TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

B-03-BAS-2019/24

DESIGN, FABRICATION AND BENCH TEST OF FLAPPING WING AERIAL VEHICLE

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SUBMITTED TO:
THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEEREING
PULCHOWK CAMPUS

March 13, 2024

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DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

LETTER OF APPROVAL

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a project report entitled **”DESIGN, FABRICATION AND BENCH TESTING OF FLAPPING WING AERIAL VEHICLE.”** submitted by **Anil Kumar Yadav, Ashmit Timsina, Gopal Thada Magar and Santosh Thapa** in partial fulfillment of the requirements for the Bachelor’s Degree in Aerospace Engineering.

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ABSTRACT

This project presents the comprehensive development and completion of a flapping wing mechanism, encompassing critical aspects including CAD modeling, gearbox design, wing structure design, tail design and overall body fabrication. Our efforts have culminated in the successful realization of a large-scale ornithopter, colloquially termed the flapping wing bird, intended to serve as a platform for the study of flapping wing flight control. On moving forward, our project has successfully performed bench tests including wind tunnel experiments for lift analysis through the load cell, smoke flow visualization and tuft flow analysis to validate the functionality, performance and aerodynamics of the developed flapping wing mechanism. The successful completion of this project marks a significant milestone in the advancement of flapping wing technology, demonstrating its potential for various applications in aerodynamics, bio-mimicry, and unmanned aerial vehicles.

keywords: Ornithopter, flapping wing mechanism, wind tunnel experimentt ,aerodynamics, flow visualization

ACKNOWLEDGEMENT

In the intricate realm of flapping wing research, words often falter, finding themselves misplaced in the attempt to convey the depth of our sincere sentiments. This contribution transcends the ordinary, rendering mere expressions a ritual devoid of true essence.

Our heartfelt appreciation extends to Associate Prof. Rajesh Kaji Kayastha, Mechancial and Aerospace engineering department , our esteemed supervisor, whose unwavering guidance and support have been indispensable on this journey. Gratitude resonates towards Assistant prof. Dr. Sudip Bhattarai (Head of Department of Mechanical and Aerospace Engineering) and Assistant prof. Ashish karki for having intellectual support on our project.

We would like to express our sincere gratitude to our Assistant prof.Kamal Darlami (Deputy Head of Mechanical and Aerospace Engineering Department, and Head of IIEC) for his guidance on our flapping wing project's flow visualization. Your expertise and support have been invaluable, and we are truly grateful for your mentorship. we would also like to thanks to Mechanical and Aerospace engineering department for providing the opportunity to explore our flapping wing project through the undergraduate program. we express our special thanks for the incubation, innovation, entrepreneurship centre (IIEC) for the invaluable support and resources and providing a space where innovation thrives, and entrepreneurs like ourself can flourish.

To our cherished family and friends, whose indirect contributions through assistance and encouragement have woven an unseen thread into the fabric of this project, we extend our deepest thanks. Lastly, a profound acknowledgment to the almighty for bestowing the strength needed to navigate the intricate path of this undertaking.

To my friends and family

“To invent an airplane is nothing. To build one is something. To fly is everything.” — Otto Lilientha

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1. INTRODUCTION

1.1. History of the Ornithopter

The history of flapping wings goes back to prehistoric times when people observed birds and insects and tried to draw inspiration from them. Ancient civilizations, such as the Greeks and Chinese, observed birds and insects flying with flapping wings. The Florentine scientist and painter, Leonardo da Vinci made sketches and conceptual designs of flying machines, including those with flapping wings[4].

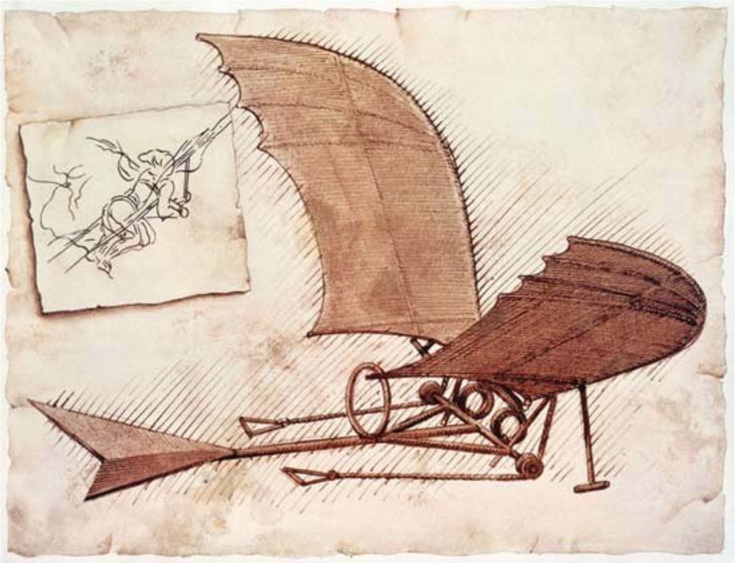


Figure 1.1: Leonardo da Vinci's human powered ornithopter design.

In Da Vinci's range of ornithopter designs, the pilot would either be standing or prone control the flapping wing by pushing or pulling on a number of levers in turn. The pilot's role in each sketch was to supply the motive power needed for the machine to produce both lift and propelling energy. After Da Vinci, however, not much progress was made in flapping wing aviation until the 19th century.

Italian scientist Giovanni Borelli described the flapping flight of birds in his well-known book De Motu Animalium, which was published in the 17th century. He illustrated how birds change horizontal direction, or yaw, by beating one wing at a different pace than the other, demonstrating his grasp of the intricate principles of aerodynamics. Similar to earlier studies made by Leonardo da Vinci, Borelli's observations were essential to the understanding of the physics of bird flight.

Edward Frost constructed an ornithopter in 1902 from feathers, silk, and willow. Despite the fact that his designs mimicked the appearance of birds, the device was too heavy to lift.

Many projects with flapping wings have been initiated and completed recently. One such project is the Phoenix Bird [1], a bigger ornithopter that resembles a bird and can carry weights of up to 400 g. Scientists and engineers have long been attracted by the study of flapping wing, which led to the creation of bio mimetic wing technology.

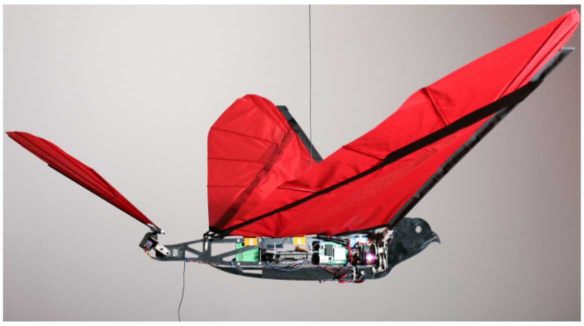


Figure 1.2: Phoenix bird.[1]

1.2. Brief introduction about flight

The flapping-wing aerial vehicle reflects the flying way of bird, insect. In contrast to conventional aircraft, which rely on jet engines and propellers to provide lift and thrust, it depends on the flapping of the wings to produce the lift and thrust necessary for flight. It has benefits of higher energy efficiency, low noise , bionic form and flapping characteristics which makes it ideal for both military and civilian usage.

(a) Downstroke

(b) Upstroke

Figure 1.3: Folding of large-sized bird during upstrokes.[2]

In general, the airflow through wings during flapping and the air pressure difference between the upper and lower surfaces of the wings and are greatly influenced by the flapping law, mechanical structural, and the air tightness at joints. The smaller bird and larger bird have different flying technique, different wing structure, and flapping frequency. The larger bird has lower flapping frequency as they have larger wingspan. Within one cycle of flapping of wing of larger bird it includes 4 part i.e. down stroke, folding stroke, lift stroke and unfolding stroke. During the flapping of the wing, it affects the the angle of attack which is shown in figure. During the cruise of larger bird, the wing is fixed and they use wind energy for farther travel. They use wing and tail combination to roll and change their direction. In this, we use tail for the longitudinal stability and to achieve basic flight maneuverability. The dihedral angle is used to maintain lateral stability.

Large and medium-sized flapping-wing birds have the ability to achieve extremely high flight efficiency and have a wide range of possible applications in outdoor jobs, including military surveillance, environment exploration, disaster relief, and so on.

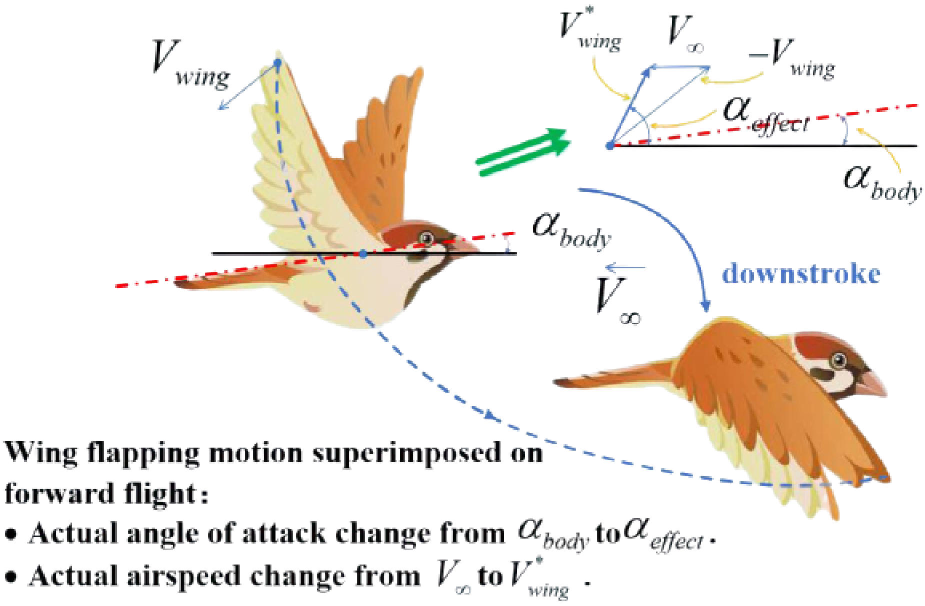


Figure 1.4: Flapping affects the actual angle of attack and airspeed of the wing.[2]

1.3. Aerodynamic mechanism

Some of the essential unsteady aerodynamic mechanisms that significantly affect lift and thrust production in flapping wings are listed below.

1. Leading Edge Vortex:

   At the wing's leading edge, a stable, expanding vortex[5], is created as the wing travels through the surrounding fluid. This high-rotation vortex, which forms on top of the wing, travels at tremendous speeds. A low pressure area develops on the wing surface as a result of the pressure differential caused by the high velocity. Lift is produced on the wing surface when this area of low pressure is present. In a similar way, the lift decreases once the vortex sheds. Regarding a wide variety of flying insects, the LEV is stable.

2. Rotational Circulation:

   This effect is present only during stroke reversal. The rotational velocities are high during stroke reversal. As the wing rotates, certain vortices are created and shed, and the wing must then deal with the flow field these vortices induce. The lift generated can be adjusted by changing the timing of the wing rotation. The effect is very similar to the Magnus effect, which makes a spinning ball curve from it's path. Lift is produced if the wing flips prior to direction reversal[6]. On the other hand, if the wing flips after reversing direction, then a downward force is generated.

3. Wake Capture: A stroke's flow can potentially increase the lift force produced in following strokes by increasing the velocity of the surrounding fluid at the beginning of the next stroke. Moreover, vortices shed during a stroke interact with the wing surface during the subsequent stroke, increasing drag forces at the beginning of each translational stroke. The wake capture effect is most noticeable while the motion is in its stroke reversal phase. Wake capture can vary in amplitude and direction, but its timing is generally constant. Positive lift is produced if wing rotation happens before stroke reversal. Nevertheless, the wing intercepts its own wake at an angle that results in negative lift if it flips following stroke reversal[6].

1.4. Flapping mechanism

The flapping mechanism's function is to transform the motor's rotating motion into the reciprocating action of flapping wings. There are several ways to accomplish this, we will simply list a few of the most typical ones below. The mechanism must be compact and pretty straightforward. To ensure that the ornithopter flies straight, it must also have a somewhat symmetrical wing action.
A ”four-bar linkage” is the foundation of the majority of mechanisms. The motor turns a crank shaft that rotates. The connecting rods push the wings up and down as the crank rotates. This method will, regrettably, result in asymmetric flapping when a second wing is introduced. Different angles separate the two connecting rods as they exit the crank. They react differently because of this. The ornithopter wants to turn to one side as a result of the asymmetric flapping, which reduces efficiency. There are several methods to enhance the symmetry:

- Staggered Crank
- Outboard Wing Hinge
- Dual Cranks
- Transverse Shaft

Dual cranks form the foundation of the bird flapping machine. In the mechanism shown below another driving gear is connected to one of the gear.The two gear rotate in the opposite direction, which create flapping motion:

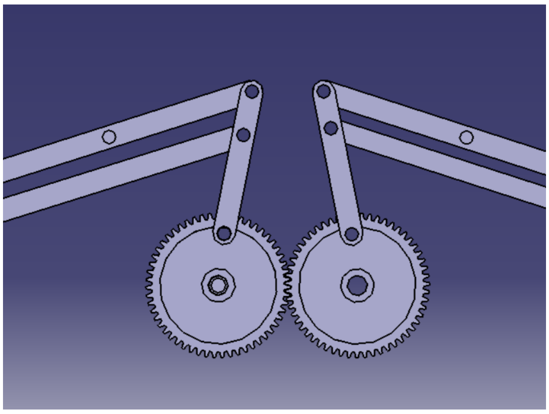


Figure 1.5: Dual Crank-rod Mechanism

1.5. Objectives

The main and secondary objectives of this project are mentioned below:

1.5.1. Main Objective

1. To design, fabricate and flight test of flapping-wing aerial vehicle.

1.5.2. Secondary Objective

1. To create effective and proficient flapping-wing platforms that are able to fly stable for extended periods of time.
2. To achieve reliable and responsive control of flapping-wing platforms under various flight conditions.
3. To extend the flying length and durability of systems with flapping wings.
4. To maintain flight performance while optimizing the design to accommodate payload capacity. Weight distribution, structural integrity, and aerodynamic concerns must all be taken into account.

1.6. Problem Statement

Detail problem description and its solution are mentioned below:

1.6.1. Problem Description

The problem at hand is the design and development of a flapping wing system. There are several challenges to be addressed in order to achieve an efficient and stable flapping wing platform.The key challenges are:

1. Structure Integration: Difficulties encounter at wing structure and body connection and wing structure. It must resist the aerodynamic load generated during the flapping.
2. Stability and Control: Flapping wing systems require precise control to maintain stable flight.

3. Aerodynamic Efficiency: To achieve continuous flight, flapping wing systems must produce enough lift and thrust during both the upstroke and the downstroke. The difficulty lies in maximizing efficiency and minimizing energy consumption by optimizing wing design, motion, and aerodynamic profiles, stability and control. Flapping wing systems require precise control to maintain stable flight.

1.6.2. Proposed Solution

Conduct extensive aerodynamic analysis and computational simulations to optimize the wing shape, size, and aspect ratio.To ensure stable flight, employ adaptive control algorithms to alter wing motion, wing angles, or thrust distribution in response to changes in the dynamics and disturbances of the aircraft. Reduce the weight of the flapping wing system by using lightweight materials and creative structural designs.

1.7. System Requirement

1.7.1. Hardware Requirement

1. Computer
2. 3D Printer
3. Laser Cutting Machine

1.7.2. Software Requirement

1. CAD Software
2. Ansys Fluent
3. GIM software

2. LITERATURE REVIEW

Researchers are becoming more and more interested in unmanned aerial vehicles (UAVs) with flapping wings, often known as ornithopters. Such UAVs are designed to resemble birds and insects by taking inspiration from nature. Over fixed wing devices, flapping wing UAVs have a number of potential advantages, including superior manoeuvrability, low speed, and vertical take-off and landing. Many small and large flapping wing aerial vehicle have been developed in which larger flapping wing vehicle has greater load capacity, longer endurance, and has capability to glide compared to small flapping wing aerial vehicle. From the historical data analysis, following graph shows the relation between flapping frequency and wing span:[3]

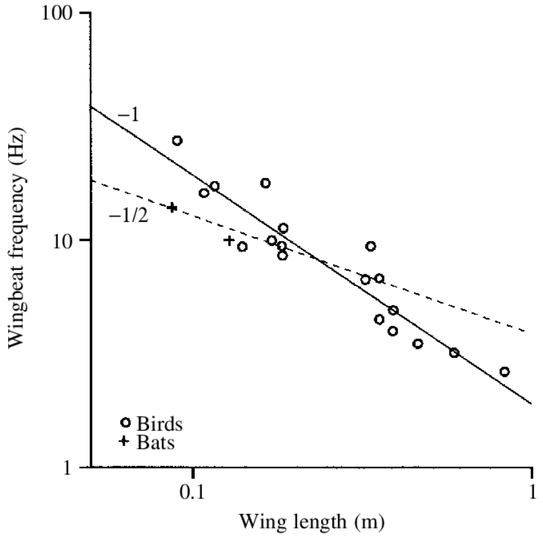


Figure 2.1: Wing beat frequency vs wing length.

The relationship between wing loading and weight are shown on fig 2.2:

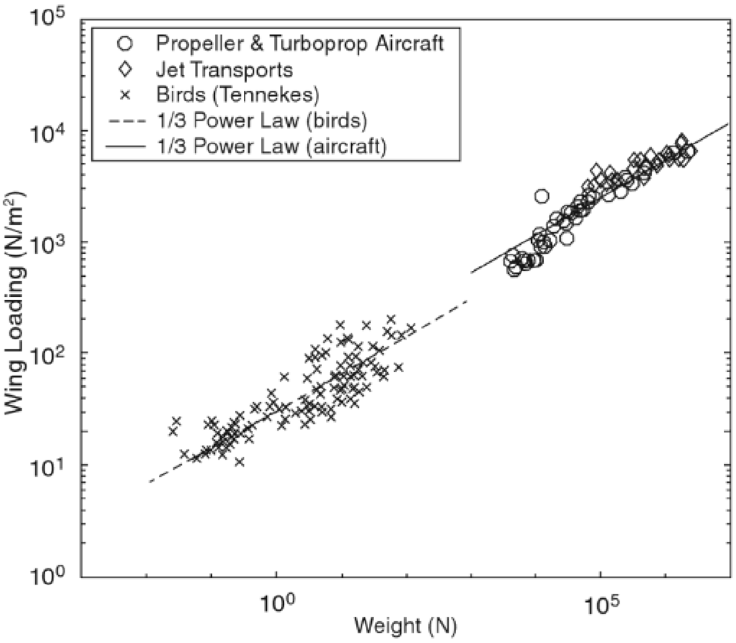


Figure 2.2: Wing loading vs weight.[3]

newpage From the analysis of the graph, we can estimate the weight, wing span,and wing area based on the application.The flapping wing aerial vehicle named HIT-Hawks and HIT-Phoenix of wing span beyond 2m were made by Erzhen Pan, Hui Xu , Han Yuan , Jianqing Peng , Wenfu Xuin, Harbin Institute of Technology, China[2].Their main purposes is to create dedicated and stable flapping wing aircraft prototype.The developed control system was integrated to the robotic prototype, HIT-phoenix, to make them autonomous flight.[7]

`major_project_report/sec/phoenis.png`

Figure 2.3: Aerodynamic layout of Hit-Phoenix during flight.[2]

We have different mechanism to transform rotary motion into flapping motion. Based on the study of the mechanism , one more connecting rod can be added to increase the degree of freedom. From the research of flying bird, on adding more degree of freedom within wingspan in further increases the performance. In this mechanism, during the down-stroke, the wing completely open and while going up it bends, due to this reason it reduces drag, which result increase in performance of flight. The mechanism is shown below:

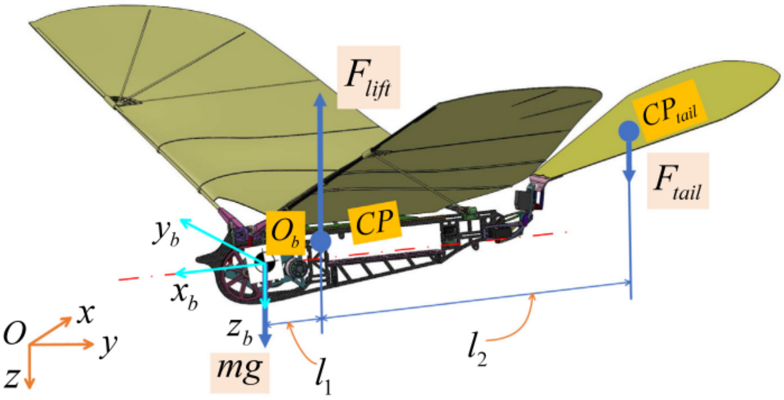


Figure 2.4: Aerodynamic layout of Hawks during flight.[2]

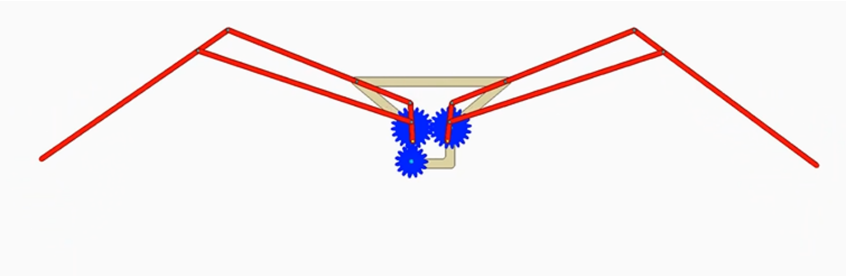


Figure 2.5: flight mechanism .[2]

3.0.1. Linkage Design and Kinematics analysis

The initial phase of the project involved designing the flapping wing mechanism. Appropriate mechanism is designed using GIM software. Through CAD modeling, we created a detailed representation of the mechanism, allowing us to study its functionality and optimize its performance. The design considerations included the selection of lightweight materials and the integration of a gear mechanism to drive the flapping motion.

3. Methodology

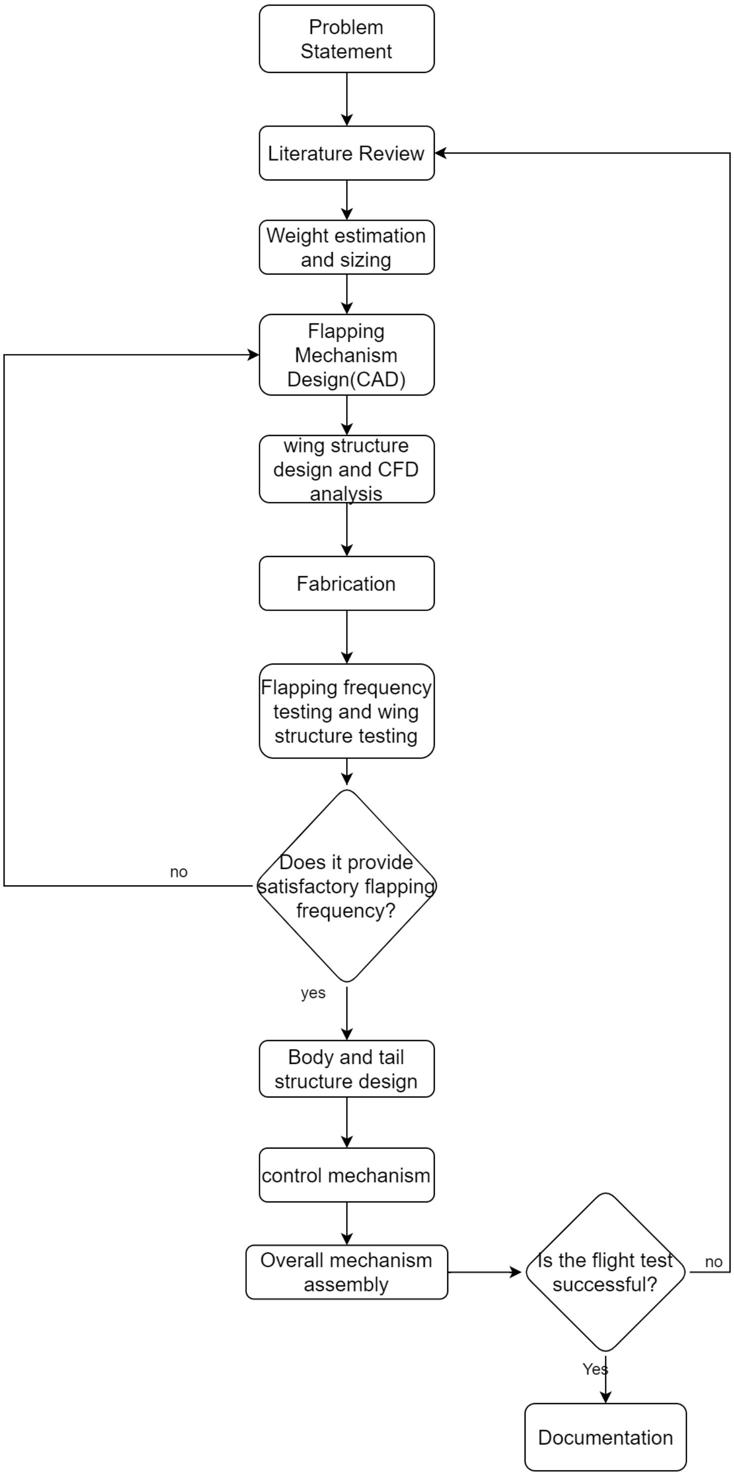


Figure 3.1: Methodology flowchart.

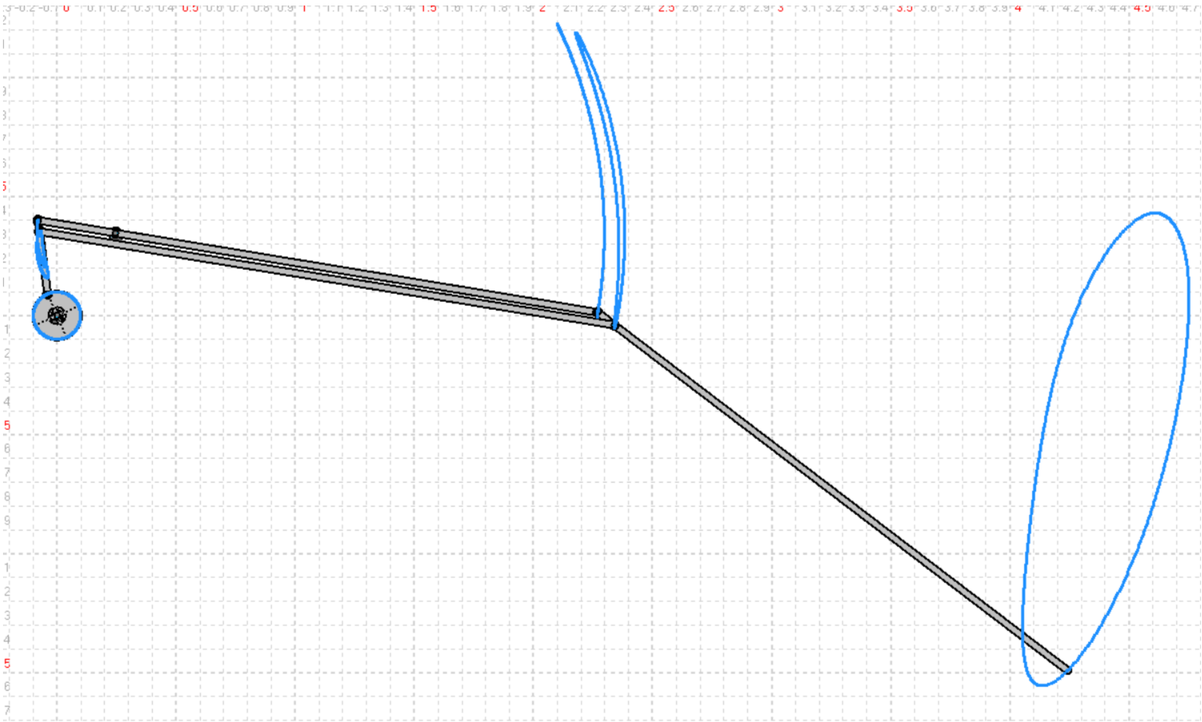


Figure 3.2: Linkage design and kinematics analysis

3.0.2. Mechanism Design

Based on the research into flapping mechanism of bird and the use of the bionic design principle, we had designed flapping wing mechanism in Computer-aided design(CAD) and GIM software. The upward and downward flapping motion of the wings serves as the source of both lift and push.The folding of the wings during flight can alter the wingspan area and hence regulate the forces interacting with the air.The flapping mechanism mimics the bird flying technique to reduce drag while flying.This mechanism include following 4 parts:

Down stroke ,Folding stroke ,Lift stroke and Unfolding stroke .

3.0.3. Gearbox

The gearbox of the flapping wing serves as the mechanical heart of the system, translating rotational motion into the intricate flapping motion essential for flight. It consists of carefully engineered gears and mechanisms that transmit power from the motor to the wing's articulating mechanism. This gearbox must be robust yet lightweight, capable of withstanding the dynamic forces generated during flight while minimizing energy losses. Precision and reliability are paramount in ensuring smooth and efficient operation, allowing the flapping wing to achieve optimal aerodynamic performance.

In our project, the gear system plays a crucial role in propelling the flapping motion of the wing. Utilizing an 11.1V battery as its power source, the driving gear rotates at a speed of around 11100 revolutions per minute (RPM). With this setup, we aimed to determine the speed of the driven gear, which features 58 teeth. Utilizing the formula T1*S1=T2*S2, we calculated the speed of the driven gear to be approximately 2679.31 RPM. Converting this speed into frequency, we found it to be approximately 44.65 Hz, significantly surpassing the required frequency for our flapping wing system. Operating at such a high frequency may exert undue stress on the mechanical structure of the ornithopter's wing, potentially leading to structural fatigue, material deformation, or even mechanical failure over time. Therefore, careful consideration and adjustments are essential to ensure that the operational frequency aligns with the mechanical capabilities of the wing structure, thereby safeguarding the reliability and longevity of the ornithopter while optimizing its performance.

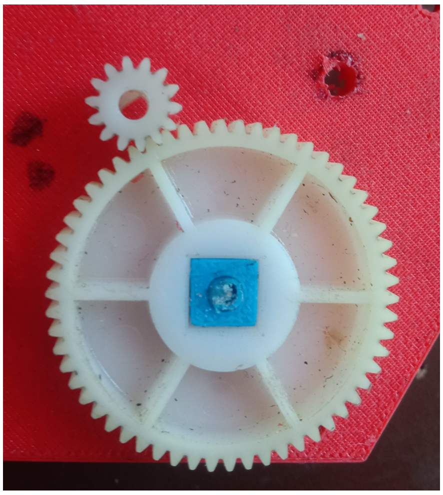


Figure 3.3: Gear reduction

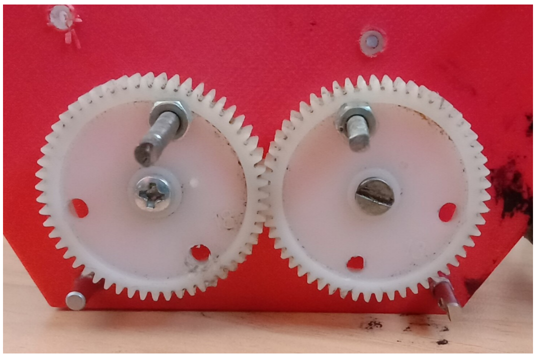


Figure 3.4: Gears

The gearbox frame serves as a critical structural element that houses and supports the intricate gears and mechanisms responsible for converting electric power into the complex flapping motion of the wings. This frame not only provides a stable housing for the gearbox components but also plays a key role in distributing and absorbing the dynamic forces generated during the flapping motion. The design of the gearbox frame requires careful consideration of materials and structural integrity to withstand the stresses imposed by the rapid and repetitive directional changes. Its robust construction is essential for ensuring the overall efficiency and reliability of the ornithopter's drive system.

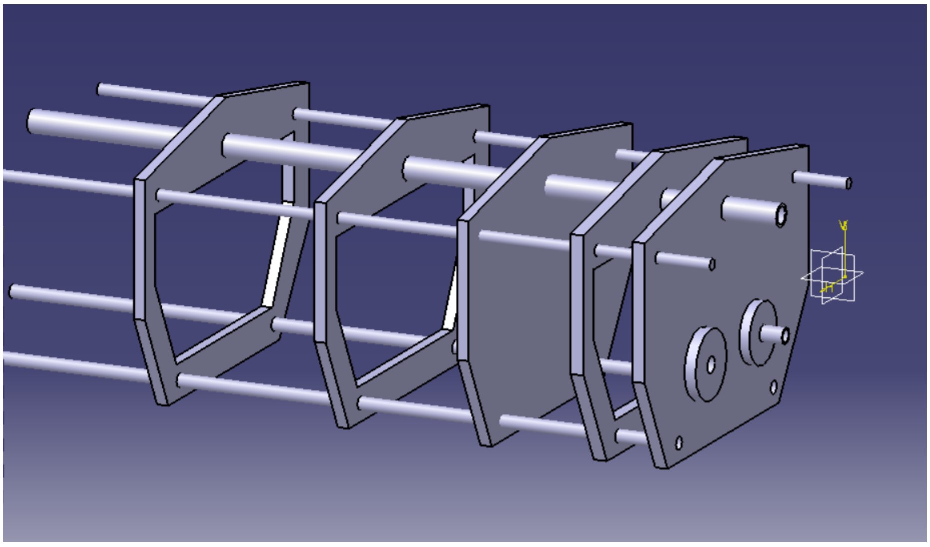


Figure 3.5: Initial Gearbox frame CAD design

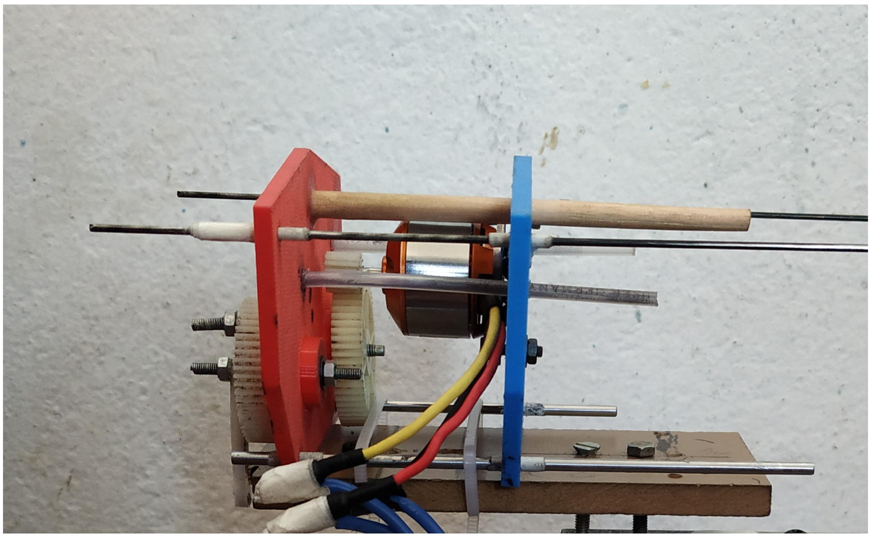


Figure 3.6: Initial Gearbox frame

After the initial analysis of the gear housing, it was evident that the existing design failed to adequately support the torque load generated by the motor, as well as the torque produced during the flapping motion of the wing. Additionally, the housing did not effectively manage the vibrations resulting from these torque loads, nor did it sufficiently address the internal loads generated by the operation of components within the gearbox. In response to these findings, a redesign of the gear housing was imperative to ensure effective operation. This redesign aimed to enhance structural integrity, minimize vibration transmission, and optimize support for both motor and wing-generated torque loads. By addressing these deficiencies, we aimed to create a robust gear housing capable of withstanding the demands of the ornithopter's operation while maintaining smooth and efficient performance.

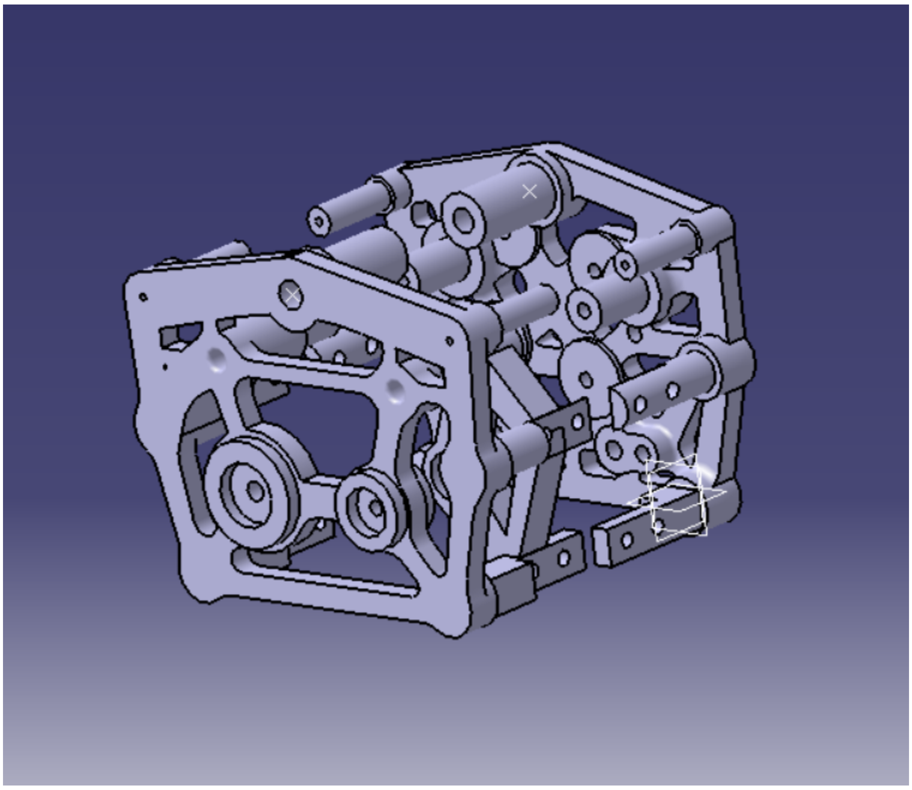


Figure 3.7: second Gearbox design

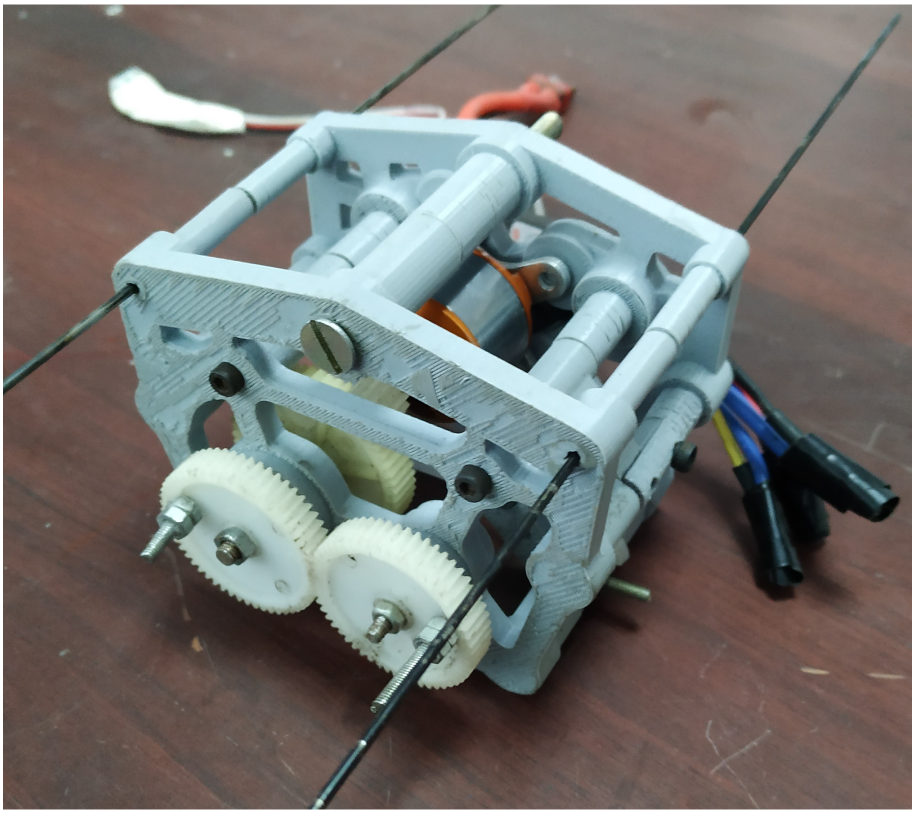


Figure 3.8: second Gearbox

3.1. Wing Design and Fabrication

3.1.1. Aerodynamics of the flapping wing:

The aerodynamics of flapping wing can be broken down into upward flapping motion and downward flapping motion.

1. Upward Flapping Motion Aerodynamics:

   In an ornithopter project, understanding the aerodynamics of the upward flapping motion is crucial for achieving stable flight, much like how a goose utilizes its wings to ascend gracefully. During the upward flapping motion, the wings of the ornithopter create an upward force by deflecting air downwards. This action generates lift, which is essential for keeping the ornithopter airborne. As the wings move upward, they push air downwards, creating a reactionary force that propels the ornithopter upwards. This upward flapping motion contributes significantly to the ornithopter's ability to gain altitude and navigate through the air.

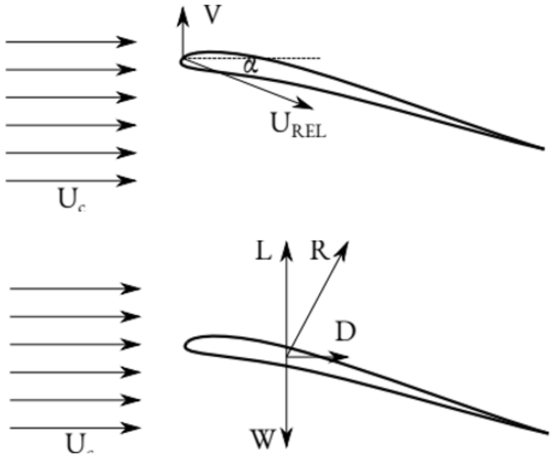


Figure 3.9: Force diagram in upward flapping motion

2. Downward Flapping Motion Aerodynamics:

   Similarly, the downward flapping motion in ornithopter flight plays a crucial role in maintaining altitude and generating forward thrust, much like the downward stroke of a goose's wings. During the downward flapping motion, the wings of the ornithopter push air downwards, creating lift that counters the force of gravity and keeps the aircraft airborne. Simultaneously, the forward movement of the wings generates thrust, propelling the ornithopter forward through the air. This downward flapping motion is essential for sustaining flight and enabling the ornithopter to move efficiently towards its destination. By understanding and optimizing the aerodynamics of both upward and downward flapping motions, we can enhance the performance and stability of our ornithopter project, allowing it to soar through the skies with agility and grace, much like its avian counterparts.

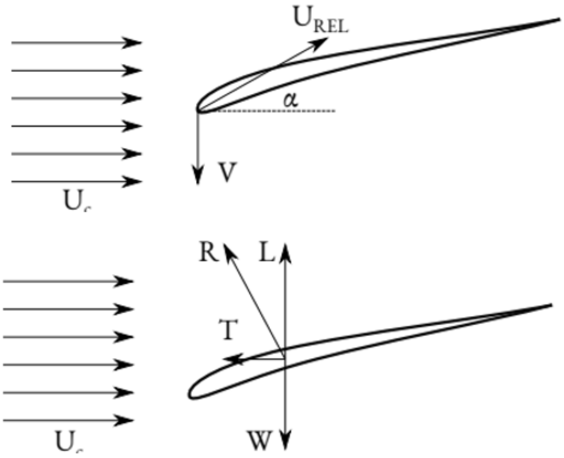


Figure 3.10: Force diagram in Downward flapping motion

3.1.2. Material selection for flapping wing

Material selection is a critical aspect of the fabrication process for flapping wings. Choosing the right materials ensures that the wings possess the necessary properties of strength, flexibility, and lightweight construction. Lightweight composites such as carbon fiber or fiberglass are commonly favored for their high strength-to-weight ratios, which are essential for efficient flight. These materials offer durability and resilience while keeping the overall weight of the wings minimal, allowing fr agile and maneuverable flight. Additionally, the selected materials must be able to withstand the dynamic stresses and strains experienced during flapping motion. By carefully considering factors such as structural integrity, weight, and aerodynamic performance, engineers can optimize the material selection process to produce flapping wings that are both robust and efficient, enabling successful flight in ornithopter and other flapping wing aircraft projects.

The material that was used in ribs was ply wood, in spars was iron and in wing skin was plastic.

3.1.3. Ribs for flapping wing:

Ribs are fundamental components in the construction of flapping wing mechanisms, serving multifaceted roles crucial to their functionality. Primarily, ribs provide structural support and define the shape of the wing, playing a pivotal role in establishing its aerodynamic profile. By delineating the wing's contour, ribs contribute to its overall stability and efficiency during flight. These structural elements help distribute aerodynamic forces evenly across the wing, enhancing its resilience against bending and torsional stresses experienced during flapping motion. Additionally, ribs serve as attachment points for other components, such as the spar and wing covering materials, facilitating the assembly and integration of the wing assembly. Furthermore, ribs aid in weight reduction, contributing to the overall lightweight design necessary for efficient flapping motion. Overall, the presence of ribs is indispensable in the design and performance of flapping wing systems, ensuring structural integrity, aerodynamic efficiency, and maneuverability during flight.

3.1.4. Airfoil for flapping wing:

During the process of manufacturing ribs, different airfoil was taken into consideration. Namely, ag14 , s1020-il. Ag-14 was chosen with following reviews:

1. Low Drag: The AG14 airfoil is designed to have low drag characteristics. This results in improved aerodynamic efficiency, allowing the ornithopter to achieve higher speeds and better overall performance.
2. High Lift: Despite its low drag, the AG14 airfoil is also capable of generating significant lift. This is crucial for ornithopters, as it enables them to remain airborne and support the weight of the aircraft during flight.
3. Stability: The AG14 airfoil is known for its stability, providing predictable aerodynamic behavior under various flight conditions. This stability is essential for maintaining control and maneuverability, particularly in the dynamic and complex flight environment of ornithopters.
4. Versatility: The AG14 airfoil is versatile and well-suited for a wide range of flight speeds and angles of attack. This versatility allows ornithopter designers to tailor the aircraft's performance characteristics to specific mission requirements or environmental conditions.

Overall, the combination of low drag, high lift, stability, and versatility makes the AG14 airfoil an excellent choice for ornithopters, providing the aerodynamic qualities necessary for efficient and controlled flight.

The lower section of the airfoil was removed to decrease weight of the wing. Then, airfoil was drafted in catia and then the ribs for flapping wing were manufactured using laser printing. Material that was used during the production of ribs is ply wood.

3.1.5. Spars for flapping wing

The spar adds rigidity to the wing, enhancing its overall structural integrity and preventing it from collapsing under the dynamic forces experienced during flight. By reinforcing the wing structure, the spar ensures that the wing maintains its shape and aerodynamic efficiency, allowing for stable and efficient flight in flapping wing systems. Hollow cylindrical spars was chosen due to various reasons such as easy fabrication. The spar had the diameter of 2mm. Only one main spar was used.

3.1.6. Wing shape for flapping Wing:

1. Rectangular Wing Shape: The rectangular wing shape is a basic yet practical design used in flapping wing systems. Its simplicity facilitates ease of fabrication, making it

suitable for initial testing and prototyping phases. This wing shape offers stability and straightforward control, making it ideal for experimental setups aimed at understanding basic flight dynamics.

2. Tapered Wing Shape: Tapered wing shapes, which narrow towards the wingtips, are favored for their improved aerodynamic efficiency. By reducing induced drag and enhancing lift-to-drag ratios, tapered wings offer superior flight performance and endurance. This configuration is well-suited for applications requiring prolonged flight durations, where efficiency and endurance are paramount.

3. Elliptical Wing Shape: The elliptical wing shape is characterized by its smooth curvature and evenly distributed lift. This design provides optimal aerodynamic efficiency and minimal drag, resulting in exceptional flight stability and maneuverability. The wing of the different bird such as goose, whose reference was taken during the process can be approximated in elliptical shape. Thus, the elliptical wing was taken into choice.

3.1.7. Wing Fabrication:

With the major account of the above design considerations, the flapping wing fabrication was done through iterative process.

The initial fabrication of the ornithopter wing involved the construction using only four ribs, indicating a simplified prototype design. However, a notable issue arose regarding the symmetry of the linkage or spar between the two wings, leading to an imbalance that could compromise the ornithopter's stability during flight. Furthermore, the actual wingspan fell short of the intended design, potentially impacting the aerodynamic performance of the aircraft. The materials utilized in the fabrication process included posyster for the skin, iron rod for the spar, and thick plywood for the ribs. Addressing these challenges will likely necessitate a redesign to ensure symmetry, achieve the desired wingspan, and possibly reconsider the materials chosen to optimize both weight and strength properties. Ensuring balanced symmetry in the linkage or spar between the wings will be crucial for enhancing the flight stability of the ornithopter.

Figure 3.11: Initial wing Fabrication

In the second fabrication iteration, significant improvements were implemented to enhance the ornithopter's performance and durability. A key enhancement involved the adoption of multiple spars along with thinner ribs in the wing structure. This modification aimed to optimize load distribution and reinforce the wing assembly, addressing previous issues of imbalance and instability. Additionally, the materials chosen for this iteration were carefully selected to enhance the wing's resilience and aerodynamic efficiency. Vinyl plastic was employed for the wing surface, offering lightweight yet sturdy coverage, while fiberglass was utilized for the spars due to its superior flexibility, strength, and resistance to breakage under adverse conditions. This deliberate choice of materials and structural design parameters yielded notable improvements over the initial fabrication, resulting in a wing assembly that demonstrated enhanced performance and reliability.

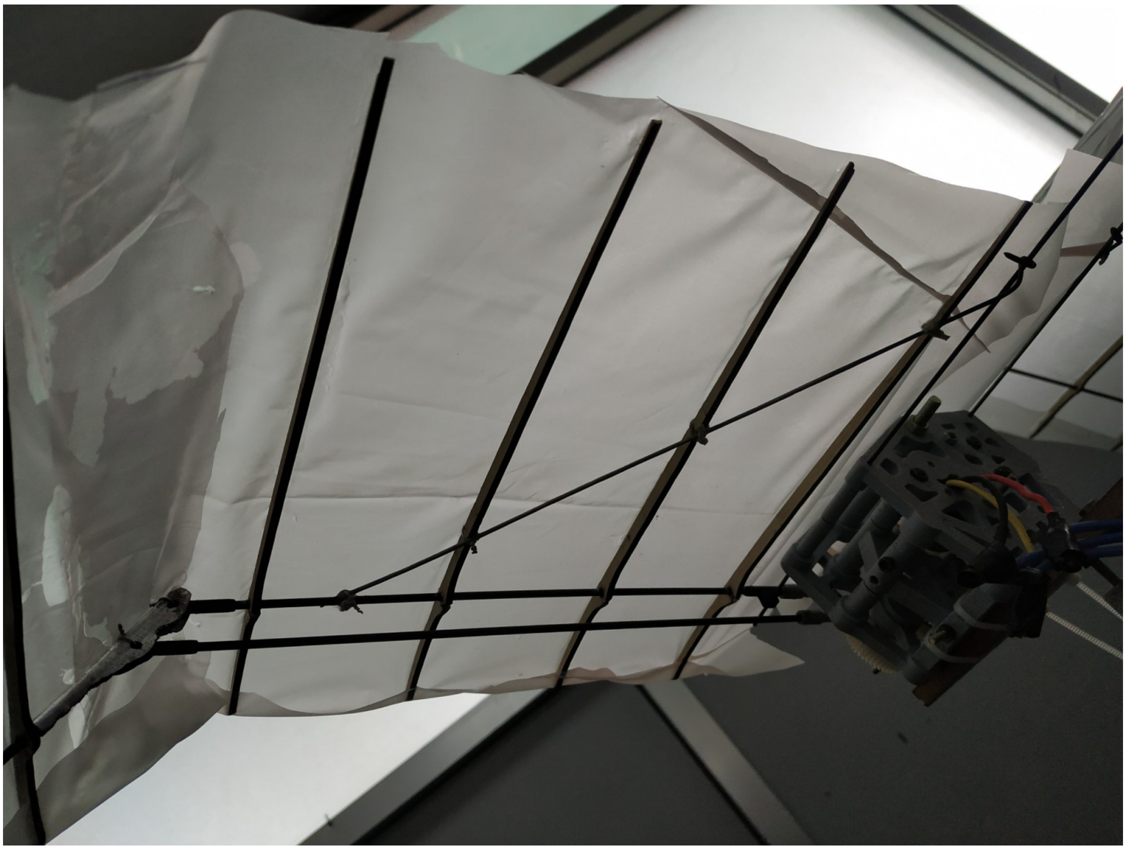


Figure 3.12: second wing Fabrication

3.2. Load Cell for Thrust and Lift Measurement

Accurate measurement of thrust and lift forces generated by the flapping wing mechanism is crucial for performance evaluation. To achieve this, we incorporated a load cell into our experimental setup. The load cell allowed us to quantify the forces in real-time, providing valuable data for analysis and improvement.The load cell is designed in CAD software and its physical fabrication which is applicable to measure lift and thrust produced by the flapping wing mechanism is shown in figure 5.10.

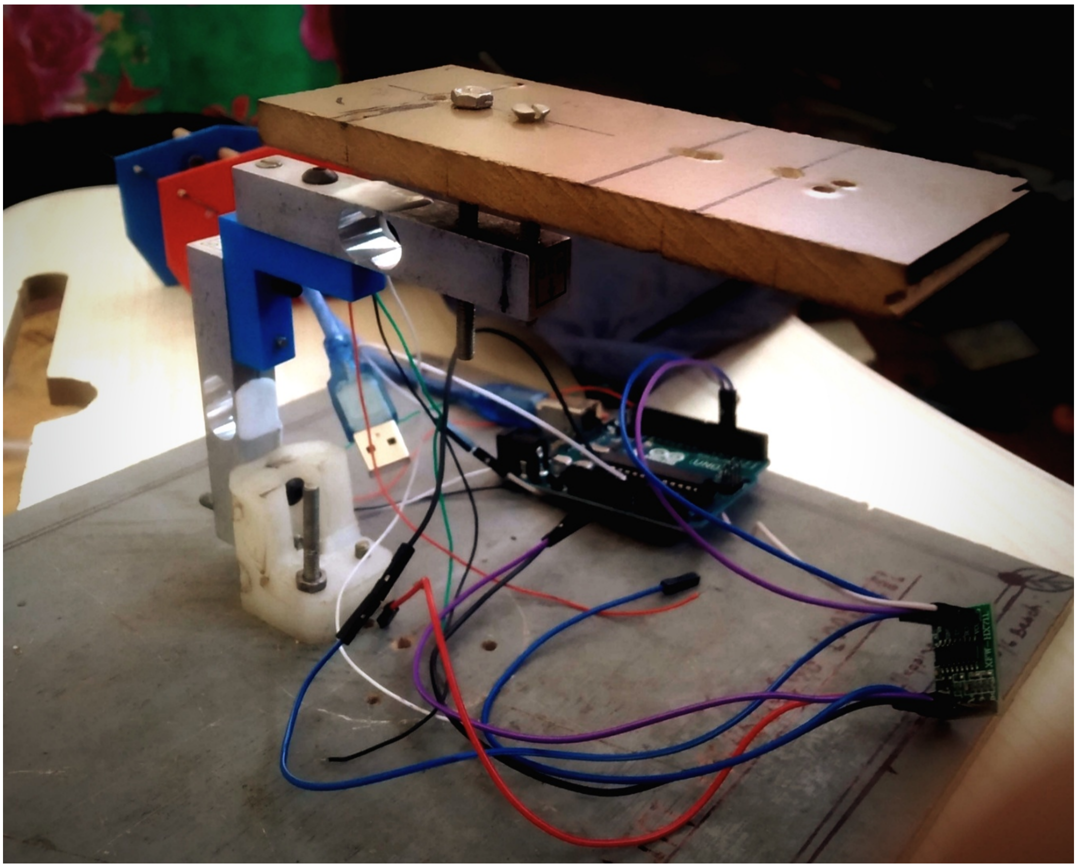


Figure 3.13: Mechanism

3.3. Body Fabrication and Analysis

In the body fabrication phase, integration efforts focused on incorporating the wing with the gearbox to ensure seamless operation of the ornithopter. Initially, static testing yielded promising results, demonstrating effective flapping at the desired frequency. However, a significant challenge emerged concerning the gearbox's ability to withstand the generated torque effectively. This limitation hindered the ornithopter's overall functionality and raised concerns about its long-term performance and reliability. Addressing this issue require re-designing or reinforcing the gearbox to enhance its torque resistance capabilities, ensuring optimal functionality and longevity of the ornithopter.

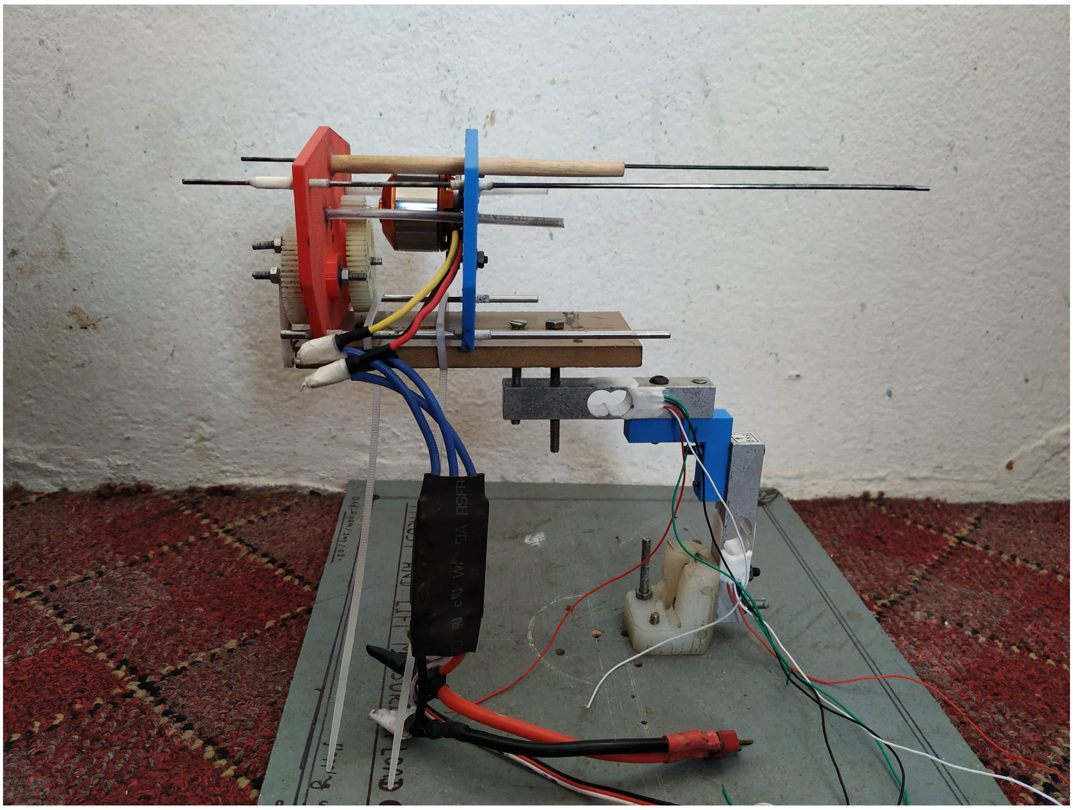


Figure 3.14: Initial Fabrication

Figure 3.15: Initial Fabrication

Figure 3.16: Initial Fabrication

The second fabrication phase demonstrated significant improvement over the initial iteration, notably due to the inclusion of a modified gearbox. This revised gearbox exhibited enhanced capabilities, successfully withstanding the forces exerted during operation. As a result, the ornithopter's performance markedly improved, achieving greater efficiency and reliability in its flapping motion. The successful integration of the modified gearbox represents a pivotal advancement in the design and functionality of the ornithopter, overcoming previous limitations and contributing to its overall success. With this critical component now optimized, the ornithopter is poised to fulfill its intended purpose more effectively, demonstrating the progress made through iterative design and refinement.

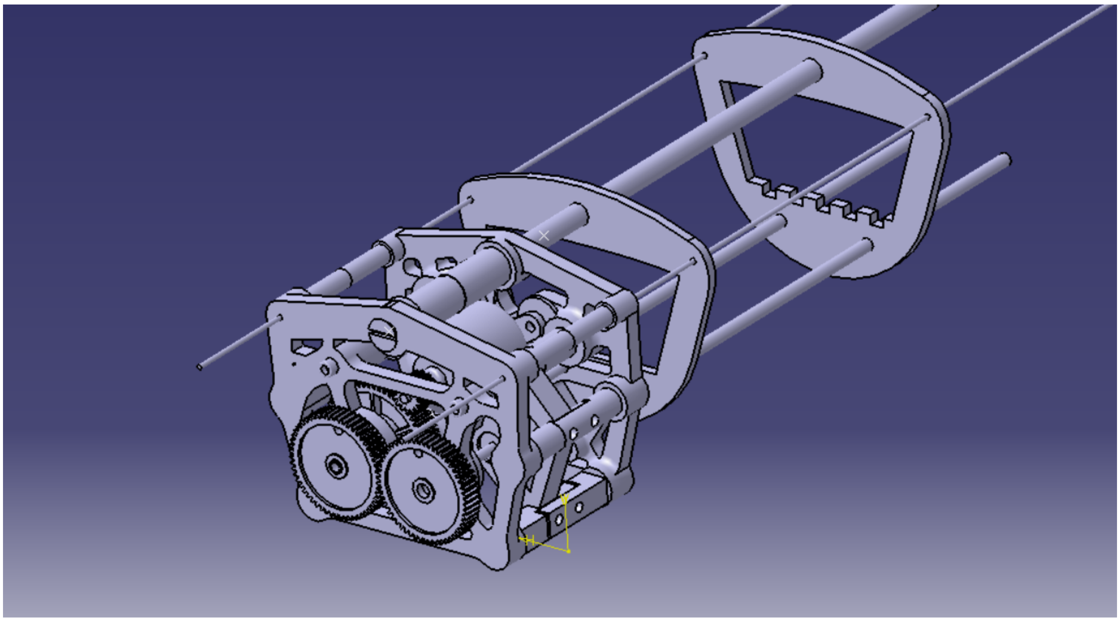


Figure 3.17: CAD Design

Figure 3.18: second Fabrication

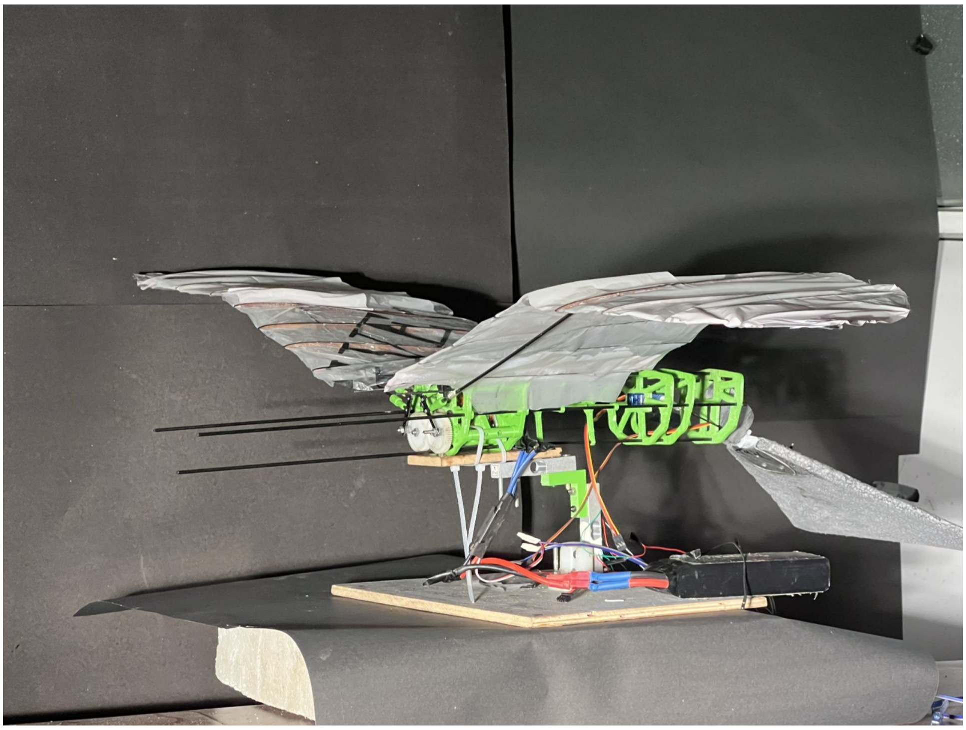


Figure 3.19: second Fabrication

3.4. Tail design

In terms of tail design, our strategy involves a exactly exploration of biological mimicry, investigating the intricate aerodynamic structures found in natural flyers, and translating these findings into optimized wing loading, aspect ratios, and shapes to enhance lift and maneuverability. Concurrently, we will delve into advanced lightweight materials, such as bio mimetic composites, and integrate flexible elements to mirror the deformable features observed in natural wings.

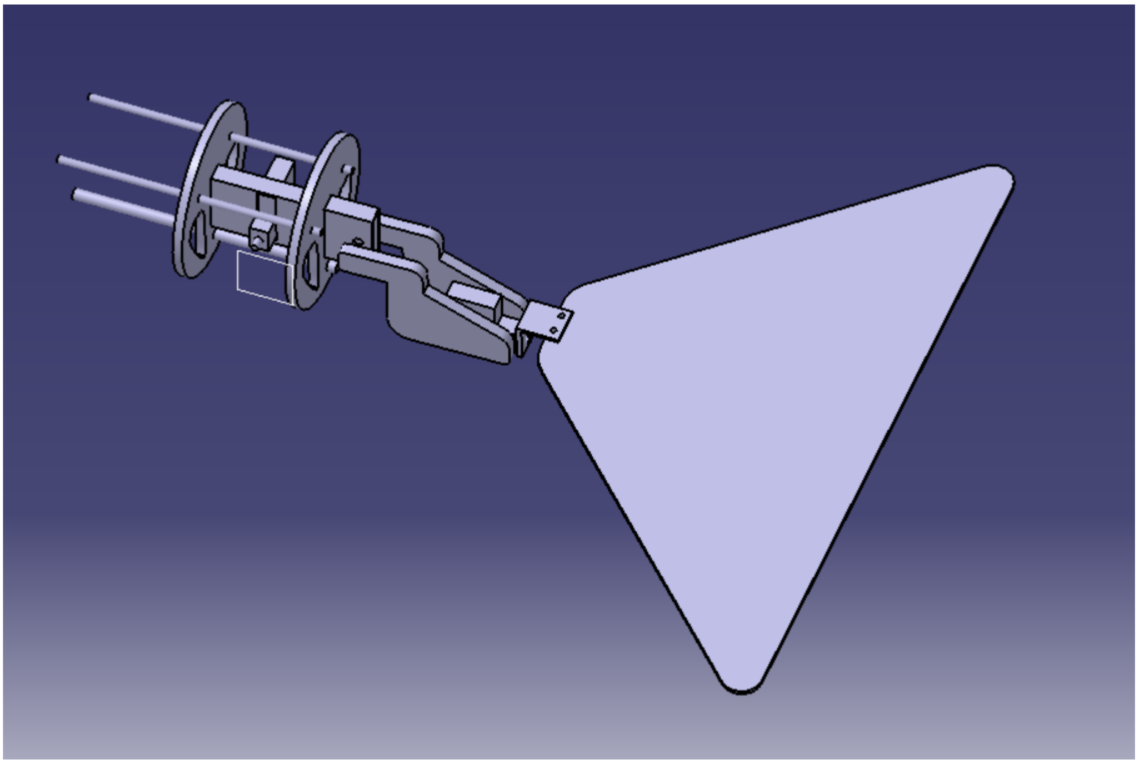


Figure 3.20: Tail CAD Design

The tail is designed to provide pitch and roll control, achieved through the use of two servos: one for pitch adjustment and the other for roll adjustment. The tail body structure is created using two circular-shaped sections connected by an inserted section, where the servos are mounted. The hinge mechanism allows for controlled movement of the tail to facilitate maneuverability. High-strength, lightweight materials are essential for the fabrication of the tail to ensure optimal flight performance. The nylon cloth is used for the fabrication of tail. Three ribs are strategically positioned within the tail structure to provide support and stability. The two servo motors each 9g is used for roll and pitch movement. The motors are placed in a manner to balance and maintain uniform weight distribution. A strong hinge mechanism is implemented to facilitate controlled movement of the tail for pitch and roll adjustments. The tail components are carefully assembled using adhesives techniques to achieve maximum strength and durability. Attention is paid to proper alignment and fitment to obtain well flight operations.

3.5. Overall fabrication

In terms of overall fabrication, we are poised to explore advanced composite materials for structural and flexible components, with a keen eye on materials exhibiting self-healing properties to enhance durability. 3D printing technology will play a pivotal role, facilitating rapid prototyping and enabling the realization of intricate, bio-inspired designs that may be challenging to achieve through traditional manufacturing methods. Smart materials, capable of responding to external stimuli, will also be integrated to enhance adaptability and control. We will explore the possibility of multi-material integration within a single structure, optimizing strength, flexibility, and weight characteristics.

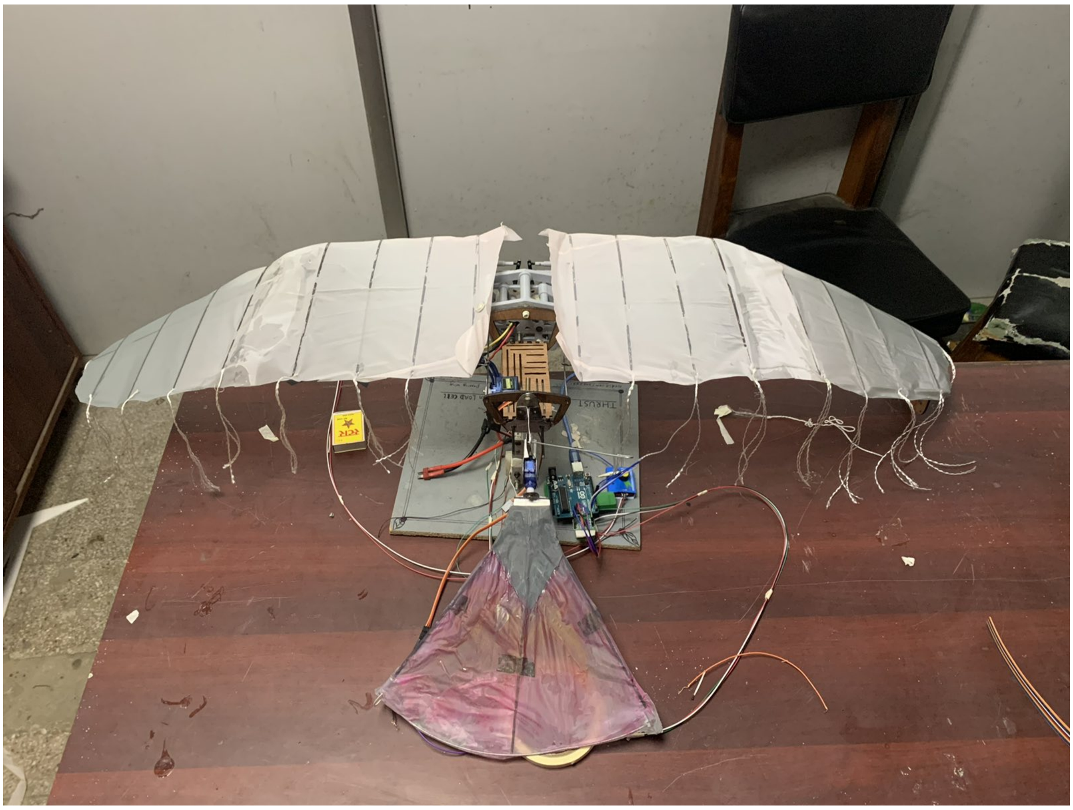


Figure 3.21: Overall Fabrication

3.6. Work Completed

The project unfolded through several key stages: The initial phase encompassed intricate design and simulation of the flapping wing mechanism utilizing GIM software and computer-aided design (CAD). This phase focused on optimizing aerodynamics, kinematics, and structural integrity for enhanced flight performance. Subsequently, attention shifted to gearbox design, followed by wing design. These phases involved meticulous refinement of the gearbox mechanism and wing structure to ensure compatibility, functionality, and optimal performance within the ornithopter system.

Additionally ,considerable attention was given to the structural design of the wings, ensuring lightweight yet robust materials were employed to withstand the cyclic stresses induced by the flapping motion .The wing structure design aimed at achieving a delicate balance between weight reduction and structural resilience for sustained and efficient flight .

Following these stages, the project progressed to tail design, fabrication, and testing. This phase entailed the design and construction of the tail component, followed by rigorous testing to evaluate its aerodynamic properties and overall performance. Each stage contributed to the comprehensive development of the ornithopter, culminating in the integration of all components for successful flight testing and validation.

4. Result and analysis

4.1. Wing analysis (Tuft flow visualization with Wind Tunnel)

Tuft flow visualization offers a qualitative method to observe flow patterns and phenomena around flapping wings, providing valuable insights into their aerodynamic behavior. The experiment involved attaching tufts to a flapping wing model and subjecting it to controlled airflow in a wind tunnel. High quality cameras were used to capture the movement of tufts, allowing for the analysis of flow patterns. We completed a detailed analysis of our flapping wing by looking closely at how air flows around it using tuft flow visualization technics. What we found was that there were swirling patterns of air, called vortices, forming in specific places on the wing. These spots were at the tips of the wing, at the front where it flaps, and in the air trailing behind the wing. Vortices were consistently observed forming at the leading edge of the flapping wing during both the upstroke and down-stroke phases. These vortices manifested as swirling patterns of tufts, indicating the presence of concentrated regions of rotational flow. Additionally, tufts at the wingtips exhibited a tendency to align with the airflow, indicative of vortices shedding from the wingtips. Furthermore, the formation of wake capture was evident behind the flapping wing. Tufts in the wake region displayed chaotic movement, suggesting the entrapment of airflow within the wake structure. These findings underscore the importance of vortical structures in lift generation and highlight the aerodynamic mechanisms involved in flapping wing flight. Further research in this area could lead to advancements in biomimetic flight technology and the development of more efficient flapping wing .

Figure 4.1: Upstroke

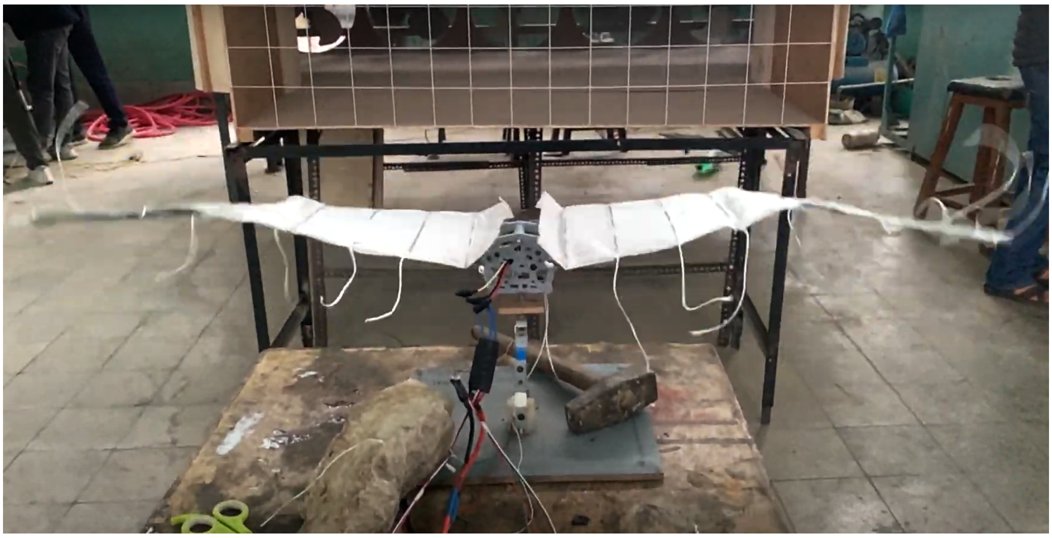


Figure 4.2: Downstroke

4.2. Lift analysis

In analysis of lift and drag force in flapping wings, we utilized a load stand equipped with sensors to measure the forces acting on the wing during controlled flapping motions. Our focus was primarily on observing lift generation during the downstroke phase of the wing's motion. Results from the experiment revealed significant lift forces being generated during this phase, indicating the effectiveness of the wing design in mimicking natural avian flight. Additionally, drag forces were found to be within expected ranges, showcasing efficient aerodynamic performance. A lift-drag analysis further confirmed the favorable lift-to-drag ratio of the mechanism, as depicted in the accompanying plot. Looking ahead, we propose several enhancements to the design to achieve higher lift capabilities. These include weight reduction, aerodynamic profile optimization, mechanism efficiency improvements, and integration of advanced control systems. A comprehensive weight sizing estimation will be conducted to ensure that the redesigned mechanism maintains structural integrity while minimizing overall weight. Ultimately, these advancements hold promise for applications requiring high lift generation, such as aerial robotics and unmanned aerial vehicles (UAVs).

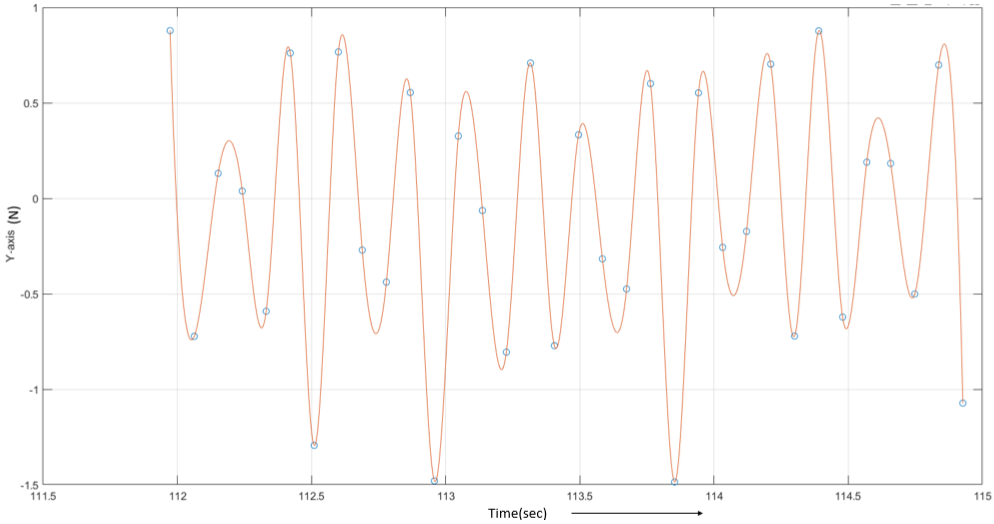


Figure 4.3: Data from Load cell

4.3. Smoke visualization

We wanted to understand how flapping wings work, so we conducted experiments in a wind tunnel. The wind tunnel kept the air moving at a steady speed of about 3 meters per second. We used smoke to see how the air moved around the flapping wing and filmed it with high-speed cameras.

In our experiments, we saw some interesting things. When the wing moved up, we noticed swirls of air forming near its front edge. These swirls, called vortices, showed us how the air moved around the wing. We also saw a sort of trail behind the wing, called a wake, which showed how the air was affected by the wing's movement.

However, we also encountered some challenges. Sometimes, the airflow became turbulent and disrupted. We found out that this happened when the wing flapped too fast or if there were problems with how it moved. These challenges reminded us how important it is to get the wing's motion just right for it to work properly.

Despite these challenges, our experiments taught us a lot about how flapping wings interact with the air. We gained insights into the forces at play during different phases of the wing's movement. This knowledge helps us appreciate the complexity of flapping wing aerodynamics and holds potential for improving technologies like bio-mimetic flight and aerial robotics.

In conclusion, our experiments in the wind tunnel gave us valuable insights into how wings move through the air. We learned about the intricate dance of airflow around flapping wings and the challenges involved in designing efficient wing systems. As we move forward, we are excited about the possibilities of applying this knowledge to create better flying machines for the future.

Figure 4.4: smoke visualization

4.4. Limitations:

The development of a flapping wing mechanism for our project faced several limitations and challenges. Firstly, we encountered difficulty in designing and implementing effective control mechanisms for the wing's flapping motion. This involved finding the right balance between the control system's responsiveness and stability, which proved to be a complex task.Secondly, constructing the wing structure, body, and gear system posed challenges as well. The intricate design and interlocking components required meticulous assembly, often leading to time-consuming and labor-intensive efforts.Moreover, the lack of suitable fabrication resources hindered our progress. Finding the right materials for lightweight fabrication proved challenging, and the limited availability of certain components, such as carbon fiber rods, posed significant obstacles. The associated costs for specialized tools and equipment were also a factor to consider. These limitations necessitated several design modifications throughout the project to accommodate the materials and resources available to us. Despite these challenges, we persisted in finding alternative solutions to ensure the functionality and efficiency of the flapping wing mechanism.

In summary, the key limitations faced during the development of the flapping wing mechanism included difficulties with control mechanisms, construction complexities, lack of suitable fabrication resources, and material restrictions. Overcoming these hurdles required adaptability, ingenuity, and persistence to achieve a successful outcome.

4.5. Problem faced

During the flapping wing project, we encountered several challenges that affected the progress and development of the mechanism. The following problems were specifically related to the information mentioned above:

4.5.1. Control Mechanisms:

The difficulty in designing effective control mechanisms for wing flapping posed a significant challenge. Achieving the right balance between responsiveness and stability was crucial, and it required extensive experimentation and fine-tuning. Overcoming this obstacle required a deep understanding of aerodynamics, kinematics, and control theory to ensure precise wing movements.

4.5.2. Construction Complexities:

During the construction of the wing structure, body, and gear system, there has been significant challenges stemming from the intricate design and the interlocking nature of the parts. Achieving precise assembly was crucial, as even minor variations could have profound effects on the overall performance and durability of the mechanism. One specific issue that arose was the slightly unsymmetry of the wing, which was caused by minute differences in distances between linkages.

4.5.3. Fabrication Resources:

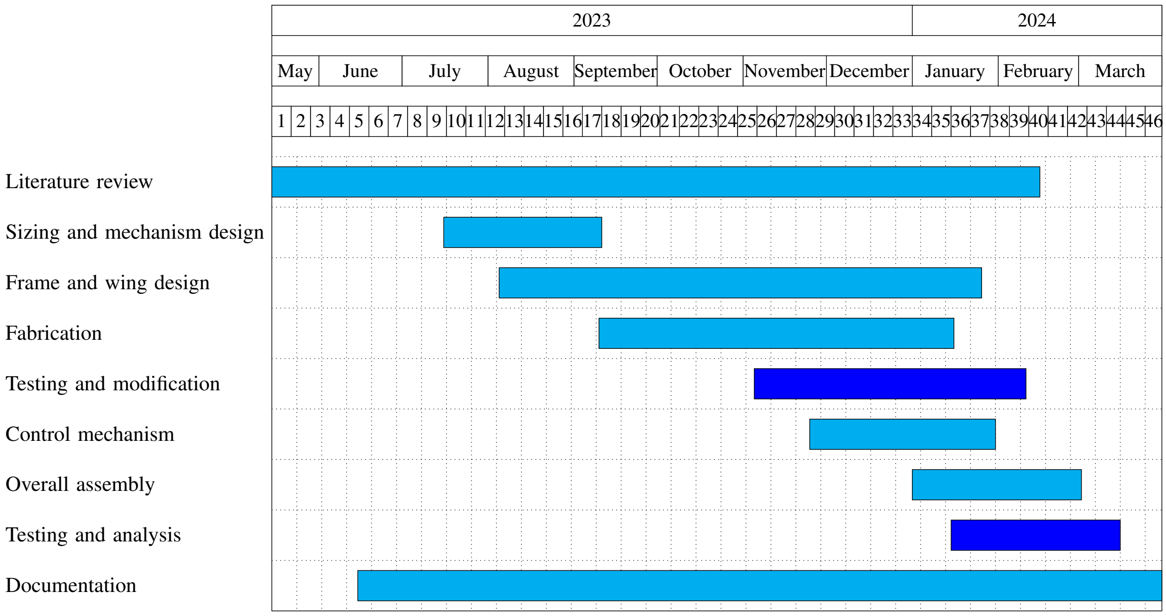
The project faced limitations due to the lack of appropriate fabrication resources. Finding lightweight materials suitable for the construction of the flapping wing posed a challenge, especially since the desired materials were not easily accessible in the market. This obstacle necessitated exploring alternative materials that could provide the desired strength-to-weight ratio while being readily available and cost-effective.

4.6. Gantt chart

Complete working days are broken down into the several periods. Using the Gantt chart shown below as a guide, we have been working on our tasks:

Title	Duration
Literature review	May,2023-Fev,2024
Sizing and mechanism design	July,2023-Sep,2023
Frame and Wing design	Aug,2023-Jan,2024
Fabrication	July,2023-Jan,2024
Testing and modification	Nov,2023- Fev,2024
Control mechanism	Nov,2023-Jan,2024
Overall assembly	Dec,2023-Fev,2024
Testing and analysis	Jan,2024- Mar,2024
Documentation	Jun,2023-Mar,2024

Table 4.1: Work Schedule



The above figure show the gantt chart of our project.

4.7. Budget analysis

It mainly includes different electronic components and structure material. Following is a rough breakdown of the projected budget:

particulars	Quantity	Rate(NRs.)	Net Amount(NRs.)
Li-po battery	1	2700/-	2700/-
BLDC motor	1	990/-	990/-
Servo motor	2	350/-	700/-
Radio Control Transmitter	1	8000/-	8000/-
ESC	1	940/-	940/-
Arduino	1	1100/-	1100/-
connection wire			340/-
Miscellaneous			2000/-
Total			16770/-

Table 4.2: Budget Estimation

5. Conclusion and Future enhancement

5.1. Conclusion

Our team is pleased to present the culmination of our flapping wing project, which has been a journey marked by innovation, challenges, and ultimately, success. The project encompasses the completion of the mechanism design, where our careful attention was paid to every detail to ensure optimal functionality. We overcame material challenges by strategically implementing fiberglass rods for wing support, enabling greater structural integrity and durability.

Integral to our project's success was the incorporation of a thrust and lift measuring load cell, providing precise data for performance evaluation. Additionally, the development of a comprehensive CAD model facilitated seamless integration of various components and streamlined the design process.

Furthermore, our team successfully completed wing analysis of the flapping wing system, utilizing wind tunnel tuft flow analysis, smoke flow visualization to assess aerodynamic performance. The load cell played a crucial role in lift analysis, contributing valuable insights into the system's functionality.

Overall, our project represents a significant achievement in the field of flapping wing technology. Through innovative design, meticulous bench test, and strategic use of materials, we have laid the foundation for future advancements in this exciting area of research.

5.2. Scope for Future Enhancement

By this Flapping wing mechanism technology, it has a wide range of scope across various fields. Here are some notable scope of flapping wing.

1. The gearbox that we had designed has capable of holding high torque and dynamic load capacity, so it can be used as the testing for fast flapping wing if necessary .
2. This project can further be extended by modifying the structure and its electronics and can be make autonomous flight that perform various task i.e. surveillance, gathering data and so on.

3. The ability to mimic the birds, insect helps in study and research birds nature, habitat and also in entomology and pollination. Also it can be employed for wildlife surveillance.
4. The advance flapping wing can be used in search and rescue operation, especially in environments where access is challenging and rigorous.
5. The development of tiny aerial vehicles known as Micro Aerial Vehicles (MAVs) may make use of flapping wing technology. These little flapping wing systems can be employed for jobs like keeping watch in tight locations, exploring inaccessible places, or helping in emergency situations.

These scope demonstrate the versatility and potential of flapping wing technology in various domains. Continued research and development in this field are expected to unlock further possibilities and advancements, enabling the deployment of flapping wing systems in new and innovative applications.

References

[1] Z. J. Jackowski, “Design and construction of an autonomous ornithopter,” Ph.D. dissertation, Massachusetts Institute of Technology, 2009.

[2] E. Pan, H. Xu, H. Yuan, J. Peng, and W. Xu, “Hit-hawk and hit-phoenix: Two kinds of flapping-wing flying robotic birds with wingspans beyond 2 meters,” *Biomimetic Intelligence and Robotics*, vol. 1, p. 100002, 2021.

[3] W. Shyy, H. Aono, C.-k. Kang, and H. Liu, *An introduction to flapping wing aerodynamics*. Cambridge University Press, 2013, vol. 37.

[4] B. J. Goodheart, “Tracing the history of the ornithopter: past, present, and future,” *Journal of Aviation/Aerospace Education & Research*, vol. 21, no. 1, pp. 31–44, 2011.

[5] C. P. Ellington, C. Van Den Berg, A. P. Willmott, and A. L. Thomas, “Leading-edge vortices in insect flight,” *Nature*, vol. 384, no. 6610, pp. 626–630, 1996.

[6] M. H. Dickinson, F.-O. Lehmann, and S. P. Sane, “Wing rotation and the aerodynamic basis of insect flight,” *Science*, vol. 284, no. 5422, pp. 1954–1960, 1999.

[7] M. F. B. Abas, A. S. B. M. Rafie, H. B. Yusoff, and K. A. B. Ahmad, “Flapping wing micro-aerial-vehicle: Kinematics, membranes, and flapping mechanisms of ornithopter and insect flight,” *Chinese Journal of Aeronautics*, vol. 29, no. 5, pp. 1159–1177, 2016.