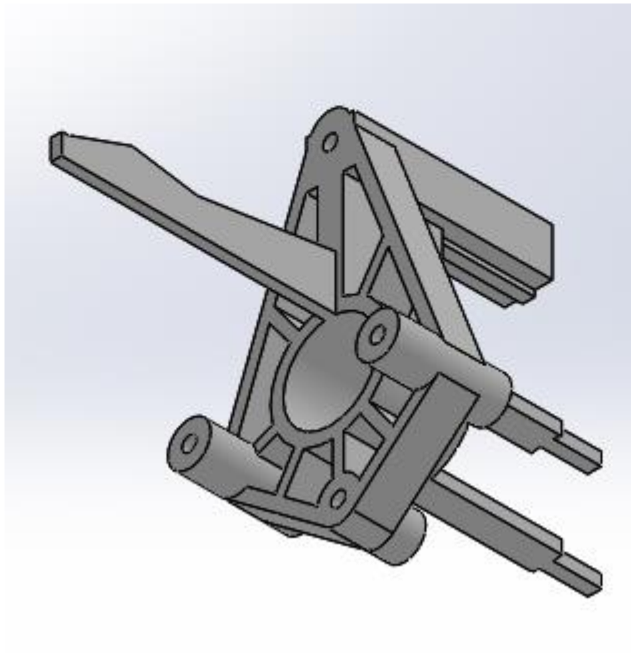

Figure 4.5: Holding for motor base

4.4 String Based Flapping Mechanism:

A string based flapping mechanism is a mechanism which relies on strings to transmit rotational energy from the motor to the wings in order for them to flap. This is the flapping mechanism selected for the ornithopter based on the flight mechanics of a hummingbird.

Reason for selection:

The two main reasons for selecting this type of flapping mechanism are:

1. It only requires a single motor to actuate.
2. It is a simple mechanism that does not have many parts in it.

Both reasons contribute to minimizing the mass of the mechanism, making it more lightweight and suitable to be used in an ornithopter.

Parts of string based flapping mechanism:

There are three main parts of a string based flapping mechanism:

1. Pulleys
2. Crank

3. Strings

There are two pulleys in the mechanism, one on each side, the left and the right. There is a crank right in the middle of the two pulleys. There are three strings in the mechanism which enables the proper running of the mechanism. It is the positions of these strings that allow the proper flapping of the wings.

The strings are of two types:

1. Sync String

   The sync string is connected between the two pulleys. This string is actually responsible for keeping the flapping of both the wings synchronized. Otherwise, if the flaps of both the wings were not synchronized, they would be out of phase resulting in inconsistent lift production at different times.

2. Drive Strings

   These strings are connected between the crank and the pulleys. There are two drive strings, one for each pulley. These are the strings which are actually responsible for transmitting the rotational energy from the motor to the pulleys which in turn transfer it to the wings.

Working:

The general process for this flapping mechanism(illustrated in figure 4.6 [27]) is described below:

- The motor will be connected to the crank which will rotate the crank continuously.
- For the first 180 degrees, the right pulley will be rotated, and it will rotate the left pulley through the sync string.
- For the next 180 degrees, the left pulley will be rotated and it will rotate the right pulley through the sync string.

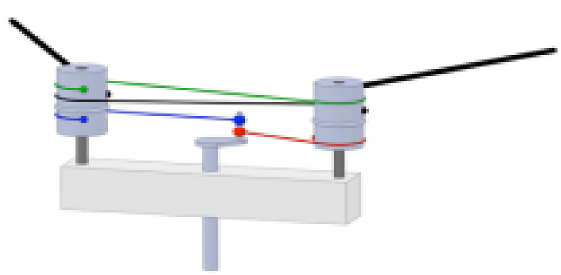

Figure 4.6: Illustration for String-based flapping mechanism

4.4.1 Large scale prototype:

A string based flapping mechanism was selected for the ornithopter. The problem with string based flapping mechanism was the analysis of such a mechanism as it could not be analyzed in the same manner as the mechanism made of solid links. In this mechanism, to get the right flapping of wings, the length, and positions of strings on the pulleys were very much critical. This optimization of string positions and lengths was not possible to be done on the actual sized model as the actual sized model of the pulleys was in the range of 5 to 10 mm. This was the main reason why this decision was taken by us to go for a large scale prototype. The scale for the large scale prototype was selected to be 1:10 which means that the large scale prototype would be 10 times that of the actual size.

Material Used:

For the manufacturing of the large scale prototype, the following materials were being used:

- Wood
- Steel rods
- Nuts and Bolts
- Nylon Strings

Manufacturing Processes Used:

Following are the main processes involved in the manufacturing of the prototype:

- Wood Working
- Machining
- Welding
- Press Fitting

Manufacturing Steps:

Following steps were carried out for the manufacturing of the prototype:

- First step was the planning. During planning, a drawing was made which was followed to manufacture the whole prototype. That drawing is shown in figure 4.7.

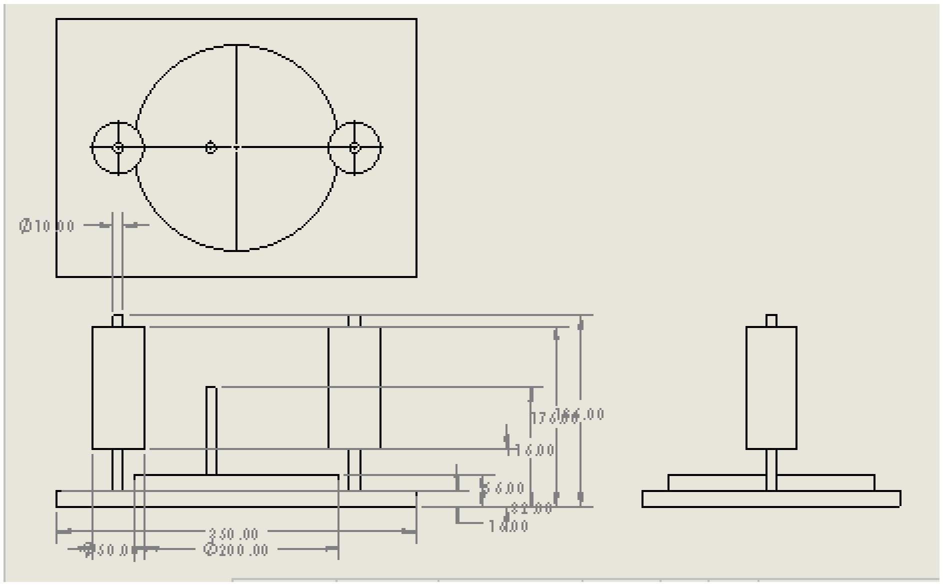

Figure 4.7: Drawing for designing the flapping mechanism prototype

- After planning, first, the wooden sheet is cut using a chain saw. This sheet is for the base of the prototype. The dimensions of this sheet are 35x25 cm.
- The crank base is also cut using the chain saw. The diameter of this base is kept being 20 cm.
- After that, a wooden rod is machined(shown in figure 4.8) to make the pulleys of the mechanism. The dimensions of the pulleys are kept being 5 cm each.

Figure 4.8: Machining the pulley

- After this, holes were drilled(figure 4.9) in the center of all the three bodies which include the two pulleys and one crank base.

- Holes are also drilled in the base where the pulleys and crank base is to be positioned.

Figure 4.9: Drilling holes in Pulley

- Steel rods are cut now to pass through the holes. The lengths of the steel rods are according to the figure 4.9.
- Nuts are used on the two ends of these steel rods as stoppers.
- These nuts are welded (shown in figure 4.10) to the steel rods.

Figure 4.10: Welding of nuts to the steel rods

- Then, holes are made in the crank base (shown in figure 4.11). These are the slots for the crank. 8 different holes are made in the base at different diameters which will be used later for the optimization purpose.

Figure 4.11: Drilling holes into the crank base

- A crank is also made using the lathe machine as shown in figure 4.12.

Figure 4.12: Machining the crank

- This crank can now be press fitted(shown in figure 4.13) into any of the 8 holes in the base.

Figure 4.13: Pressing the crank into the crank base.

Testing and Optimization:

After the manufacturing process was completed, strings are connected using adhesive. For this the position and length of the string is selected using the hit and trial method. All this testing and optimization was being done so that now the positions and lengths of the strings that we have come up with can be used after scaling them down.

This must be noted that during the testing process, different crank diameters were used to get to the most optimum diameter. Apart from using different crank diameters, the crank was also placed at an offset from the center. This was done for the case if we decided to use a simple gear train which was not used later.

For the sake of testing the angle of flap produced under different configurations, videos of different configurations were being recorded in their running form. These videos were then imported into a software named tracker where the angle of the flap was evaluated for each of the configurations.

After analyzing all the different configurations, it was concluded that the most optimum result was for the crank diameter of 5 cm which would translate to a crank diameter of 5mm in the actual sized model. This crank diameter gave a flap of 140^o.

The finalized correct positioning of the strings is shown in figure 4.14.

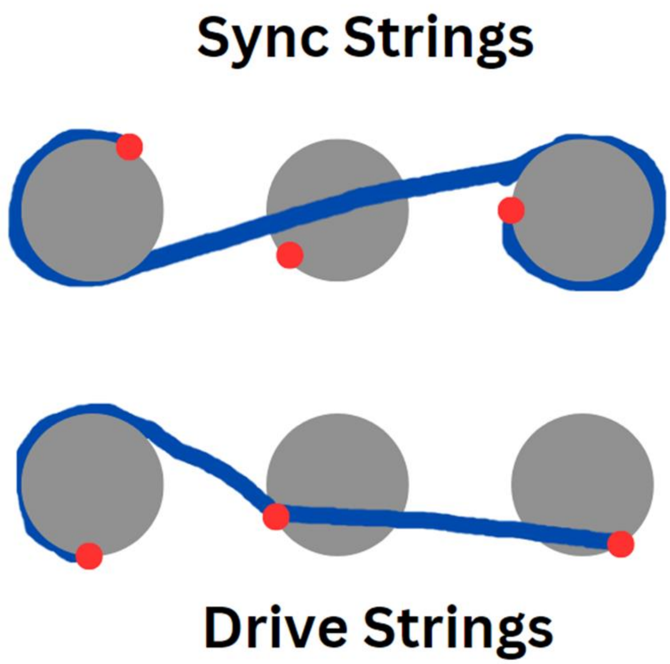

Figure 4.14: Positions for the sync and drive strings on pulleys

4.4.2 Selection of Gear Train:

For this ornithopter, we used the motor CL-8520 which is a coreless motor. Generally, the coreless motors have a very high revolution speed. The speed of this model is no different. It has a maximum speed of 54500 rpm. The wings of the ornithopter would have not been able to withstand such a high speed. This means that this speed needed to be controlled. One of the ways to do this would have been to provide the motor with a lower voltage, but that would have affected the torque provided to the flapping mechanism. Another way was to use a gear train instead.

Many gear trains could serve the purpose of reducing the speed and not compromising on the torque provided by the motor. To select the correct gear train, some gear trains were brought into consideration. Before selecting the final gear train two more gear trains were considered which were rejected based on a few of their short comings. Those two gear trains and the final gear train selected are being discussed below:

a. **Planetary Gear Train:**

A planetary gear train is a type of gear train which consists of more than one spur gear rotating around a central spur gear while all of them are enclosed in an internal gear at the same time. There are three main types of gears in this gear train:

Sun Gear: This is the central spur gear. This gear is usually the one which is rotated by an input shaft or a motor.

Planetary Gear: This is the gear which is rotating around the sun gear. This type of gear is generally more than one in this gear train. These gears are positioned and held by a carrier around the sun gear.

Annulus: This is the internal gear which holds the sun gear and the planetary gears.

This gear train would have reduced the speed of the motor effectively and it would also have increased the torque provided by the motor to the flapping mechanism as well. Apart from this it would also have maintained the symmetry of the whole flapping mechanism as this would have allowed for the crank to be placed in the middle. Despite of all these advantages there were some limitations due to which we could not go with this gear train. Those limitations are being listed below:

The planetary gear system that was required in this case was so small that it could not be found in the scrap material.

b. Simple Gear Train:

The simple gear train consisted of just two gears. One of them was a small gear which would have been connected to the input shaft of the motor. The other gear would have been a larger gear on which the crank would be mounted. This gear assembly could be used as it had only two spur gears which could be easily found in the market. The only shortcoming of using this gear train was that, it was affecting the overall symmetry of the flapping mechanism. By using this gear train, the crank of the string based flapping mechanism would have to be off-centered. Asymmetry may be there in the ornithopter but by moving the crank from the center the whole flapping mechanism is affected as the testing on the large scale prototype showed that the string based flapping mechanism is more effective when the crank is not at an offset from the center.

c. Compound Gear Train:

After the first two gear trains, the final gear train which was also selected to be used to reduce the motor speed and increase the torque provided to the flapping mechanism was the compound gear train.

This gear train comprised of three gears:

The first gear was a small gear which had 8 number of teeth and a pitch diameter of 4 mm. This gear was mounted on the motor and is responsible for transmitting the input from the motor to the further mechanism.

The second gear was a compound gear. The larger gear of the compound gear is meshed up with the first gear which was mounted on the motor. This larger gear had 32 number of teeth and a pitch diameter of 16 mm. The smaller gear of the compound gear had 8 number of teeth and a pitch diameter of 4 mm. The compound gear is the gear which is responsible for keeping the crank of the flapping mechanism in the center of the pulleys of the mechanism and not at an offset.

The third gear was again a large gear that had 32 number of teeth and a pitch diameter of 16 mm. This gear was attached to the crank of the mechanism and is responsible for transmitting the power to the crank which actuates the whole mechanism. This gear would mesh with the smaller gear of the compound gear.

4.4.3 CAD Modelling:

After the optimization of the crank diameter and positioning of the strings and the selection of an appropriate gear train, the next step was to design the CAD model for all the parts of the string based mechanism.

a. Gears for the Compound Gear Train:

The gears were being designed in SolidWorks following the steps that were been discussed before. A total of three gears were designed. The first gear was a small gear that had 8 teeth and pitch diameter of 4 mm. The second gear was a compound gear which comprised of a larger gear and a smaller gear. The larger gear had a pitch diameter of 16 mm and 32 number of teeth. The smaller gear had 8 teeth and a pitch diameter of 4 mm. The last gear was also a large gear which had the pitch diameter of 16 mm and 32 teeth.

The module of all these gears was kept as 0.5 which was necessary for them to mesh properly.

b. Gear Ratio of Compound Gear Train:

The flapping mechanism of humming bird uses a compound gear train to transmit power from the motor to the mechanism. In this section, the total gear ratio of the gear train used in this mechanism is calculated using the formula:

$$Gear\ ratio = \frac{Number\ of\ teeth\ in\ second\ gear}{Number\ of\ teeth\ in\ first\ gear} \quad (15)$$

The first gear ratio calculated is between the gear mounted on the motor and the larger gear of the compound gear:

$$(Gear\ ratio)_1 = \frac{32}{8} = 4 \quad (16)$$

The second gear ratio calculated is between the smaller gear of the compound gear and the gear of the mechanism:

$$(Gear\ ratio)_2 = \frac{32}{8} = 4 \quad (17)$$

The total gear ratio of the gear train can be calculated as:

$$Total\ Gear\ Ratio = (Gear\ ratio)_1 * (Gear\ ratio)_2 \quad (18)$$

$$Total\ Gear\ Ratio = 4 * 4 = 16:1 \quad (19)$$

The gear ratio of 16:1 reduces output gear speed while increasing motor torque by the same factor.

c. Base:

First of all, the base of the flapping mechanism is designed. This base was designed for it to be able to place the gear train. In the gear train, the gear that has the maximum height is the compound gear which has a height of 16.5 mm. This is why the top and bottom internal ends of the base are 16.6 mm apart so that the base can hold the compound gear.

Apart from this, 4 holes are being cut in the base. Two of the holes on the right and the left are for the pin connection of the pulleys. One of the holes which is right between the two holes of the pulleys is for the crank’s pin connection. The last hole which is a little bit offset from the center towards the back is for the pin which will be mounting the compound gear.

The enclosing of the main motor which will run the whole mechanism was also designed in this base. The enclosing for the motor comes right below the hole for the pin of the crank.

d. Pulleys:

The pulleys now have a limitation which is that their height cannot exceed 16.6 mm. During the CAD design, the height of the pulleys was kept as 16.5 mm. Two slots were made in each pulley which was to keep the drive and sync strings straight. The depth of these slots was kept as 0.4 mm and the width was kept to be 0.8 mm. These dimensions were decided based of the diameter of the string that we were using which was 0.37 mm. The first slot was made at a distance of 10.4 mm from the top of the pulley. This slot is for the drive strings. The second slot was made at a distance of 2 mm from the bottom of the pulley.

Initially, we had the idea that we would perform experiments on the large scale prototype. The results of those experiments would give us the string positions on the pulleys. Apart from the positions of the strings, these experiments would also give us the lengths of the strings which could then be decreased by a scale of 10 and then incorporated in the actual sized model. But later, we realized that attaching these very small sized strings to these extremely small pulleys using some sort of adhesive would also be next to impossible. Apart from this, the target was to attach the strings such that all the strings be always in tension. So, even if we were able to attach the strings at the desired spots, there was no way we could have maintained all the strings in tension.

For this problem the solution devised by us was to make holes in the pulleys at the points where the strings were supposed to be attached. These holes would go through these pulleys such that the string would enter from the points where it is supposed to be and will exit at some other point from where it can easily be pulled to bring the string under tension.

These holes are also made in the pulleys at the selected points. Each hole is of the diameter of 0.6 mm so that the string can pass through it easily.

One last thing that was designed on the pulleys were the holding for the leading edge of the wing.

e. Crank:

The next part to be designed in CAD is the crank for the string based mechanism. The crank base is kept to be 2 mm. The most optimum diameter for the crank came out to be 5 cm during experimentation. This was scaled down by a factor of 10 making the actual diameter of crank to 5mm. The crank which was coming out of the base also had a slot which coincided with the slot of the drive strings of the pulleys.

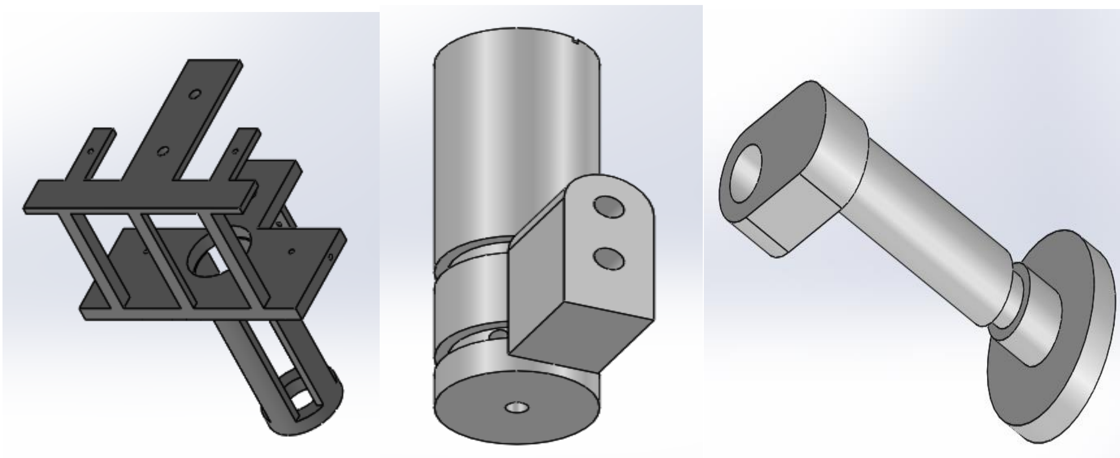

Figure 4.14: Parts of string-based flapping mechanism

4.5 Manufacturing:

Both the flapping mechanisms were manufactured by the process of SLA 3D printing. The material used for SLA printing was tough engineering resin. The infill used during the 3D printing was 100 % which is generally the case for SLA printing.

Chapter 5:
WING DESIGN

The design and manufacturing of ornithopters encompass various critical aspects, with wing design standing out as a vital component. This chapter places a particular emphasis on the crucial task of selecting suitable materials for the wings. The wings of an ornithopter play a pivotal role in determining its performance, maneuverability, and overall flight capabilities. Choosing the right material for the wings is essential to ensure their structural integrity, durability, and efficiency. The selected material should possess specific characteristics such as high strength-to-weight ratio, excellent fatigue resistance, and favorable stiffness properties. Additionally, factors such as cost, availability, and ease of manufacturing must also be taken into account during the material selection process.

5.1 Required Properties of the Material used for Wings:

When selecting a material for ornithopter wings, several key properties must be considered to ensure optimal performance and durability. The following are the essential properties to look for in the material:

Lightweight: Since the wings are responsible for generating lift and supporting the weight of the ornithopter, the chosen material should have a low density to minimize overall weight.

High Strength: The material must have sufficient strength to withstand the aerodynamic forces and mechanical stresses experienced during flight. It should be able to resist bending, torsion, and fatigue without compromising its structural integrity.

Stiffness: Wing stiffness is crucial for maintaining the desired wing shape and preventing excessive deflection or deformation during flight. A high modulus of elasticity in the material helps maintain structural stability and minimizes unwanted flutter or vibration.

Fatigue Resistance: Wings undergo cyclic loading during the flapping motion, making fatigue resistance an essential property. The chosen material should exhibit excellent resistance to fatigue failure, ensuring longevity and reliability over repeated flight cycles.

Ductility and Flexibility: Ornithopter wings experience various degrees of bending and flexing during flapping and maneuvering. The material should possess a certain level of ductility and flexibility to accommodate these deformations without undergoing permanent damage.

5.2 Wing of Ornithopter Based on Pigeon:

The material selected for the wings of the ornithopter, based on a pigeon, was plastic sheet. This decision was made as plastic sheet lies under the criteria that were discussed above. Plastic has good strength that can withstand the mechanical and aerodynamic forces which will be applied on the wings during flapping. Additionally, plastic sheets are very light and having high fatigue resistance and flexibility.

These wings were acquired by us. the thickness of the plastic sheets used in these wings was 20 micrometers. The total wingspan of these wings was 275 mm. This makes the leading-edge length of a single wing 137.5 mm. The surface area of the wings is 16921 mm^2. This surface area was found using SolidWorks.

The aspect ratio of the wings can be found as:

$$Aspect\ Ratio = \frac{b^2}{S} = \frac{275^2}{16921} = \frac{75625}{16921} = 4.47 \qquad (20)$$

5.3 Wing of Ornithopter Based on Hummingbird:

The material selected for the wings of the ornithopter, based on a humming bird, was polyimide film. The thickness of the film acquired was 6 micrometers.

The wings for this ornithopter were manufactured by us. To manufacture the wings, the following steps were taken:

First of all, the outline of the wing was made in SolidWorks. The leading-edge length was kept as 85 mm. This made the total wingspan 210 mm.

Figure 5.1: Wing design in SolidWorks

In the next step, this wing outline was cut on a laser cutter on wood.

Then this outline was cut on the polyimide by placing the pattern made on wood. This cutting was done by hand using a pair of scissors.

After that the carbon fiber rods were placed and attached to the wings to provide them further strength to withstand the flapping.

The aspect ratio of these wings can be found as:

$$Aspect\ Ratio = \frac{b^2}{S} = \frac{210^2}{12600} = \frac{44100}{12600} = 3.5 \qquad (21)$$

Chapter 6:
CONTROL MECHANISM

This chapter focuses on the vital aspect of controlling the attitude of the ornithopters, which is crucial for achieving stable and maneuverable flight. This chapter explores the various control mechanisms and strategies employed in the manufacturing of ornithopters to ensure precise and responsive control over its flight characteristics. By examining the principles and technologies behind control mechanisms, this chapter aims to provide insights into the design considerations and challenges associated with implementing effective control systems. Understanding and optimizing the control mechanism is essential for achieving controlled flight, maintaining stability, adjusting attitude, and executing precise maneuvers. Through this chapter, we delve into the fundamental concepts and techniques that underpin the control mechanisms used in ornithopters, shedding light on the key components and approaches that contribute to successful control mechanism design.

6.1 Control Mechanism Based on the Tailed Approach:

The control mechanism of the ornithopter, mimicking the pigeon, is based on a tailed approach. The tailed approach is the one generally used in aircrafts.

The main parts of the control mechanism used in the ornithopter based on the pigeon are given below:

1. Horizontal Tail
2. Vertical Tail
3. Rudder

Horizontal Tail:

The horizontal tail is responsible for generating the pitch attitude in the ornithopter. This is done when the thrust force produced by the wings is applied on the horizontal tail which in turn generates pitching torque which elevates the ornithopter.

Vertical tail:

The role of this tail is to mount the rudder. In actual aircrafts, the shape of this tail from the top cross section is that of an airfoil but in our case, this was a straight. Due to this shape, it plays a major role in the stability of the aircraft.

Rudder:

Rudder is the control surface used to generate yaw torque.

6.1.1 Working of Tailed Control Mechanism:

The tailed control mechanism relies on a servo motor as its core component, serving as the means to manipulate the rudder according to user commands. This mechanism allows users to control the ornithopter's yaw motion by operating the servo motor, which, in turn, moves the rudder through a series of interconnected strings and rockers.

The servo motor serves as the actuator for the control mechanism, responding to user input and translating it into mechanical motion. By adjusting the position of the servo motor, users can precisely position the rudder, influencing the aircraft's attitude and controlling its yaw movement.

To transmit the motion from the servo motor to the rudder, a system of carefully designed strings and rockers is employed. These components form a linkage mechanism that ensures the movement of the servo motor is effectively translated to the desired motion of the rudder. The strings connect the servo motor's output arm to the rockers, which, in turn, transmit the motion to the rudder assembly.

By manipulating the servo motor, users can adjust the tension in the strings and control the angular displacement of the rockers, resulting in the corresponding movement of the rudder.

6.1.2 Manufacturing of Tailed Control Approach:

The whole control mechanism of the ornithopter, based on the pigeon, is mainly made of Balsa wood of 1.5 mm thickness. The manufacturing steps are given below:

- The first step was to design the three parts of the control mechanism in CAD to get ready for the laser cutting.
- After designing, the three parts were cut using laser cutting.
- To assemble the whole control mechanism, strings were tied to the rockers of the servo and then after passing them through the body they were tied to the rudder.
- The vertical and horizontal tails were fitted in the slots of each other.
- The hinge for the rudder was made using X-ray sheets which were fit in the Balsa wood, and the tail is visible in figure 6.1.

Figure 6.1: Tailed approach after manufacturing

6.2 Control Mechanism Based on the Tailless Approach:

The tailless control mechanism was based on stroke plane modulation and wing twist modulation:

6.2.1 Stroke Plane Modulation:

Figure 6.2 shows control torque generation mechanism for pitch attitude changes. The flapping wing mechanism is able to rotate about the hinge. The rotating hinge is designed to locate it about the center of gravity of the flapping wing mechanism. By tilting the flapping wing mechanism around the hinge, the wing stroke plane is tilted in the same direction to the change in direction of force for pitch torque generation.

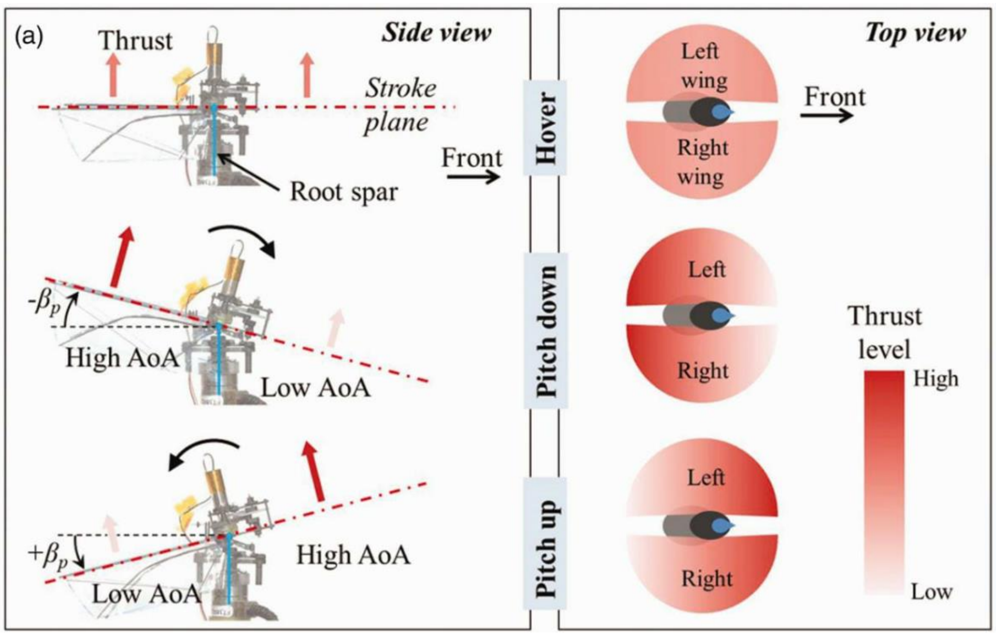

Figure 6.2: Stroke Plane Modulation

6.2.2 Wing Twist Modulation:

Wing twist modulation is the change in the shape of both the wings which will change the amount of drag on both the wings which will cause a net torque in the yaw axis which will cause the yaw of the body.

The purpose of control mechanism was designed such that it allows the bird to move in all three dimensions of space. The movement in different dimensions in space would be achieved by the following methods:

The up and down movement of the ornithopter, which is also called the lift, will be controlled by the main driving motor which is running the whole mechanism. The speed of this motor can be varied in order to change the amount of lift generated. When the lift generated greater than the weight of the ornithopter, then the ornithopter will move up and it will move down in the case when lift generated will be less than the weight of the ornithopter. The ornithopter will hover in the case of equal weight and lift force.

The front and back movement, which is also called the pitch will be controlled by a servo motor which will tilt the whole body towards the front or the back to move the ornithopter in the forward or backward direction respectively.

The last movement required is the right and left movement which will be achieved by incorporating both the pitch and the yaw. For yaw there is another servo motor which will bend the trailing edge of the wind such that this will induce yaw in the ornithopter as visible in figure 6.3.

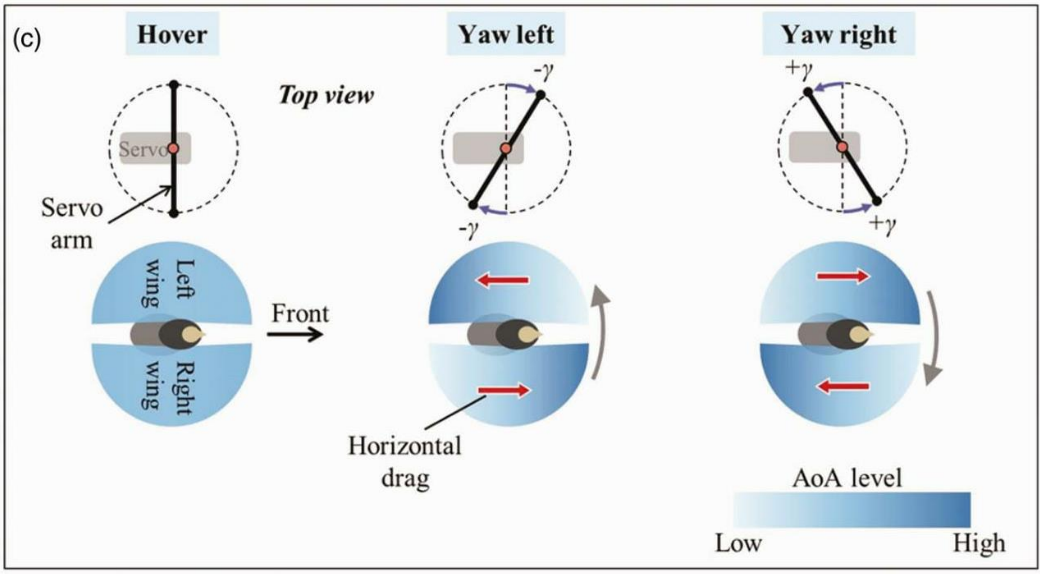

Figure 6.3: Wing Twist Modulation

6.2.3 CAD Modelling:

The controlling mechanism of the hummingbird based ornithopter required two servo motors. One of these servo motors was the yaw servo motor and the other was the pitch servo motor. While designing the CAD model of the control mechanism, the first thing to be done is to make something that could hold these servo motors.

a. Outer Frame:

An outer frame was specifically designed to accommodate and secure the two servo motors, with one of the servos positioned on top of the other. The holding on the top was specifically designed for the yaw servo motor which will be oriented horizontally to facilitate the yaw movement. The holding for the pitch servo motor is positioned right beneath the holding for the yaw servo motor, which is designed to support the vertical placement of the pitch servo motor for effective pitch control.

For the sake of holding the two servos, an outer frame was designed in which the holdings for the two servo motors were made, one on top of the other. The holding for the yaw servo was made on the top. This holding is placed such that the servo is placed in a horizontal manner for the sake of yaw. The holding for the pitch servo is placed beneath the holding for the yaw servo. The holding for the pitch servo is placed such that the servo motor will be placed in a vertical manner in this holding. The outer frame will be connected to the base using a pin connection with a holding for the trailing edge between both the sides.

Underneath these two holdings is a plate for accommodating the other electrical components which includes the battery, receiver, flight control board and the ESC.

While designing this part, care has been taken regarding the mass of the part. This is because mass is a critical factor in this project. This is why this part is designed to keep the mass to a minimum.

b. Extension for rockers of yaw servo:

The trailing edge of the wings of the ornithopter were supposed to be attached to the rocker of the yaw servo motor which would rotate the trailing edge, hence changing the shape of the wings and consequently producing yaw in the ornithopter. But unfortunately, none of the rockers that were being acquired with the servo motor were long enough to reach the trailing. This was the main reason why these extensions were designed.

It was planned that the extensions would have a slot in them into which the rockers of the servo motor will enter. Some calculations were being done to obtain the length of the extension required. This calculation is being shown in figure 6.4.

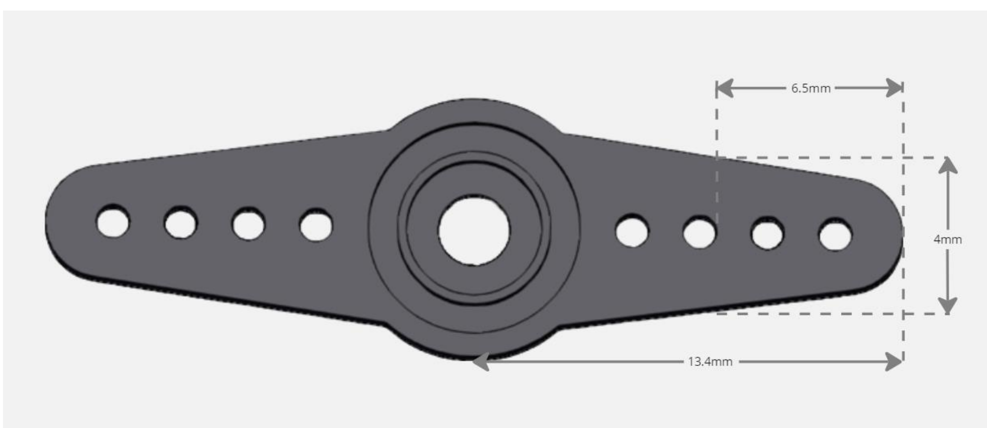

Figure 6.4: Servo rocker

Distance Between two trailing edges=35.6mm

Distance between edge and centers=17.8mm

Length of extension=6.5mm+17.8mm-13.4mm

=10.9mm

As the extension is being planned to go into a point where its width is 4 mm, and the height of the rocker is 1 mm throughout. Hence, the dimensions of the slot would be 4 mm × 1 mm. A hole was also made at the point where the trailing edge was supposed to pass. The trailing edge would not be fixed here by some adhesive or any other method. The trailing edge would simply be a little bit longer such that it extends downwards from the extension.

c. **Connecting rod for pitch:**

For the sake of pitch, the piston crank mechanism was decided. For that two links are required apart from the ground and the sliding piston. In this case the sliding piston is the base of the flapping mechanism. A slot was being made in the base where one the pin connections of the connecting rod was to be made. The other pin connection of the connecting was to be made with the rocker acquired with the servo motor. After all this, only one part was left to be designed, which was the connecting rod. This target was kept in mind that the base should stay straight when the servo motor is at 45 degrees of rotation. This is because the servo motors were able to rotate a total of 90 degrees, so by keeping the base straight at 45 degrees, the base could be moved both upwards and downwards as required during the testing part of the control mechanism.

The calculations for the length of the connecting rod are shown in figure 6.4.

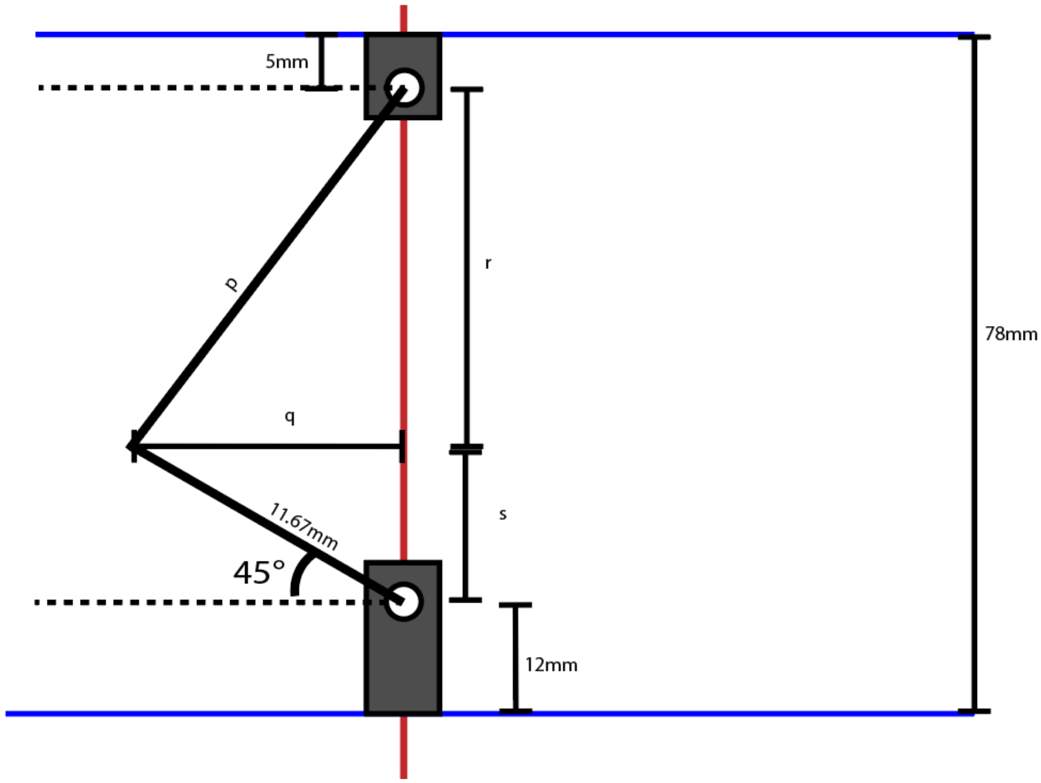

Figure 6.5: Illustration for the calculations

For s and q, we solve for the cosine and sine for the angle subtended between the face of the frame on which the servo is placed and the attachment on the servo as under:

$s = 11.67 * \cos(45°)$ (22)

$= 8.25mm$

$q = 11.67 * \sin(45°)$ (23)

$= 8.25mm$

For r, we consider the total length between the two opposite faces: $r = 51.75mm$

Since q is the length of the hypotenuse in the right triangle with q and r as base and perpendicular, thus, using Pythagorean theorem we get: $p = 52.4mm$

78 mm is the distance between the base on which the servo is placed and the lower face of the base. 11.67mm is the length of the rocker attached to the servo motor. The length of the connecting rod turned out to be 52.4mm as shown in figure 6.5.

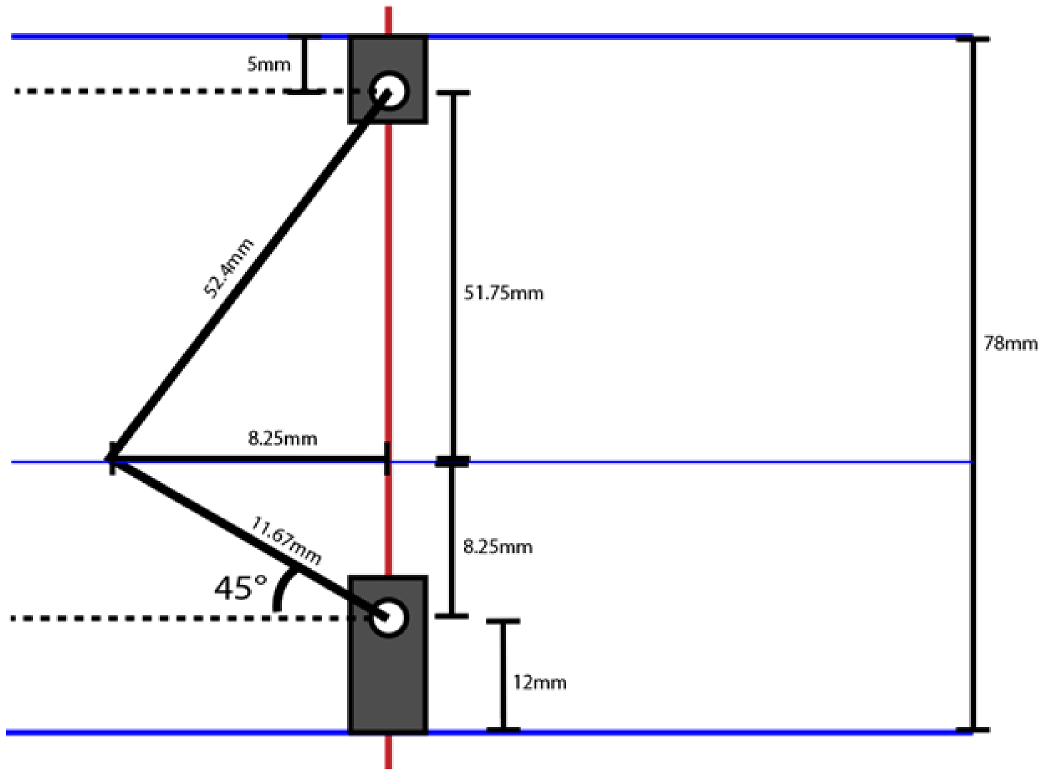

Figure 6.6: Solved unknowns in the illustration

The length that has come out is the length of the hole to hole of the connecting rod where the pin connections are to be made, and different parts for the hummingbird based micro aerial vehicle can be seen in figure 6.6.

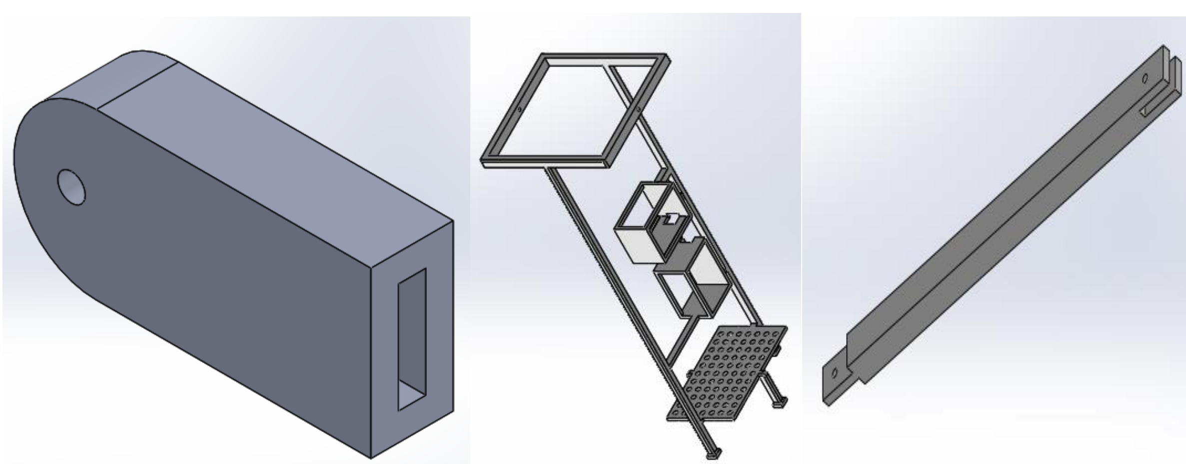

Figure 6.7: Parts of hummingbird

6.2.4 Static Structural Analysis:

The part of the control mechanism that required a static structural analysis was the frame in which the servo motors were supposed to be fit and some other electronic components were also going to be placed on this part such as the battery, flight control board, receiver etc. It implied that most of the mass was to be borne by this part, hence for the sake of safety, a static structural analysis was carried out on this part in which a force equivalent to the mass of the components placed on this frame was applied on this frame.

The material used for the frame is tough engineering resin which has a strength of 55 MPa and a density of 1150 kg/m^3. The static structural analysis was performed in ANSYS Workbench. In this software we were not able to find the exact material but instead we used a material that had very similar properties such as strength, elasticity and density which was PETG.

The equivalent stress or the Von mises stresses are shown in the figure ______. Apart from that the factor of safety is also calculated which came out to be greater than 15 for all for all points on the body which meant that the structure would survive the load of the weights applied on it when the components are placed in it. The contour for the factor of safety can be seen in figure 6.7

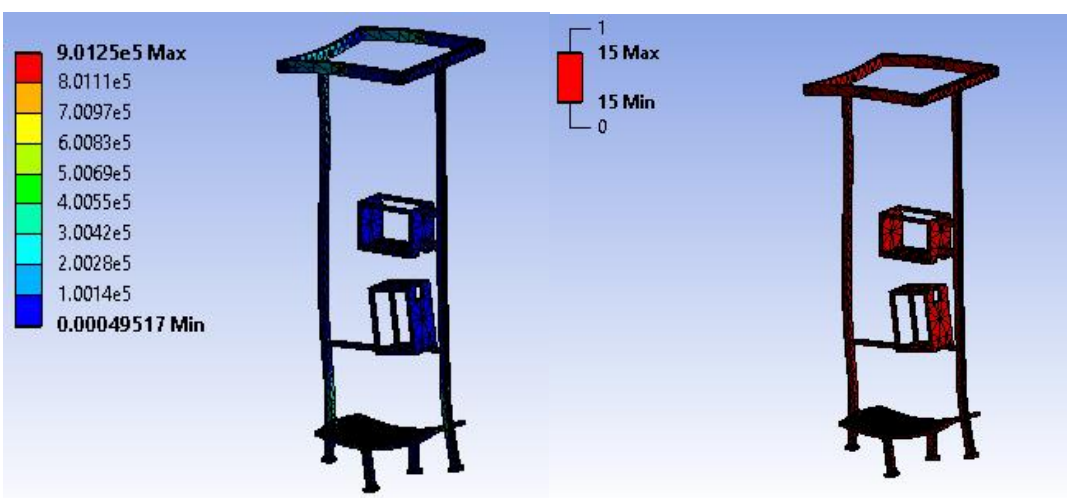

Figure 6.8: Von mises stress contour and factor of safety contour

Chapter 7:
ON-BOARD AVIONICS AND COMPONENT SELECTION

For a micro aerial vehicle, component selection and the electrical circuitry are the things which define their true limitations, their success, at the end it decided by the clever choice of electrical components and the logic which was used to tune the receiver, controller or the micro controller which makes decisions according to the input values. Some of the most common reasons for the failure of such micro aerial vehicles is often related to the poor choice of electrical components which eventually results in burning out of the motor because the load exceeded the load for which the motor was rated, or the battery that has enough capacity to drive the available components added too much to the weight of the micro aerial vehicle that the selected motor for the micro aerial vehicle was unable to generate enough lift to keep the micro aerial vehicle in the air for too long without burning out.

7.1 Avionics System Requirements Analysis

After finalizing the flapping mechanism and wing design, the next step involved requirement analysis and component selection. This stage ensured that the chosen components aligned with the previously selected mechanism and design. The avionics system requirements were thoroughly analyzed to identify and prioritize the necessary functional and non-functional aspects. Following the analysis, careful component selection took place, considering factors such as compatibility, performance, and reliability. This step was crucial in ensuring a seamless integration of components into the avionics system for the micro aerial vehicle.

7.2 Component Selection and Integration

Before discussing the component selection, we will enlist the elements which are crucial to a micro aerial vehicle:

1. DC Motor
2. ESC
3. Servo
4. RC Receiver and Transmitter
5. Battery

These are the elements, in order, which are crucial to the fabrication of a micro aerial vehicle. For example, you can even use a single DC motor to drive a MAV by connecting it to a flapping mechanism which has the wings mounted on it. But without using a battery, it will be a tethered MAV, just like the Delfly[1] , and will be left as a one-dimensional micro aerial vehicle which can just go up or down.

Adding a servo would enable the MAV to steer left and right by connecting the horns (attachments on a servo) to a control surface or using some other kind of control mechanism to make the MAV change its direction along the yaw axis.

Moreover, adding more servos can enable the MAV able to do motion along the roll, pitch and yaw axis.

But to remove the wire and make it remote-controlled, we needed to add a battery. The majority of the mass in a micro aerial vehicle was usually that of a battery. Unfortunately, due to the import ban on batteries in Pakistan, we had to use the batteries available in the market.

We had a choice of using a flight control board, which could operate autonomously to some extent, but that wasn't necessary. Alternatively, we needed to add an RC receiver that could be controlled by a compatible RC transmitter. Besides these two options, directly connecting a micro aerial vehicle to a battery without any control wouldn't have been a wise choice.

We decided to also try out a flight control board as well as use an RC Receiver and Transmitter pair to check and try out the level of complexity we would need to make the second prototype have a stable flight using some attitude control.

7.2.1 DC Motor

The motor selection holds paramount importance among the electrical components involved in the circuitry of our prototype. An electric motor is an essential device that converts electrical energy into mechanical energy, generating rotational motion.

When considering projects related to remote control (RC) planes, we typically utilize either cored or brushed motors. In regular brushed DC motors, an inner iron core is present to hold the windings. However, in the case of a coreless DC motor, the iron core is eliminated and replaced with a novel coil design. The coreless motors are coated with epoxy, which provides protection to the rotor coils, strengthening them and preventing potential damage. By removing the iron core, various iron losses are eliminated, resulting in higher efficiency compared to motors with traditional iron cores.

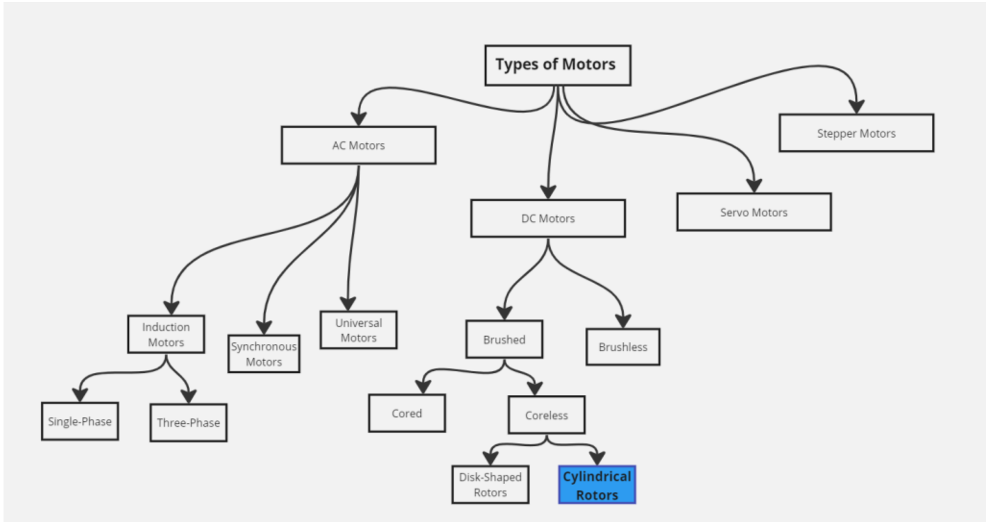

Figure 7.1: Classification of motors and the selected motors

Figure 7.2: Cylindrical Coreless Brushed Motors

The decision to select a coreless DC motor over a Brushless DC (BLDC) motor for our micro aerial vehicle (MAV) with a mass of less than 30g was based on several considerations like the smooth operation, lightweight, smaller size, and high power-to-weight ratio.

The revolutionary design of coreless DC motors offers numerous benefits, including the eradication of the cogging phenomenon, where sudden snaps occur during tooth alignment. These motors are smaller, lighter, and possess an excellent power-to-weight ratio due to the absence of an iron core. In our lightweight MAV project, the Coreless 614 and Coreless 8251 motors were chosen for their favorable power-to-weight ratio, optimizing thrust-to-weight and flight efficiency. Moreover, coreless motors exhibit higher efficiency by eliminating iron losses and reducing eddy current losses, resulting in longer flight times and improved battery utilization. Considering budget constraints, the cost-effective 614 coreless DC motor was an ideal choice for our project without compromising performance.

7.2.2 Electronic Speed Controller

The Electronic Speed Controller (ESC) is a crucial component in the flight control system of an MAV as it modulates power supply to regulate motor speed. Distinct from other components, ESCs are specifically designed for motor control, converting signals from the flight controller or receiver into appropriate power outputs. They effectively manage power to the motor, ensuring smooth acceleration, precise speed control, and rapid response while safeguarding against stalling, overcurrent, or overheating. Additionally, ESCs are compatible with control signals generated by flight controllers or receivers, supporting protocols such as OneShot, MultiShot, or DShot to facilitate efficient communication and control between the flight control system and the motor.

An ESC was selected by keeping in mind the electrical compatibility with the other components, its cost, weight, and dimensions.

The Electronic Speed Controller which we selected was a brushed ESC 5V 1A and in shown in figure 7.3.

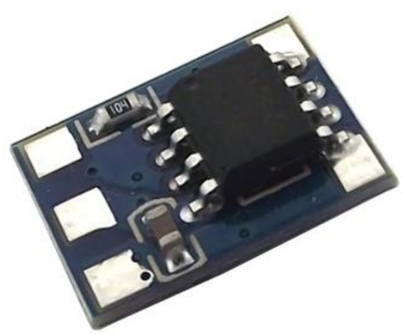

Figure 7.3: DOMAN Mini 1A Bidirectional DIY CW CCW Brushed ESC Board 3.5V &6V

This ESC has a weight of 0.4g and a size of 12mm by 8.5mm and its summary can be seen in table 7.1.

Table 7.1: Specifications of the selected Electronic Speed Controller

Name	Weight	Dimensions	Cost (PKR)
DM ESC-001	0.4g	12mm * 8.5mm	300-500

7.2.3 Servo Motor

When it came to selecting a servo motor for our project, we faced several considerations and challenges. Factors like weight, cost, availability, and performance were taken into account.

Given the weight limitations of our Micro Aerial Vehicle (MAV), it was crucial to choose a servo motor that was compact and lightweight. We opted for the AFRC D1602 servo motor, as it satisfied the requirements for being small and lightweight.

In addition to size and weight, the servo motor needed to provide sufficient torque to actuate the control surfaces or mechanisms on the MAV. We also considered the motor's response time and precision to ensure accurate control during flight maneuvers.

Considering the power consumption of the servo motor was essential as well. High power consumption would negatively impact the overall flight time of the MAV. Therefore, selecting a servo motor with low power consumption helped maximize the MAV's operational duration within the available battery capacity.

Availability and cost-effectiveness were also important factors to consider. By sourcing the AFRC D1602 servo motor locally, we were able to overcome availability challenges. Furthermore, its cost was reasonable and fit within the project's budget.

It's worth noting that typically, the SG90 servo is the locally lightest servo available. However, the lack of lightweight components in the market has often resulted in the failure of various projects related to micro aerial vehicles.

After conducting market research and performing calculations, we decided to select the AFRC D1602 servo motor. In the comparison with a locally available small servo, we found that the AFRC D1602 met our requirements effectively.

By breaking down the information into separate paragraphs, we can provide a more detailed and organized explanation of the considerations and decisions made during the servo motor selection process for the project and for comparison with other servos, we have table 7.2 and table 7.3.

Figure 7.4: Servo Motors AFRC D1602(left) and TowerPro SG90(right) - not to scale

Table 7.2: Specification of the Servos and their comparison

Name	**Weight**	**Dimensions**	**Cost**	**Torque**
AFRC D1602	2	16*8.2*16.5	2000?	0.14 kg/cm
TowerPro SG-90	9	23*12.2*29	380	2.5 kg/cm

Table 7.3: Comparison of various servos

Servo Model	Dimensions (mm)	Mass (g)	Torque (kgcm)	Speed (sec/600)	Current Consumption (mA)
AFRC D1602	16x 8.2 x 16.5	2 (without cord)	0.12 (at 3.79	0.09 (at 3.7V)	Unknown
SG90	22.2 x 11.8 x31	9	1.8 (at 4.8V)	0.1 (at 4.8V)	160 (at 4.8V)
MG90	22.8 x 12.2 x28.5	13.4	2.2 (at 4.8V)	0.11 (at 4.8V)	450 (at 4.8V)
Hitec HS-35HD	23.6 x 11.6 x 24.4	9.3	1.7 (at 4.8V)	0.11 (at 4.89	120 (at 4.8V)

Emax ES08MA II	23 x 11.5 x 24	12	1.6 (at 4.8V)	0.12 (at 4.89	250 (at 4.8V)
Futaba S3150	29x 13 x 30.5	20	3.8 (at 4.8V)	0.23 (at 4.8V)	350 (at 4.8V)
KST X08 VS	23 x 10 x 23	11	1.8 (at 4.8V)	0.08 (at 4.8V)	300 (at 4.8V)

We cannot use piezoelectric material instead of a servo motor here because even though they have great accuracy and a faster response they are meant for low-duty cycle operations and are not designed for continuous operations over extended periods. And considering the availability and cost for both things at the time, we decided to move forward with servo motors, instead of piezoelectric materials.

7.2.4 RC Receiver and Transmitter

The radio-controlled (RC) system is an essential component for controlling the flight of RC planes and quadcopters. This section provides an overview of the RC system used in this project, including the transmitter, receiver, and electronic speed controller. Additionally, it covers the channels and configuration required for proper operation.

The two main components of an RC system are the transmitter and receiver. The transmitter is a switch-controller device used to send input commands from the user to the receiver mounted on the aerial vehicle. The receiver, on the other hand, is an electronic unit installed on the aerial vehicle, responsible for receiving the user input and sending corresponding PWM pulses to servos or motors.

The radio transmitter plays a crucial role in controlling the flapping mechanism of micro aerial vehicle. It is used to transmit commands and control inputs from the pilot to the receiver on the aerial vehicle.

The receiver, located on the aerial vehicle, receives the transmitted signal from the transmitter. It then processes the signal and sends it as PWM pulses to the servos or motors responsible for controlling the flapping mechanism.

Through thorough online research and market visits, we have identified two potential receivers suitable for our MAV project: the Flysky FS X6B and the FrSky XM Plus Mini. Our assessment encompassed factors such as cost, dimensions, mass, channels, compatibility with available transmitters, and any additional costs involved, and a comparison can be seen in table 7.4.

Table 7.4: Analysis of additional cost and other things for both receivers

Components	**FS-X6B 2900**	**FrSky XM+ Mini**
Cost	2900 PKR	4900 PKR
Dimensions	36 x 22 x 7.5	
Mass	4.5g	1.5g
Channels	6 PWM. 18 iBus	16 SBUS
Compatible with Available Transmitter	Yes	No
Additional Costs	0	39500 PKR (Fr Sky compatible Transmitter)

After careful comparison and considering compatibility with the transmitter procured from the AeroModeling Club, we have made the informed decision to proceed with the Flysky FS X6B receiver. It fulfills our requirements and seamlessly integrates with the existing transmitter.

The Flysky FS X6B receiver operates on the AFHDS wireless protocol, ensuring reliable and efficient communication within our RC system.

By assimilating these components and comprehending their respective functionalities, we can effectively govern the flapping mechanism micro aerial vehicle using our meticulously designed radio-controlled system.

The transmitter and receiver can be seen in figure 7.5.

Figure 7.5: FS-i4 Transmitter and FS-X6B Receiver

Configuration of the transmitter and receiver:

One of the vital steps in establishing communication in between the transmitter and receiver is to bind them and to make sure that we have connected the components in their suitable channels.

For the receiver, the channels are shown in figure 7.6.

Figure 7.6: PWM and other wires on the FS X6B receiver

And for the transmitter, figure 7.7 explains their channels well.

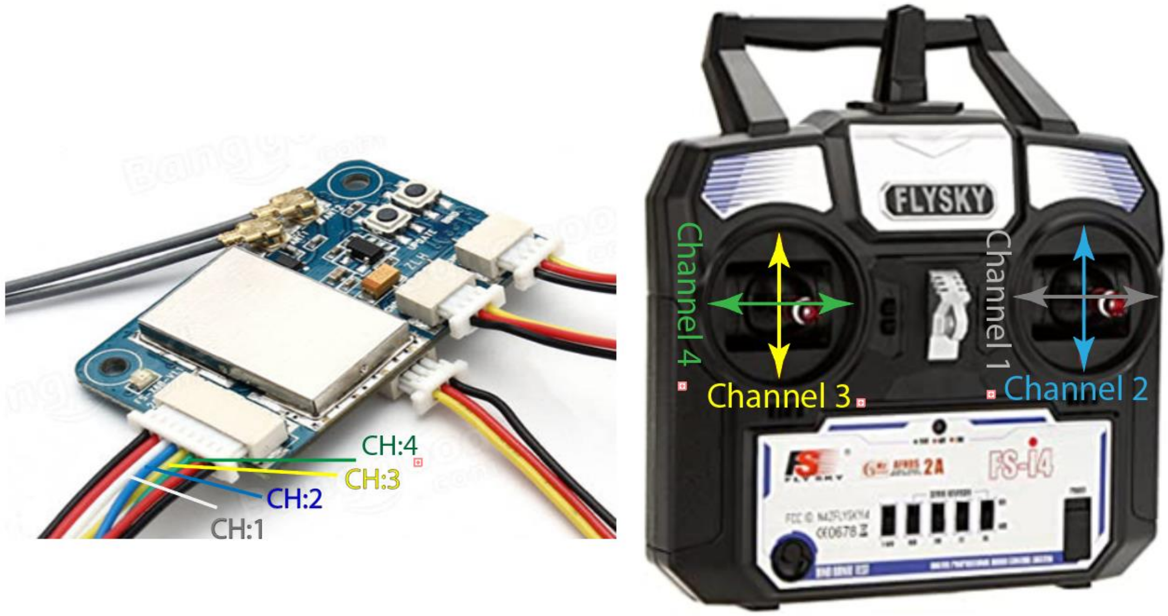

Figure 7.7: Figure showing the different channels and their assignment on the transmitter

We can also make our own radio transmitter and receiver using Arduino nano and two radio modules, but that will eventually lead to an increase in weight and wiring, not to mention increase in space occupied by the components as well, so we decided to go with those selected receiver and transmitter pair for this project.

For our first prototype BORAK, we would only need two channels, and for our second prototype, the EME-thopter, we would need one more channel for the additional servo which is being used in its control mechanism.

7.2.5 Battery

When considering the fabrication of an aerial vehicle, fuel and batteries are very crucial and their selection defines the final outcome. We also have to keep in mind the components and their power-ratings, and then on the basis of those values, we have to select a power source with a high energy density.

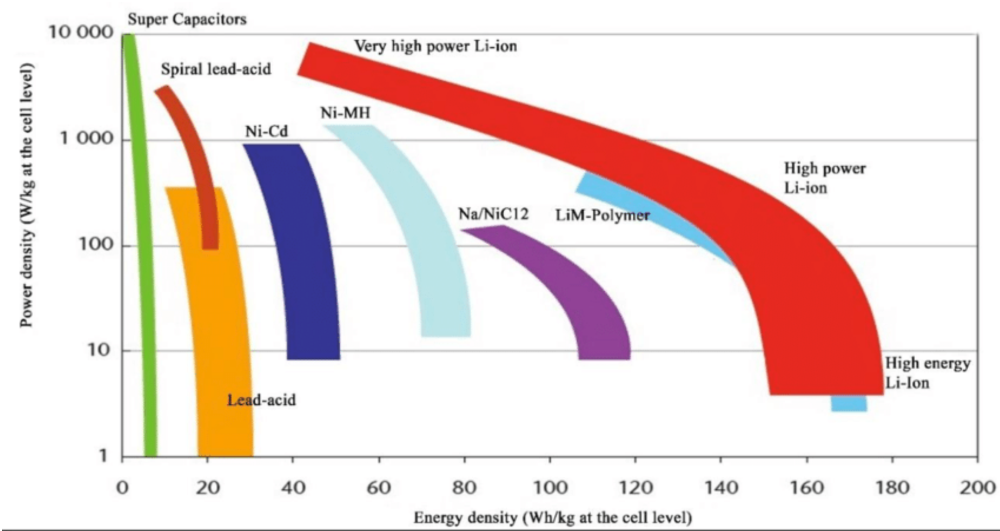

Figure 7.8: Battery Power density and Energy density of various sources [36]

We decided to move forward with a 3.7V Lithium ion battery since its power and energy density(comparison can be seen in figure 7.8) and relative weight with 50mAh capacity in 1.3grams, which was later on connected to another identical battery to make it 100mAh for 3.7V in 2.6g.

1.2.6 Flight Control Board

Flight control boards (FCBs) play a crucial role in the development of intelligent drones, as they simplify the process through the availability of compatible configuration software. These boards handle changes in current and voltage and are equipped with built-in IMU and other sensors essential for state estimation in aviation-related drones. In our project, we opted for an all-in-one FCB, eliminating the need for additional power distribution boards during prototyping. While some successful flapping wing aerial vehicle projects had the resources to fabricate their own FCBs, considering our time and cost limitations, we chose a commercially available FCB. Creating a flight control board requires extensive knowledge of power electronics and printed circuit boards, making the commercially available option a more practical choice.

Initially, we started our search for a perfect flight control board suitable for this project by not only keeping in mind the cost, market availability and time in mind, but also the number of rpms and dimensions for the project.

Initially, we considered various flight control boards like NAZE32, CC3D, Pixhawk, Arduino Nano etc., but after some calculations and research, we finalized the Racewhoop v1 board for our EME-thopter.

For comparison with dimensions and mass, the following table 7.5.

Table 7.5: Comparison of various Flight Control Boards

Name	Weight(g)	Dimensions(mm)	Cost (PKR)
Naze32	7.3	60 x 60	5200
CC3D Evo	18	11.68 x 5.33	3000
Pixhawk	38	81.5 x 50	29500
Arduino Nano	7	45 x 18	5000
Arduino Uno	25	68.6 x 53.4	1900
Racewhoop v1	1.7	20 x 20	5400

By comparing their ease of use, cost, weight, and their dimensions, we decided to move forward with the Racewhoop v1(shown in figure 7.9).

The specifications for the selected Flight Controller are as under:

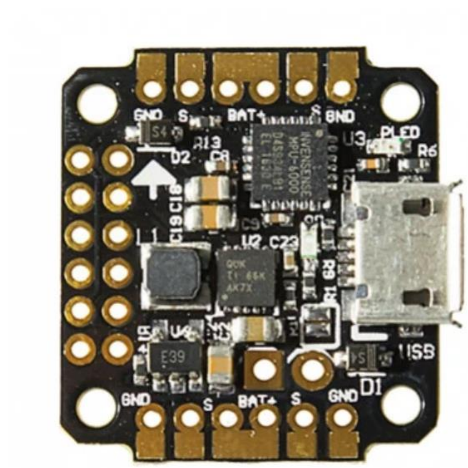

Figure 7.9: Flight Control Board

- Micro Flight Controller with F3 Chip / MPU 6000
- Smallest Brushless FC with a 20x20mm Layout and 16x16mm Hole Setup
- Atomic Light at 1.7g
- 1S 3.7V / 2S 7.4V Power Input Flexibility
- OneShot, MultiShot & DShot 100/300 ESC Protocol
- Built In 15A PDB
- Built In Current Sensor
- Heavy Duty 1.5A BEC with 5V Output
- Buzzer Port
- Gold Plated Pads for the Best Signal / Power Conductivity
- Firmware Perfection via CleanFlight & BetaFlight
- Serial based Receiver / Receiver Mode

7.3 Communication Systems for UAV Control

To ensure effective control of our aerial vehicle, we carefully chose a radio control system, specifically a transmitter and receiver. The receiver we selected, the FS-X6B, has been tested by reputable RC Plane experts and has a proven range of approximately 1.6 kilometers. In terms of compatibility, we had a FlySky i4 transmitter readily available, and thus sought a compatible RC receiver that was both cost-effective and compact in size. It is important to note that RC transmitters and receivers from different brands, such as FrSky and FlySky, are not cross-compatible, making it necessary to select components from the same brand for seamless integration.

In the realm of remote control (RC) systems, such as those used for RC drones, RC cars, and RC planes, several communication protocols are utilized, including PWM, PPM, IBUS, and SBUS. In RC systems, different control inputs and outputs are assigned for various components, and these are transmitted between the RC transmitter and receiver on specific channels. Each channel corresponds to a particular control input or output, such as throttle, elevator, aileron, rudder, or auxiliary (AUX) functions like activating a horn or arming the motors. Pulse Width Modulation (PWM) (shown in figure 7.10) is a widely adopted communication method in which the width of pulses within a fixed time period is manipulated to represent different control values, enabling the control of position or speed.

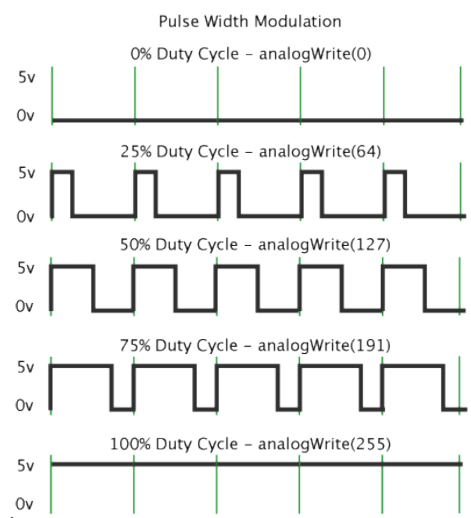

Figure 7.10: Pulse Width Modulation

Pulse Position Modulation(PPM) is an alternative to PWM where instead of varying the width of pulses within a fixed time period, we combine the data for multiple channels into a single stream of pulses and rather than using separate signals for each channel, PPM encodes the information by varying the position (the time of occurrence) of pulses within a fixed time frame which are then decoded by the receiver and separate control values are extracted for each channel as shown in figure 7.11.

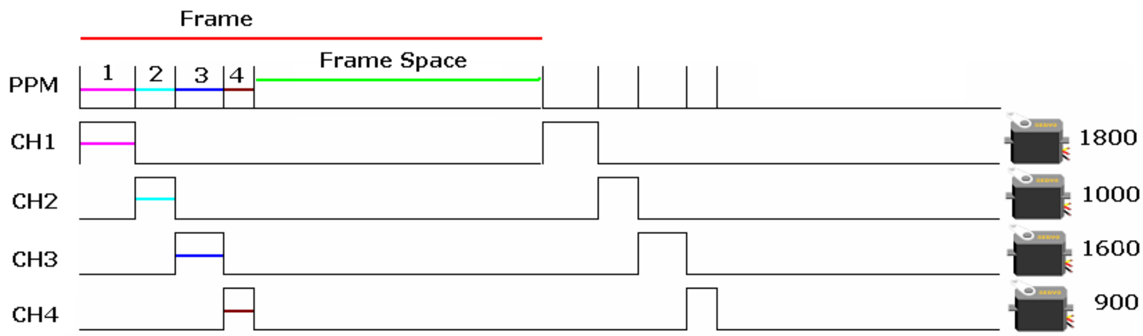

Figure 7.11: Pulse Position Modulation (PPM)

IBUS is a protocol (developed by FlySky) that uses the UART serial interface to transmit the value of each channel from the receiver. The data transmission rate is around 115200 kbps, and a new value can be read every 7 milliseconds. Moreover, we can use this to transmit data for multiple channels over a single wire.

SBUS is a digital signal communication protocol (developed by Futaba) which enables high-speed, bidirectional communication between the transmitter and receiver, allowing for more channels and providing enhanced control precision.

7.4 Testing Receiver and Transmitter:

After selecting a transmitter and receiver, we proceeded to set up the system by connecting the receiver wires to an Arduino Uno. Once the receiver was successfully bound with the transmitter, we uploaded a basic program to the Arduino Uno to print out the channel values corresponding to the movement of sticks on the transmitter. By establishing a serial interface, we received these values on our laptop via a connected wire. To decode and display the received values, we developed a simple Python program that printed the channel data on the terminal, allowing us to verify and test the functionality of various channels.

7.5 Integration of Avionics Components

Before combining all the components into the final circuit, we tested and connected them individually to check for errors and malfunctioning of the individual components within our circuitry. For the visual schematics, we have the following figure 7.12 made using fritzing software.

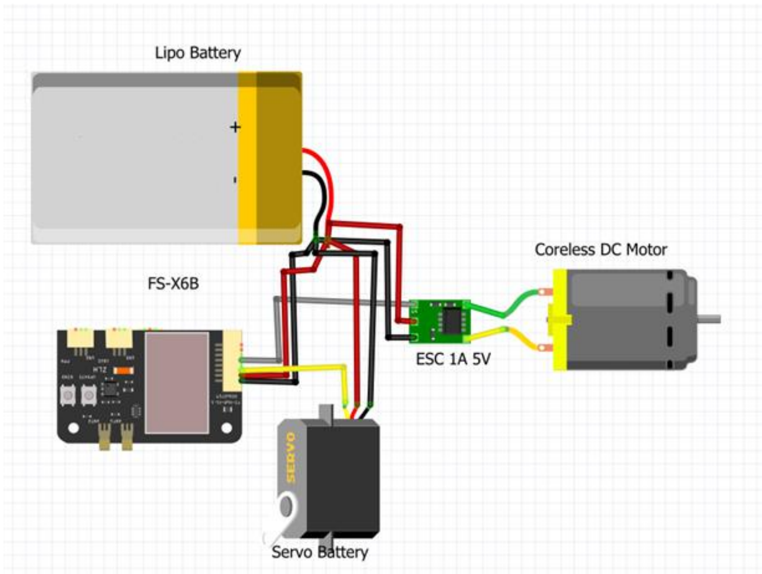

Figure 7.12: Visual Schematics for the circuitry in BORAK

For testing our DC Motor(visible in figure 7.13), we can first try to connect it to a power source directly, but we have to make sure that we are not exceeding its rated current and voltage limits to avoid burning the motor out.

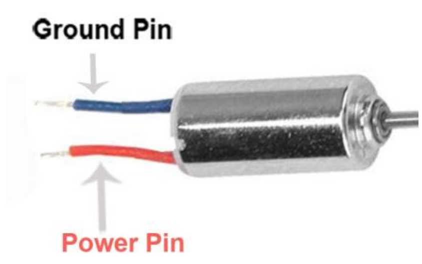

Figure 7.13: Connections of a coreless motor

The Servo tester module is quite an easy method to test the servos without the need to code an Arduino and then make several connections to it. Using a servo tester (shown in figure 7.14), just connect a battery or a power source that is compatible with the power ratings of the servo that is being utilized for the prototype.

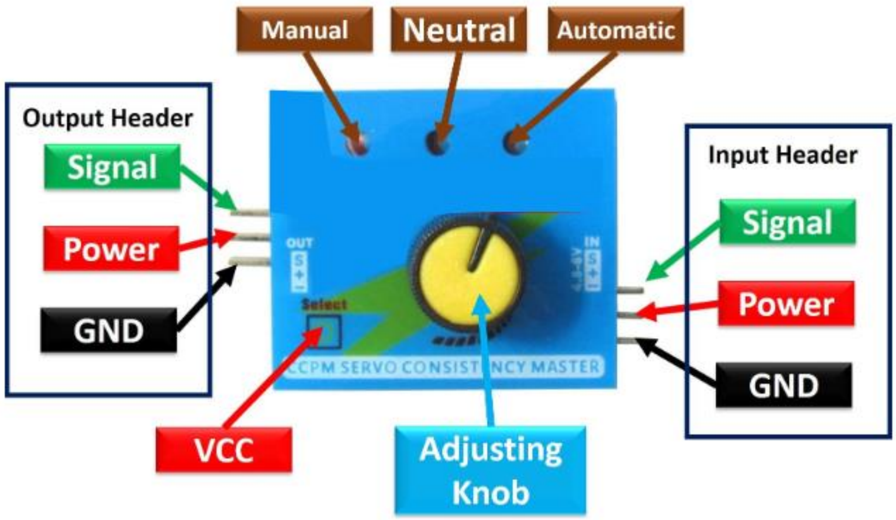

Figure 7.14: Connections shown on a servo tester.

Just connect the Power and Ground from input side to the battery and then connect the three wires to the servo on the output end, and then you can try the manual mode to test the adjusting knob or try the automatic mode to run the sweep function which makes the servo run like a car windscreen wiper.

7.6 Connecting Transmitter to the receiver:

For connecting RC Transmitter to the RC receiver, we must do the binding process. Before powering up the receiver, press and hold the bind button on it and then power it on, after that just press and hold the binding button on the transmitter and then after a successful beep is heard, that binding would be successful. Connect a component to the channel corresponding to one of the sticks for a successful check.

The circuitry for both prototypes have a major difference of an additional servo, and a flight control board.

The components for BORAK are enlisted in the table 7.6, and their dimensions and masses are mentioned in table 7.7 and table 8.8 respectively.

Table 7.6: Selected components and their model number

Name	Model
Coreless Motor	614
ESC	DSM-ESC001
Receiver	FS-X6B
LiPo Battery	100mAh
Servo	AFRC D1602

Table 7.7: Selected Components and their dimensions

Name	Dimensions (mm x mm)
Coreless Motor	6*14
ESC	12*8.5
Receiver	36*22
Lipo Battery	26.35*9.10
Servo	16*8.2*16.5

Table 7.8: Selected components and their mass

Name	Mass (g)
Coreless Motor	1.8
ESC	1
Receiver	4.9
LiPo Battery	1.5
Servo	2

And for the EME-Thopter, the components can be seen in figure 7.15:

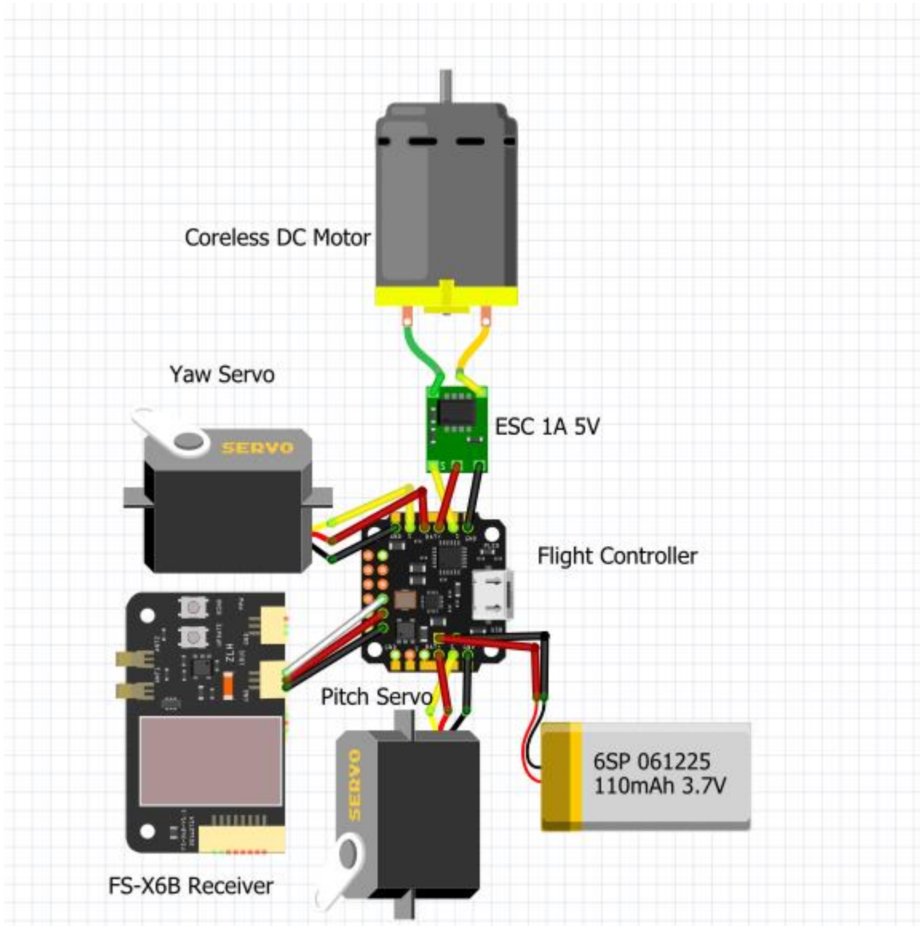

Figure 7.15: Visual Schematics of the EME-Thopter

Comparing it to the first prototype, we have an additional servo, a battery with relatively high capacity, and a flight control board to enable PID Tuning for attitude control.

Chapter 8:
BODY DESIGN

After forming the electrical circuit for the ornithopter based on the pigeon, we were required to place all these components inside the body of the ornithopter. For the design of the body of the ornithopter, the first thing that was decided was that the body will be made in two parts and after placing all the electronic components and flapping mechanism inside one half of the body, we will close the body with the other half.

8.1 1st Iteration:

To make the body, we had 3D printing in our mind before we faced some problems which will be discussed later. For 3D printing, we designed the CAD model of the bird body. As decided before, we designed two halves of the body. To fix these two halves of the ornithopter's body, we designed some pins on one of the halves. On the second half, we designed holes on the exact same points so that the pins will come and fit into these holes and lock the two bodies with each other.

Additionally, we designed a fork type structure that would hold the motor in place and hence it would be in turn holding the whole mechanism in place. We also required a holding for the servo motor which would be responsible for the control of the ornithopter.

Two holes were also made in the body, one on each half. These holes were for the strings to pass from the rocker of the servo to the rudder on the vertical tail of the ornithopter.

A large hole for the flapping mechanism was also made on top of the body. This is because the output rockers of the flapping mechanism were supposed to be outside the body so that they may not collide with the body. Holes at the bottom of the body were also made for taking out the antennas of the receiver and for fitting an on/off push button.

One last thing designed inside the bird body was a base on which all the other electronic components were supposed to be placed. These electronic components included battery, receiver, esc and the wires of the whole circuit.

The first problem faced in this design was that the walls of the body were only 0.6 mm wide and it was not possible to manufacture such a thin wall using FDM. This problem could have been solved by using SLA printing instead but apart from this problem of manufacturing there was another complication which was the weight of the body. The first design prototype is shown in the figure 8.1.

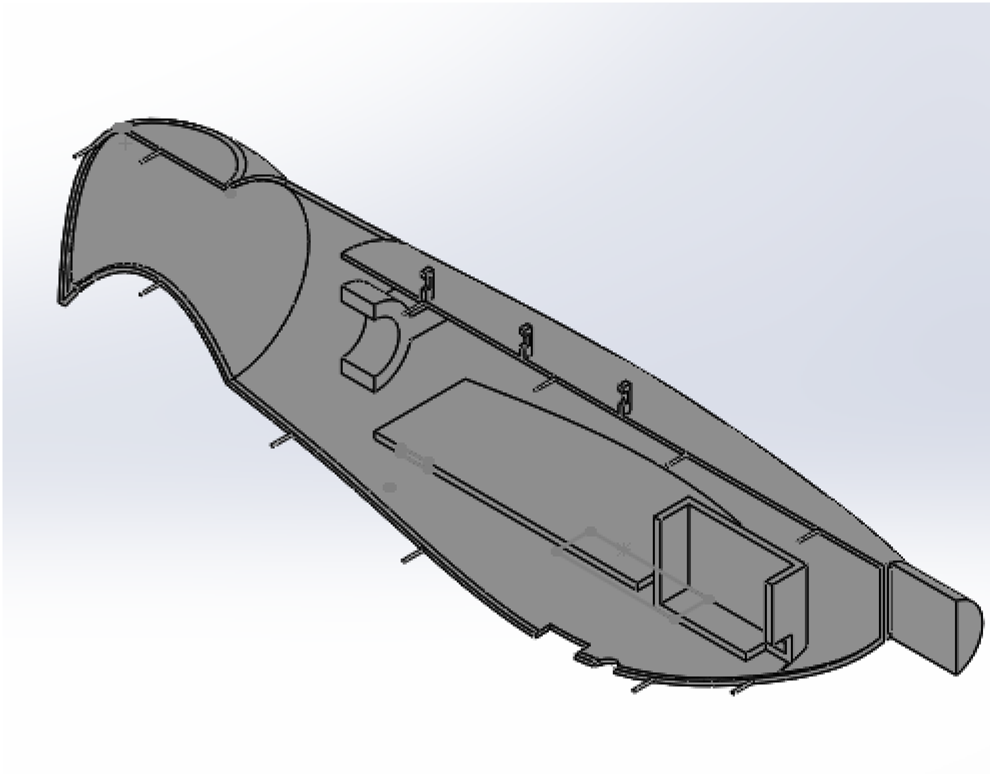

Figure 8.1: First Body Iteration

The mass of one half comes out to be 5.78 g and this means that the total mass of the whole body would be 11.56 g. After this the masses of all the other components were also measured and this was concluded that if we were to use this body, then this would make the total mass of our ornithopter more than 30 g. It would have been impossible for our motor to produce this much lift force based on its rating and the calculations that we had performed.

8.2 2nd iteration:

The next thing that we tried was to reduce the weight of the body by removing the unwanted material. We found two places from where the material could be removed without causing any problems. The first one was the holder of the servo from where some mass was reduced by removing material from its walls. Another place from where the mass was decreased was the base made for the electronic components. Holes were made in the base. In the figure ___, this can be seen that holes were not made throughout the base as by doing so the problem was arising in the mass distribution of the front and back side of the ornithopter.

By performing this reduction, the mass was only decreased to 5.58 g which can be seen in the figure 8.2 which means that the total mass of the body has now become 11.16 g which is not much of a change as compared to the previous iteration.

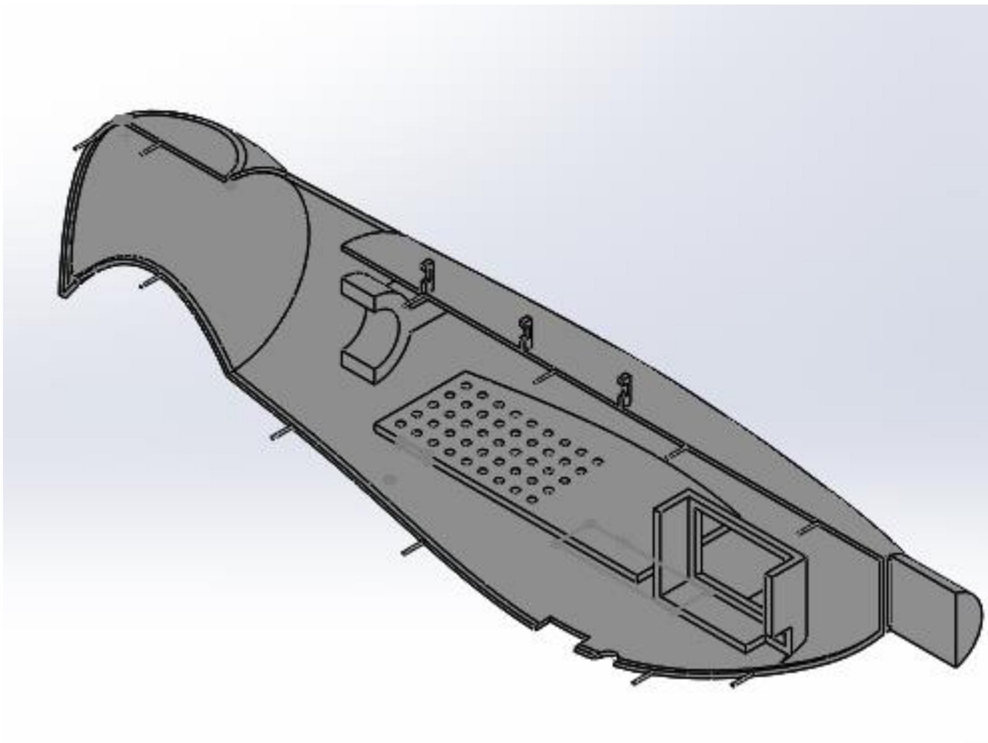

Figure 8.2: Second Iteration

8.3 3rd iteration:

After all this, the only place left from where mass could be reduced was the walls of the body itself. So, a few stripes were cut off the body as can be seen in figure 8.3. The mass of one half now decreased to 3.66 g which meant that the total body mass was now decreased to 7.32 g which still meant that the total mass of the whole ornithopter would be almost 30 g if we were to use this body. The motor that we were using would have not been able to generate this much lift as per its rating and our calculations.

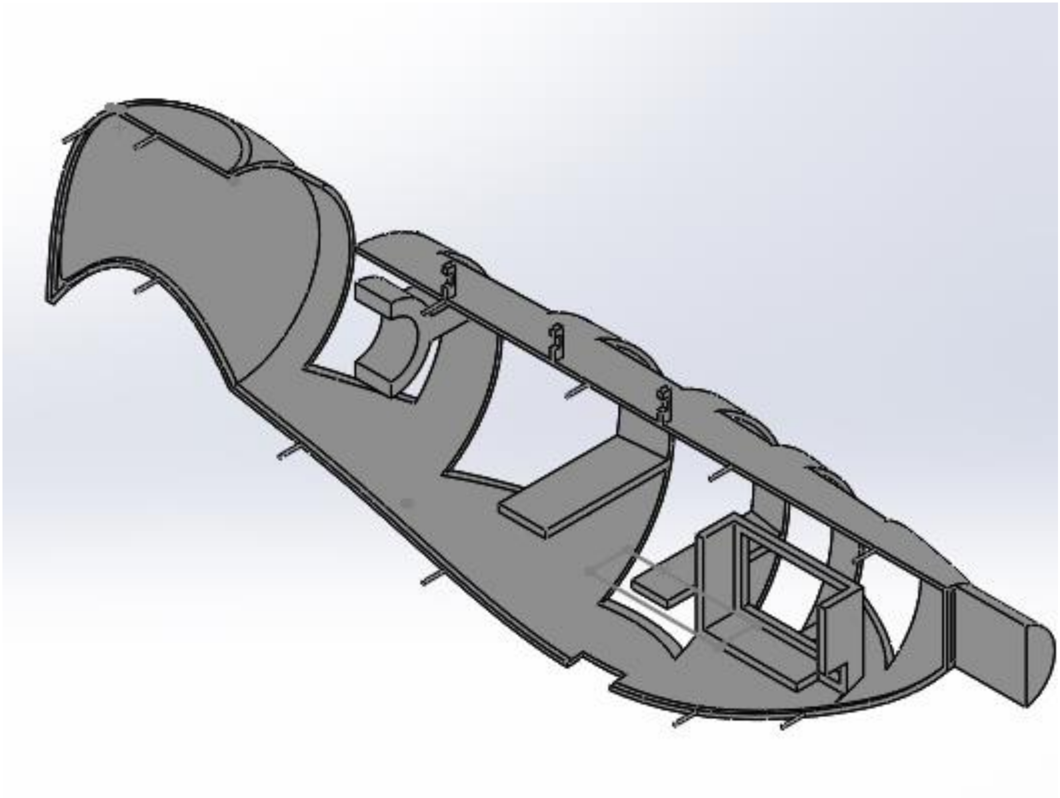

Figure 8.3: Third Iteration

8.4 4th iteration:

The final solution (shown in figure 8.4) that was devised for this problem was to use polystyrene instead of any resins or some other 3D printing material. This solution proved to be effective because the density of any 3D printing material was in the range of 1200 kg/m^3, whereas the density of polystyrene that we found was 140 kg/m^3. This decrease in density would decrease the weight substantially.

We maintained our initial decision to divide the entire body into two halves, but we made significant changes to the overall design due to the shift in material selection. The decision to utilize polystyrene necessitated a different approach, leading us to incorporate slots in the polystyrene to accommodate the various components.

By opting for polystyrene, we embraced a new strategy that involved carving out specialized slots within the material. These slots were carefully crafted to precisely fit and secure the individual components of the body. This approach allowed us to create a more efficient and streamlined design, ensuring proper placement and stability of the components within the structure.

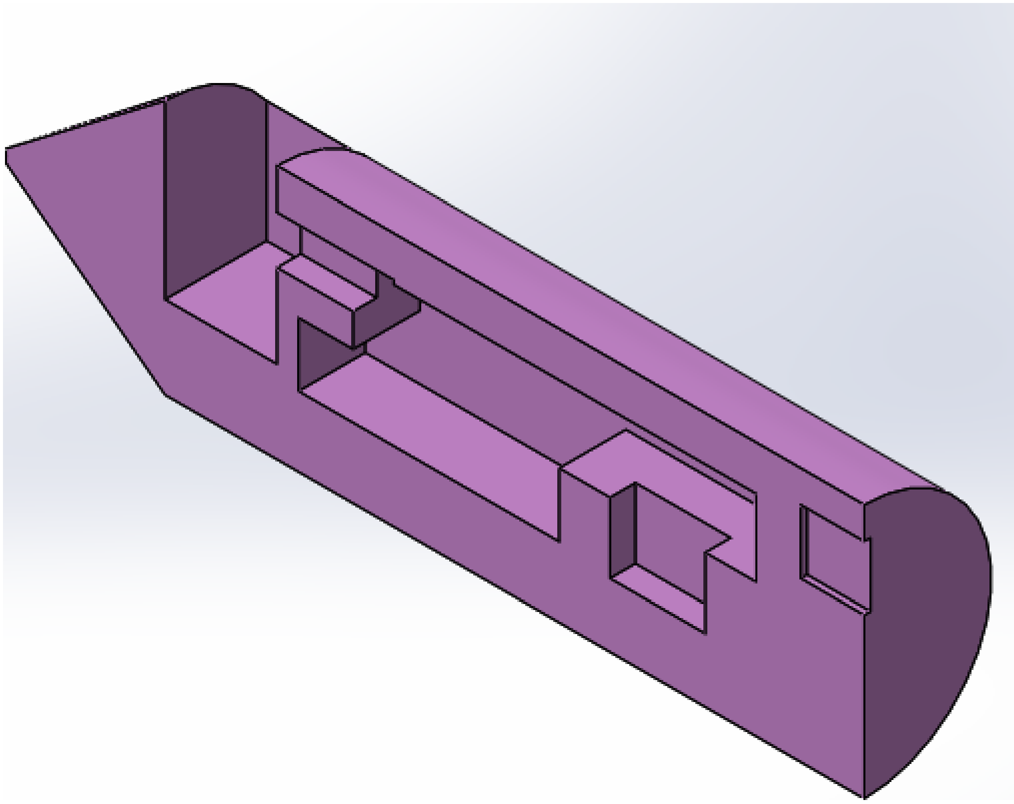

Figure 8.4: Fourth Iteration

8.4.1 Manufacturing:

The following manufacturing processes were employed to bring our design to life:

Laser cutting:

The first step was to make a drawing of the outline of the slots which were to be cut on the polystyrene. This drawing can be seen in the figure 8.5.

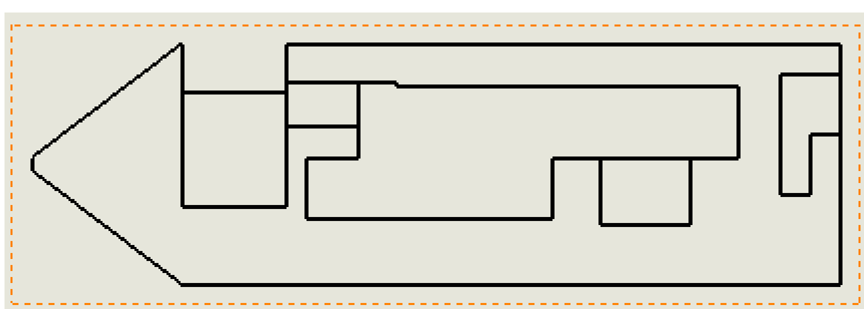

Figure 8.5: Drawing outline for laser cutting

After forming the drawing, this pattern was cut on balsa wood using a laser cutter. This pattern obtained from laser was then stuck to the face of polystyrene which was still in the shape of rectangular cuboid.

Two circles of 40 mm were also cut to be used for the sake of hot wire cutting later for the cylindrical shape of the body.

Milling:

After the pattern was stuck to the polystyrene, a milling machine was used to make the slots of required depths as per the design.

This process was repeated for two pieces of polystyrene which were actually the two halves of the body of the ornithopter.

Hot wire cutting:

The two circle that were cut before, were then used to place the two halves of the body together. Then a hot wire was used to cut along the circles to get a cylindrical shape instead of a cuboid. The last step was to use sandpaper to get the cone shape on the tip of this cylinder.

8.4.2 Evaluation of Coefficient of Drag through CFD Analysis:

After the whole manufacturing process, a CFD analysis was carried out on this body specifically to find the coefficient of drag.

For the sake of analysis, the relative velocity between the air and the body was taken to be 2.5 m/s, which was found experimentally. The roughness constant was taken as 0.5. During the analysis, 100 iterations were run and the graph for those iterations and the final value of coefficient of drag found can be seen in the figure 8.6 turns out to be 0.0036.

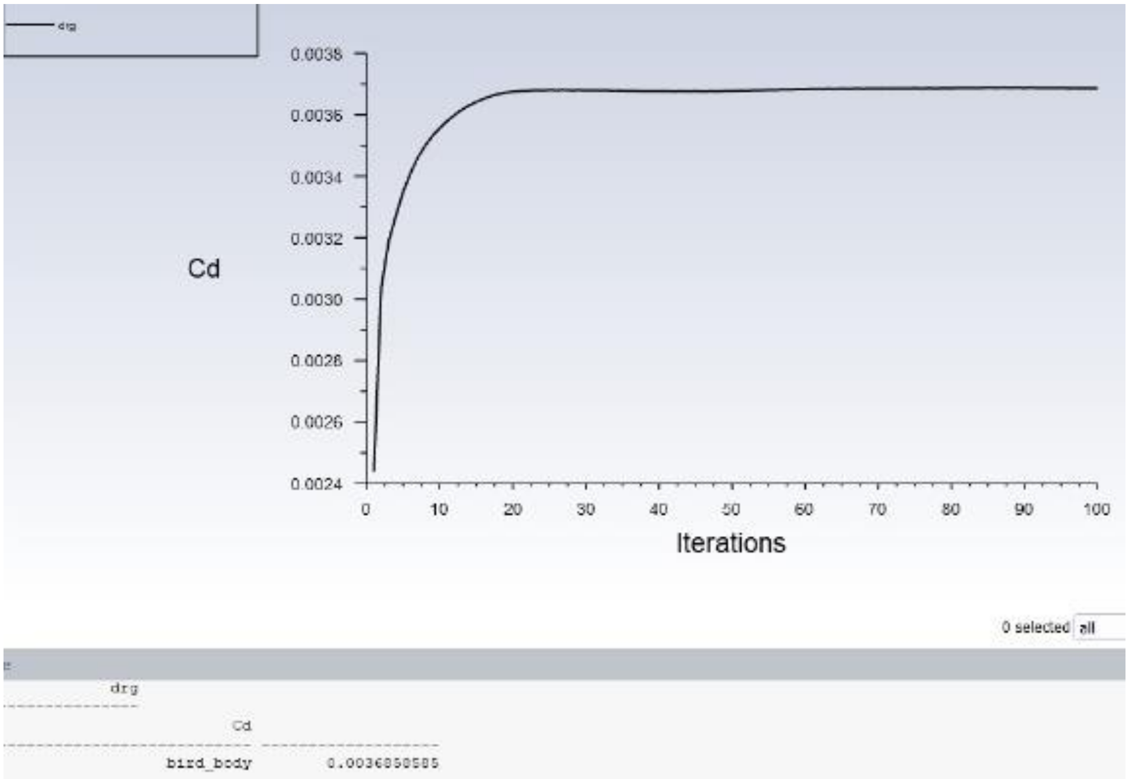

Figure 8.6: Coefficient of Drag for blunt body.

8.5 5th Iteration:

One final iteration was made in which simple polystyrene was used which merely had a density of 12 kg/m^3. This decreased the mass even further and would allow an even longer flight as compared to the previous design iteration of the body.

Apart from this an attempt to reduce drag was also made which was done by passing the hot wire over a smaller non-circular shape instead of a circular one. This resulted in a much smaller body of the bird which would mean a reduced drag. The non-circular shape used for cutting using the hot wire.

8.5.1 Evaluation of Coefficient of Drag through CFD Analysis:

A similar CFD analysis was performed in ANSYS Fluent to determine the change in the coefficient of drag after changing the shape of the body.

The same boundary conditions and physical parameters were used and a new reduced value of coefficient of drag was found as can be seen in the figure 8.7 turns out to be 0.002.

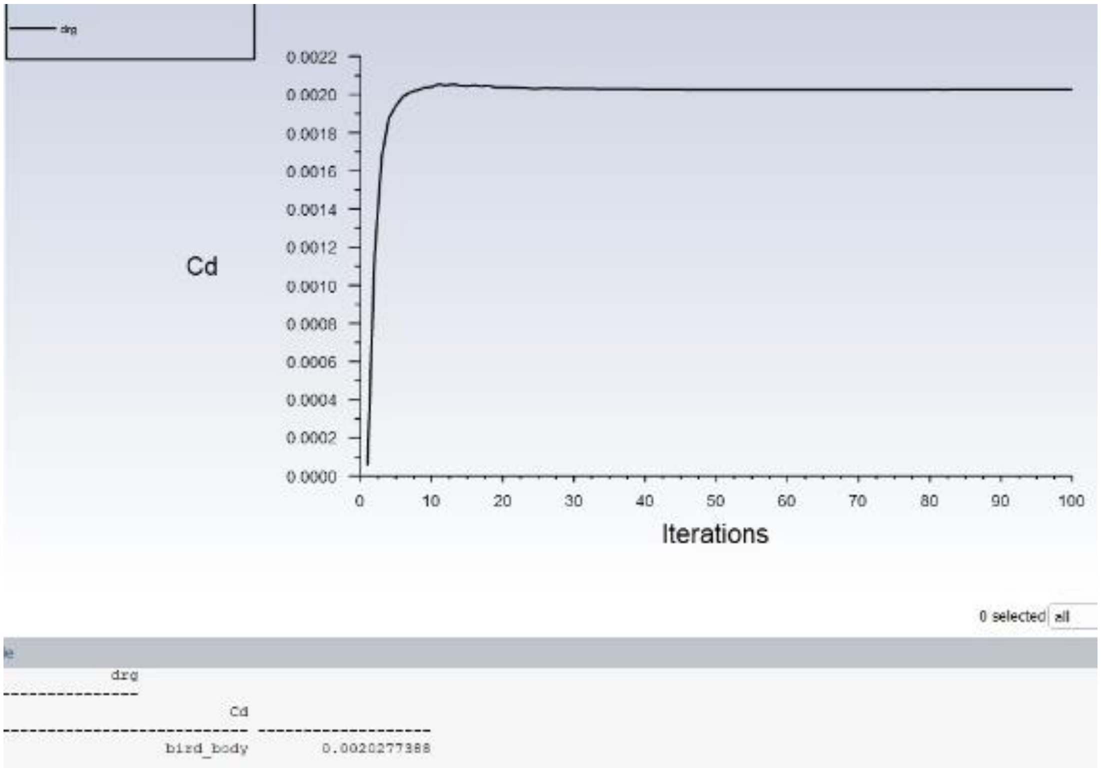

Figure 8.7: Coefficient of Drag for Slim Body

Chapter 9:
SIMULATOR AND OTHER ASSISTIVE TOOLS

We have developed a few tools to assist in our process of testing our prototypes.

9.1 Simulator in Unity

To train the aviator and to ease our visualization which deciding on various things like control mechanism and allotting channels corresponding to the sticks on the transmitter and its effect on both prototypes, we developed a simple simulator (shown in figure 9.1) in unity to ease the process.

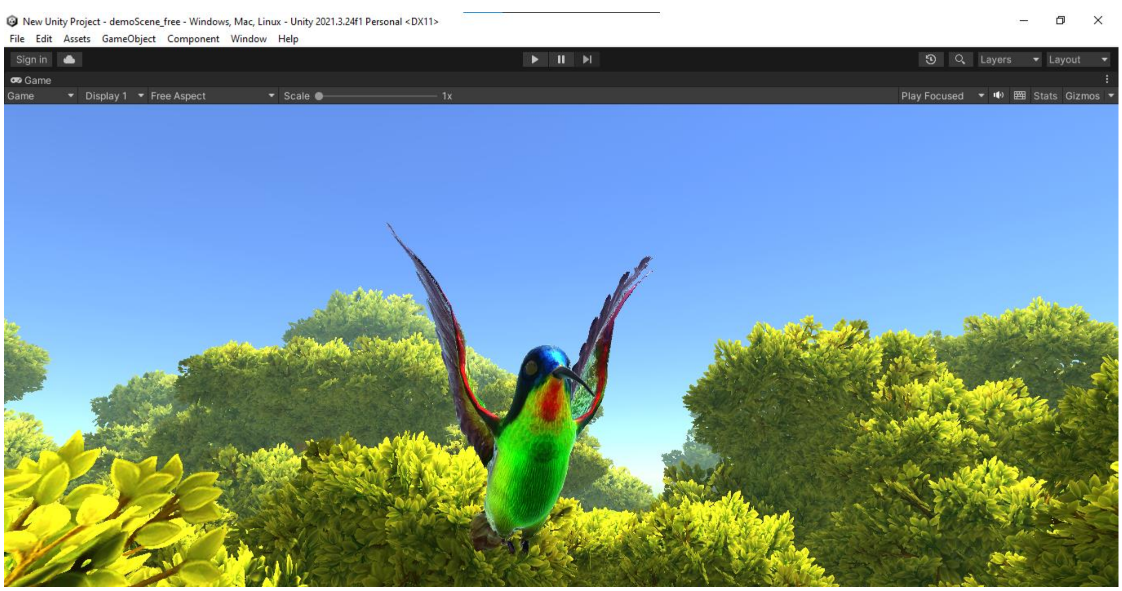

Figure 9.1: Simulator in Unity

9.2 Receiver-Transmitter Testing Module

For testing the control inputs and their corresponding signals, we have made a simple prototype by connecting Arduino Uno to the receiver as shown in figure 9.2.

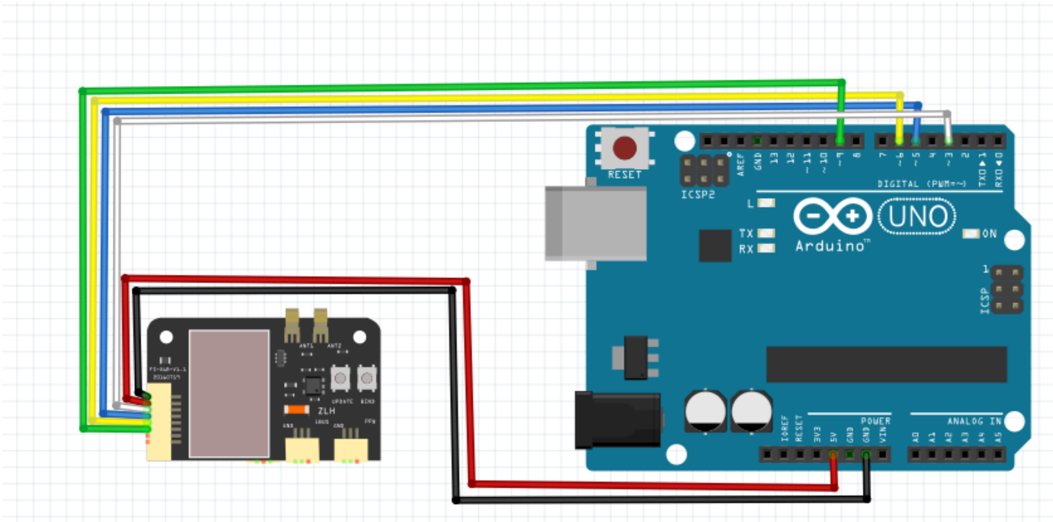

Figure 9.2: The Circuitry for the transmiter-receiver testing on Arduino Uno

For making the prototyping process a bit easy, we make utilized a perf-board(shown in figure 9.3 and figure 9.4) and made the connections easy for making the connections easy.

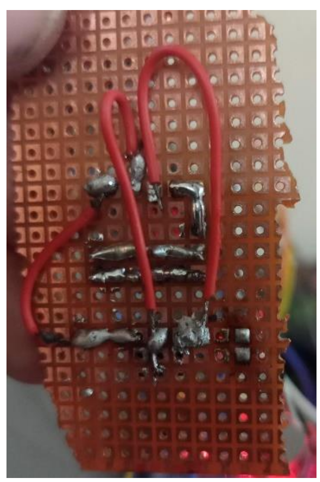

Figure 9.3: A perfboard for the transmitter-receiver module testing on Arduino Uno

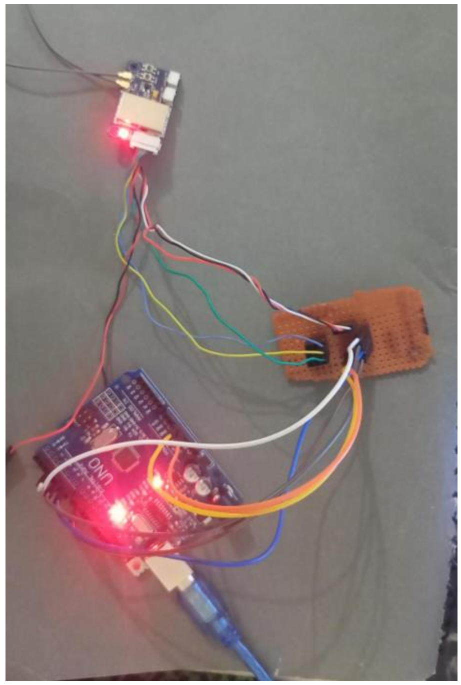

Figure 9.4: Connections for the Transmitter-Receiver Module with the Arduino Uno

For the coding part, we set the baud rate to 115200, and the corresponding code which was burned to the Arduino Uno can be seen in Appendix A.

But for checking the values, we can use the Serial Monitor to check the values, and for making a checking system without having to open the Arduino IDE, we can use a scalable python program which can later be converted to a GUI-based application when needed.

9.3 Noise Reduction for Plots

After recording the videos for the initial testing, we got some plot which had some noise in it, and to remove the noise, we implemented a filter to get a smooth result to find the flapping angle. Some of the snapshots for the slow-motion video of a hummingbird as shown in figure 9.5.

Figure 9.5: Snapshots of the slow- motion flapping motion of a hummingbird

According to the preliminary analysis from the slow-motion video, the number of flaps per second i.e. wingbeat frequency for this hummingbird in this video turned out to be 48 flaps per second. Normally the hummingbirds have a wingbeat frequency range from 40 to 60 strokes per second.

After trying to superimpose the frames for this slow-motion, we get an output from our Python program as shown in figure 9.6.

Figure 9.6: Output of the Python Program after video analysis

After subjecting the video to manual tracking using the Physlet's Tracker software, we tracked the wing tip over multiple frames as in figure 9.7, and then we get figure 9.8.

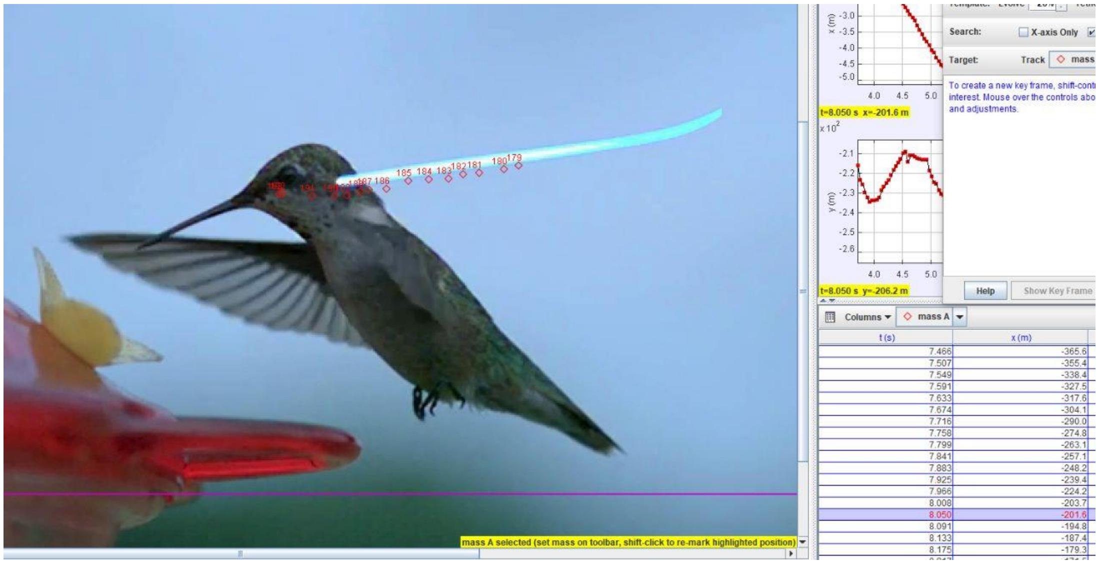

Figure 9.7: Using Physlet's Tracker for plotting the wingtip on multiple frames

The initial plot for these values were rough due to manually placing the points even though the video was a slow motion video, but since the footage was not meant for pictorial analysis but merely for just observing its motion, we get the following result after smoothening out the output using some filters in figure 9.8.

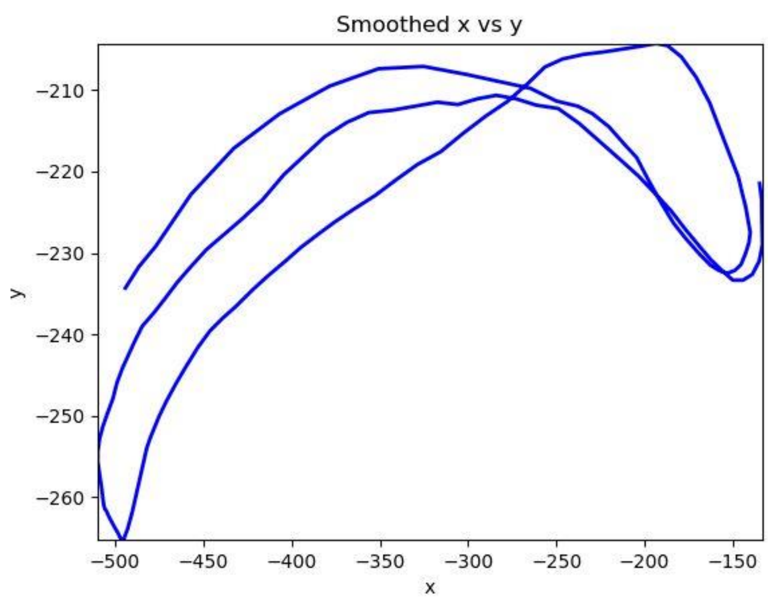

Figure 9.8: Smoothened output for the wing flap trajectory

Figure 9.9: Hummingbird, and the lemniscate-shaped flap trajectory [12]

Chapter 10:
TESTING AND EVALUATION

10.1 Thrust Testing:

After the first assembly of the flapping mechanism and wings, a dead weight of 19grams was attached with the assembly. This made the total weight 28 grams which can be seen in the figure 10.1.

Figure 10.1 : Thrust calculations on mass balance

Then, the flapping was induced and the total mass decrement on the mass balance came out to be 13.84 grams, which showed that a thrust of 14 gf was generated by the motor. This fact has also been theoretically by the calculations below:

In order to calculate the thrust being generated by the clap and fling mechanism, a basic force analysis[37] in the absence of wing-wing interactions was done. Let us take a wing section of width dr at a distance r from the wing root as shown in following figure:

The differential thrust force being generated at this wing section is written as:

$$dT(r,t) = \frac{1}{2}\rho\left(r\dot{\phi}\right)^2 c(r) C_L dr \qquad (27)$$

integrating this differential thrust force over the whole wingspan, we get:

$$T(t) = \frac{1}{2}\rho\dot{\phi}^2 C_L \int_0^R r^2 c(r) dr \qquad (28)$$

Now we will use the following relation:

$$\int_0^R r^2 c(r) dr = SR^2\hat{r}_2^2 \qquad (29)$$

also,

$$\dot{\phi} = \Phi\omega \sin(\omega t) \qquad (30)$$

The total thrust force on one wing is written as:

$$T(t) = \frac{1}{2}\rho R^2 \Phi^2 \omega^2 R \hat{r}_2^2 C_L \sin^2(\omega t) \qquad (31)$$

The average thrust generated by a multi-winged Flapping Wing Micro Aerial Vehicle over one flapping cycle can be given as:

$$T = N\left(\frac{1}{2}\rho V_{ref}^2 S C_T\right) \qquad (32)$$

Now, putting the values, for number of wings N, we have N=4, and for C_T, we get C_T=0.11 for our prototype's flapping frequency using figure 10.2.

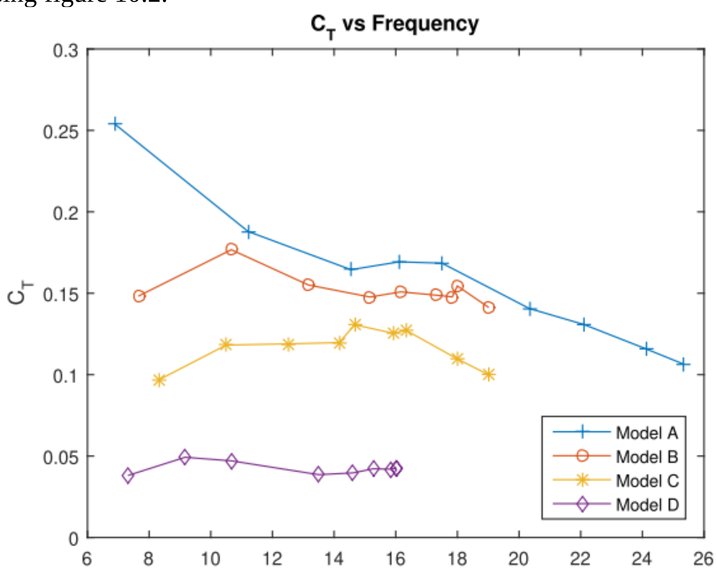

Figure 10.2: Coefficient of Thrust versus Flapping Frequency [37]

For the reference speed V_{ref} , we have the following equation:

$V_{ref} = 2\pi fR\Phi$ (33)

Putting values for f=15 Hz, R=$\frac{275\times10^{-3}}{2} = 0.1375m$, and $\Phi = 40° = 0.698\ radians$,

We get V_{ref}=9.046 ms^{-1}

Now, using equation (32), substitute V_{ref}=9.046 ms^{-1}, $\rho = 1.1kgm^{-3}$, and $S = 9.149 \times 10^{-3}$m

T=0.1812 Newtons

Now, converting the thrust force from Newtons into gramforce (gf), we will multiply it with the conversion factor:

$$T = 0.1812\ N \times \frac{101.96\ gf}{1\ N}$$

$$= 18.478\ gf$$

Chapter 11 Conclusions

11. 1 Improving the circuitry:

For the future work, several potential enhancements can be considered. Firstly, exploring the utilization of piezoelectric materials as an alternative to servo motors can significantly reduce the weight of the prototype. By employing piezoelectric materials, the overall system can achieve a lighter configuration, thereby improving its efficiency and maneuverability.

11.2 Improving the Body

Furthermore, the body of the prototype can be constructed using expanded polypropylene (EPP) foam, which offers a lower density in comparison to materials like Polystyrene (Styrofoam) and Extruded Polystyrene (Jumbolon Board). By adopting EPP foam, the resulting body will exhibit enhanced impact resistance while still maintaining a lightweight structure.

11.3 Voltage Supply

To ensure that the voltage supply adequately supports the electronic speed controller and other components, the implementation of a compact and lightweight boost circuit can be explored. This additional circuitry would serve the purpose of maintaining optimal power levels. Additionally, integrating a receiver with a built-in electronic speed controller would enable a reduction in size, leading to further miniaturization of the prototype.

11.4 Transmitter and Receiver:

Due to the unavailability of the FrSky Transmitter, the inclusion of the XM Plus Mini receiver, which boasts a smaller form factor compared to the current FS-X6B Receiver, could not be attempted. It should be noted that the flight control board selected for this project was compatible solely with a FlySky Transmitter, as the IBUS protocol employed is specific to FlySky products and would not have been compatible with the FrSky Transmitter.

Moreover, it is worth mentioning that the cost associated with acquiring a FrSky transmitter and receiver was found to be higher than the combined cost of the Flysky receiver, transmitter, and flight control board. This cost consideration played a role in the decision-making process regarding the selection of components.

By considering these proposed improvements and exploring alternative materials and components, the overall efficiency, performance, and cost-effectiveness of the prototype can be enhanced, paving the way for further advancements in future iterations of the project.

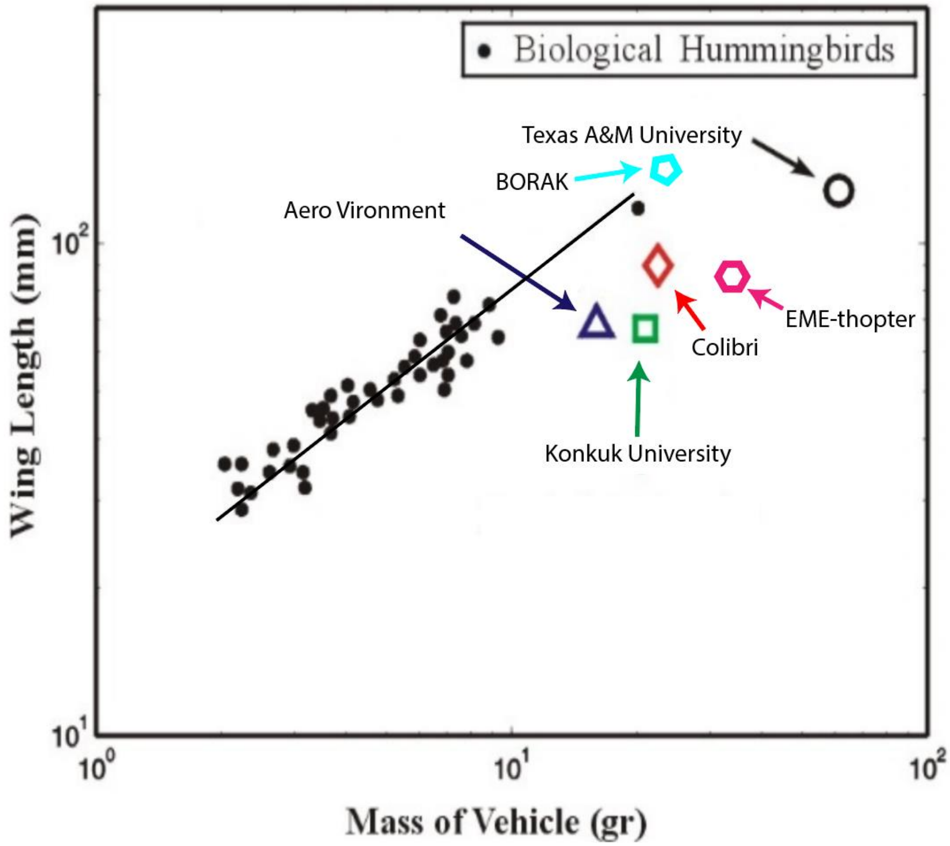

Figure 11.1: Comparison of Our Prototypes with others and biological hummingbirds

A comparison of our work can be compared with other successful projects in the field, and its wing length to mass ratio appears to be close to a biological hummingbird according to figure 11.1.

In conclusion, the development of a flapping wing micro aerial vehicle (MAV) has been explored in this report. The project has demonstrated the feasibility and potential of flapping-based MAVs for various applications.

The utilization of flapping wings offers advantages such as improved maneuverability, agility, and efficiency compared to traditional rotor-based MAVs. The prototype showcased the capability of achieving controlled flight through the integration of servo motors for wing motion.

Furthermore, several potential enhancements have been identified for future iterations. The exploration of alternative materials, such as lightweight piezoelectric materials, can significantly reduce the weight of the prototype, thereby improving its overall performance and maneuverability.

In addition, the use of expanded polypropylene (EPP) foam for constructing the body of the MAV can provide enhanced impact resistance while maintaining a lightweight structure.

To optimize the power supply, the implementation of a compact and lightweight boost circuit can be considered. This additional circuitry would ensure optimal power levels for the electronic speed controller and other components, leading to improved efficiency.

Overall, the development of a flapping wing MAV holds great promise for the field of aerial robotics. By continuing to explore and refine the design, future iterations can further enhance the efficiency, maneuverability, and applicability of this innovative MAV technology.

Figure 11.2: Hummingbird, feeding off the nectar [38]

REFERENCES:

[1] G. C. H. E. De Croon, M. A. Groen, C. De Wagter, B. Remes, R. Ruijsink, and B. W. Van Oudheusden, “Design, aerodynamics and autonomy of the DelFly,” *Bioinspir Biomim*, vol. 7, no. 2, Jun. 2012, doi: 10.1088/1748-3182/7/2/025003.

[2] “http://www.techject.com.”

[3] W. Bejgerowski, J. W. Gerdes, S. K. Gupta, H. A. Bruck, and S. Wilkerson, “DESIGN AND FABRICATION OF A MULTI-MATERIAL COMPLIANT FLAPPING WING DRIVE MECHANISM FOR MINIATURE AIR VEHICLES,” 2010. [Online]. Available: http://www.asme.org/about-asme/terms-of-use

[4] O. Vaughan, “RoboBee breaks free,” *Nature Electronics*, vol. 2, no. 7. Nature Publishing Group, p. 265, Jul. 01, 2019. doi: 10.1038/s41928-019-0280-8.

[5] M. Keennon, K. Klingebiel, H. Won, and A. Andriukov, “Development of the nano hummingbird: A tailless flapping Wing Micro Air Vehicle,” in *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2012. doi: 10.2514/6.2012-588.

[6] M. Benedict, “Design, Development and Flight-Testing of a Robotic Hummingbird,” 2015. [Online]. Available: https://www.researchgate.net/publication/281067582

[7] A. Preumont and A. Roshanbin, “COLIBRI: A Robotic Hummingbird,” 2018. [Online]. Available: http://www.youtube.com/watch?v=Hrlr45uGapQ

[8] “Sir George Cayley* ‘Father of aerial navigation’ (1773-1857),” *Notes Rec R Soc Lond*, vol. 17, no. 1, pp. 36–56, May 1962, doi: 10.1098/rsnr.1962.0005.

[9] John D. Anderson, *Fundamentals-of-aerodynamics-6-Edition*.

[10] D. O. Dommasch, S. S. Sherby, and F. Thomas, *Airplane aerodynamics*, 3rd ed. New York, Pitman Pub. Corp., 1961.

[11] W. Bejgerowski, J. W. Gerdes, S. K. Gupta, H. A. Bruck, and S. Wilkerson, “DESIGN AND FABRICATION OF A MULTI-MATERIAL COMPLIANT FLAPPING WING DRIVE MECHANISM FOR MINIATURE AIR VEHICLES,” 2010. [Online]. Available: http://www.asme.org/about-asme/terms-of-use

[12] FInio BM, Eum B, and Oland C., “Asymmetric flapping for a robotic fly using a hybrid power-control actuator,” 2009.

[13] M. A. A. Fenelon and T. Furukawa, “Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator,” *Mech Mach Theory*, vol. 45, no. 2, pp. 137–146, Feb. 2010, doi: 10.1016/j.mechmachtheory.2009.01.007.

[14] A. J. Bergou, L. Ristroph, J. Guckenheimer, I. Cohen, and Z. J. Wang, “Fruit flies modulate passive wing pitching to generate in-flight turns,” *Phys Rev Lett*, vol. 104, no. 14, Apr. 2010, doi: 10.1103/PhysRevLett.104.148101.

[15] H. V. Phan *et al.*, “Stable Vertical Takeoff of an Insect-Mimicking Flapping-Wing System Without Guide Implementing Inherent Pitching Stability,” *J Bionic Eng*, vol. 9, no. 4, pp. 391–401, Dec. 2012, doi: 10.1016/S1672-6529(11)60134-0.

[16] C. Galiński and R. Zbikowski, “Insect-like flapping wing mechanism based on a double spherical Scotch yoke,” *J R Soc Interface*, vol. 2, no. 3, pp. 223–235, 2005, doi: 10.1098/rsif.2005.0031.

[17] T. Q. Truong, V. H. Phan, S. P. Sane, and H. C. Park, “Pitching moment generation in an insect-mimicking flapping-wing system,” *J Bionic Eng*, vol. 11, no. 1, pp. 36–51, Jan. 2014, doi: 10.1016/S1672-6529(14)60018-4.

[18] H. V. Phan and H. C. Park, “Generation of Control Moments in an Insect-like Tailless Flapping-wing Micro Air Vehicle by Changing the Stroke-plane Angle,” *J Bionic Eng*, vol. 13, no. 3, pp. 449–457, Jul. 2016, doi: 10.1016/S1672-6529(16)60318-9.

[19] Y. Peng, J. Cao, L. Liu, and H. Yu, “A piezo-driven flapping wing mechanism for micro air vehicles,” *Microsystem Technologies*, vol. 23, no. 4, pp. 967–973, Apr. 2017, doi: 10.1007/s00542-015-2762-6.

[20] J. H. Jang and G. H. Yang, “Design of wing root rotation mechanism for dragonfly-inspired micro air vehicle,” *Applied Sciences (Switzerland)*, vol. 8, no. 10, Oct. 2018, doi: 10.3390/app8101868.

[21] C. Galiński and R. Zbikowski, “Insect-like flapping wing mechanism based on a double spherical Scotch yoke,” *J R Soc Interface*, vol. 2, no. 3, pp. 223–235, 2005, doi: 10.1098/rsif.2005.0031.

[22] P. Zdunich *et al.*, "Development and testing of the mentor flapping-wing micro air vehicle," *J Aircr*, vol. 44, no. 5, pp. 1701–1711, 2007, doi: 10.2514/1.28463.
[23] S. S. Baek, K. Y. Ma, and R. S. Fearing, "Efficient Resonant Drive of Flapping-Wing Robots."
[24] M. Keennon, K. Klingebiel, H. Won, and A. Andriukov, "Development of the nano hummingbird: A tailless flapping Wing Micro Air Vehicle," in *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2012. doi: 10.2514/6.2012-588.
[25] R. B. George, M. B. Colton, C. A. Mattson, and S. L. Thomson, "A Differentially Driven Flapping Wing Mechanism for Force Analysis and Trajectory Optimization," 2012.
[26] Z. E. Teoh and R. J. Wood, "A Flapping-Wing Microrobot with a Differential Angle-of-Attack Mechanism."
[27] Z. Chen, W. Zhang, J. Mou, and J. Zhao, "Development of an Insect-like Flapping-Wing Micro Air Vehicle with Parallel Control Mechanism," *Applied Sciences*, vol. 12, no. 7, p. 3509, Mar. 2022, doi: 10.3390/app12073509.
[28] T. Q. Truong, V. H. Phan, S. P. Sane, and H. C. Park, "Pitching moment generation in an insect-mimicking flapping-wing system," *J Bionic Eng*, vol. 11, no. 1, pp. 36–51, Jan. 2014, doi: 10.1016/S1672-6529(14)60018-4.
[29] W. C. M. D. Q. Nguyen, "Design, Fabrication, and Performance Test of a Hovering-Based Flapping-Wing Micro Air Vehicle Capable of Sustained and Controlled Flight".
[30] P. Zdunich *et al.*, "Development and testing of the mentor flapping-wing micro air vehicle," *J Aircr*, vol. 44, no. 5, pp. 1701–1711, 2007, doi: 10.2514/1.28463.
[31] S. S. Baek, K. Y. Ma, and R. S. Fearing, "Efficient Resonant Drive of Flapping-Wing Robots."
[32] N. Phillips and K. Knowles, "Effect of flapping kinematics on the mean lift of an insect-like flapping wing," *Proc Inst Mech Eng G J Aerosp Eng*, vol. 225, no. 7, pp. 723–736, Jul. 2011, doi: 10.1177/0954410011401705.
[33] M. Karásek, F. T. Muijres, C. De Wagter, B. D. W. Remes, and G. C. H. E. De Croon, "A tailless aerial robotic flapper reveals that flies use torque coupling in rapid banked turns." [Online]. Available: http://science.sciencemag.org/
[34] J. H. Jang and G. H. Yang, "Design of wing root rotation mechanism for dragonfly-inspired micro air vehicle," *Applied Sciences (Switzerland)*, vol. 8, no. 10, Oct. 2018, doi: 10.3390/app8101868.
[35] P. S. Sreetharan and R. J. Wood, "Passive torque regulation in an underactuated flapping wing robotic insect," in *Autonomous Robots*, Oct. 2011, pp. 225–234. doi: 10.1007/s10514-011-9242-3.
[36] J. E. da Silva and J. Urbanetz, "Converting a conventional vehicle into an electric vehicle (EV)," *Brazilian Archives of Biology and Technology*, vol. 62, no. specialissue, 2019, doi: 10.1590/1678-4324-SMART-2019190007.
[37] M. Balta, D. Deb, and H. E. Taha, "Flow visualization and force measurement of the clapping effect in bio-inspired flying robots," *Bioinspir Biomim*, vol. 16, no. 6, Nov. 2021, doi: 10.1088/1748-3190/ac2b00.
[38] A. F. Skutch, "The Life of a Hummingbird," Crown Publishers.

APPENDICES

Appendix A:
Code for Arduino Uno

```
#define CH1 3
#define CH2 5
#define CH3 6
#define CH4 9

int readChannel(int channelInput, int minLimit, int maxLimit, int defaultValue){
  int ch = pulseIn(channelInput, HIGH, 30000);
  if (ch < 100) return defaultValue;
  return map(ch, 1000, 2000, minLimit, maxLimit);
}



void setup(){
  Serial.begin(115200);
  pinMode(CH1, INPUT);
  pinMode(CH2, INPUT);
  pinMode(CH3, INPUT);
  pinMode(CH4, INPUT);
}

int ch1Value, ch2Value, ch3Value, ch4Value;

void loop() {
  ch1Value = readChannel(CH1, -100, 100, 0);
  ch2Value = readChannel(CH2, -100, 100, 0);
  ch3Value = readChannel(CH3, -100, 100, -100);
  ch4Value = readChannel(CH4, -100, 100, 0);

  Serial.print("Ch1: ");
  Serial.print(ch1Value);
  Serial.print(" Ch2: ");
```

```
  Serial.print(ch2Value);
  Serial.print(" Ch3: ");
  Serial.print(ch3Value);
  Serial.print(" Ch4: ");
  Serial.print(ch4Value);
  delay(500);
}
```