1. Introduction

1.1 Introduction

An ornithopter is an aircraft designed to achieve flight by means of flapping wings. The first ornithopters capable of flight were constructed in France in 1871 using a rubber band to power a small model bird. Gustave Trouvé was the first to use internal combustion, and his 1890 model flew 80 metres in a demonstration for the French Academy of Sciences. The wings were flapped by gunpowder charges activating a Bourdon tube. Flight models powered by steam engines were also developed. Aviation pioneers also developed flight models of manned ornithopters, powered either by muscular effort or by an engine. [2]

Flapping wing aircraft concepts have been put forth in light of the efficiency of flapping flight at small scales. These aircraft are naturally equipped with the ability to rotate their wings about the root, a form of wing articulation. It is important to point out that flapping wing flight is recognized as such when a flapping wing produces lift as well as thrust necessary to sustain flight. This definition is necessary to distinguish an ornithopter from a plane which uses flapping technology only partially to achieve flight.

While useful in describing the efficiency of maneuvering flight, steady-state (i.e., fixed wing) models of maneuvering performance cannot provide insight to the efficacy of maneuvering, particularly during low-speed flapping flight. Contrasted with airplane-analogous gliding/high speed maneuvering, the aerodynamic and biomechanical mechanisms employed by birds at low flight speeds are violent, with rapidly alternating forces routinely being developed. Recent information on the behavior and aerodynamic mechanisms of bird maneuvering flight have expanded the scope of discussions beyond wing planform, into specific and highly specialized musculoskeletal flight structures.

Development of bird-scale flapping flight has led to interesting results and advances in the flight mechanics and control of non-flapping flight as well, under the broad umbrella of wing articulation, morphing wing technologies, and bio-inspired maneuvers. Unlike airplanes, birds do not have a vertical tail. A central issue of yaw stability in birds is how the aerodynamic moments are generated to provide a restoring capability against a disturbance in sideslip [3]. Since birds do not have a vertical tail which would be an efficient means for achieving yaw stability, they rely on the wing, the body and possibly the tail to produce yawing moments due to sideslip.

Maneuverability, especially roll and yaw stability as well as aerodynamics and kinematics modeling have been identified as field of research to improve understanding of bird flight. Better understanding of these concepts will provide great support for mimicking bird flight.

1.2 Objective

The prime objective of this work is to provide the reader basic understanding of the concepts to be considered for designing an ornithopter. It also aims to provide the reader importance of the wings and tail of the bird for maneuvering at low as well as high speeds. The objective is to generate interest in this topic and to encourage the reader to take up research projects in this field of study.

Working with a much larger robot allows us to sidestep the problems of miniaturization and instead work on the problems that interest us.

This is not to say that the dynamics will be the same, they may be as far apart as the differences between how a hawk and bumble bee fly, but the body of work covering the control of any sort of flapping wing flight is extremely small, so any conclusions reached will be valuable additions as work moves forward.

1.3 Scope of work

This project is inspired by bird flight which replicates the motion of the articulated wing structure in birds. Its wings not only move up and down, but also twist at specific angles to make efficient aerial moves. We aim to achieve an overall structure with minimal overall weight, in conjunction with functional integration of propulsion and lift in the wings. Applications include camouflaged surveillance, area mapping, nature survey etc. Further development of bio-mimetic model will make it a good option for many work related to aerial vehicles.

2. Project Planning

2.1 Motivation

Interest in the design and control of ornithopters has grown in recent years as interest has grown in the area of Micro Aerial Vehicles or MAVs. These small flying machines have struck the imaginations of many as ideal platforms for a variety of tasks including systems monitoring and surveillance where a swarm of tiny agents would be unobtrusive and have better access to confined areas than larger flying vehicles. Hence, it forms an interesting research problem on stability and control of flapping flight.

2.2 Project goals

1. To design, test and build a bird like flapping wing robot which is able to sustain its flight for sufficient time.
2. To make it remote-operated.
3. To be able to perform all sorts of maneuvering.

2.3 Phases of the work

Total work is grouped in to four stages:

Phase I: Literature Survey for similar existing prototypes or working prototypes at national and international level and study their merits and demerits.

Phase II: Design of various elements of ornithopter, Modelling and Simulation of designed system.

Phase III: Fabrication of initial prototype, Testing and Trials of Fabricated prototype, needed modification in the prototype observed during the testing.

Phase IV: Confirmation of the performance analysis.

2.5 Work Span

Time needed for completing the entire project is 9 months. The stages and details of the development is shown in the project plan.

2.5.1 Development of the work in phases:

Phase I: Literature Survey and idea selection

1. Collecting the technical details of all the existing flapping wing robot for study. In detail study of most updated system.
2. Comparative study of shortlisted flapping wing robots.
3. Selecting the more suitable system which meets the required objective.
4. Detailed study of above selected systems.

Phase II: Design and Simulation

1. Finalizing the objectives to be completed and their performance parameters.
2. Design of the system according to the decided parameters.
3. Finalizing the manufacturing drawings and 3D modelling.
4. Simulation of the 3D model for confirmation of required working.

Phase III: Fabrication, Assembly, Testing and Trials of prototype

1. Listing of standard parts and various elements such as sensors, actuators, drives and controllers, etc.
2. Purchase of the selected components like actuators, sensors, controllers etc. and fabrication of the systems.
3. Fabrication and assembly.
4. Programming and testing of prototype.
5. Modifications in the prototype observed during the testing.
6. Trials and testing of robot in defined parameters.

Phase IV: Performance Analysis

1. Improving the design according to the observations during testing.
2. Performance analysis of the prototype.

2.5.2 CPM Chart

<table>
<tr><th rowspan="2">Phases</th><th colspan="9">Months</th></tr>
<tr><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th></tr>
<tr><td>I – 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="4" colspan="3">Literature Survey</td></tr>
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<tr><td>II – 1</td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="4" colspan="3">Design and Simulation</td></tr>
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<tr><td>III – 1</td><td rowspan="6" colspan="3">Fabrication, Assembly, Testing and Trials</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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3. Literature Survey

3.1 Basic flight aerodynamics

3.1.1. Aerodynamic forces

Aerodynamics is the way air moves around things. The rules of aerodynamics explain how an airplane is able to fly. Anything that moves through air reacts to aerodynamics. A rocket blasting off the launch pad and a kite in the sky react to aerodynamics. Aerodynamics even acts on cars, since air flows around cars.

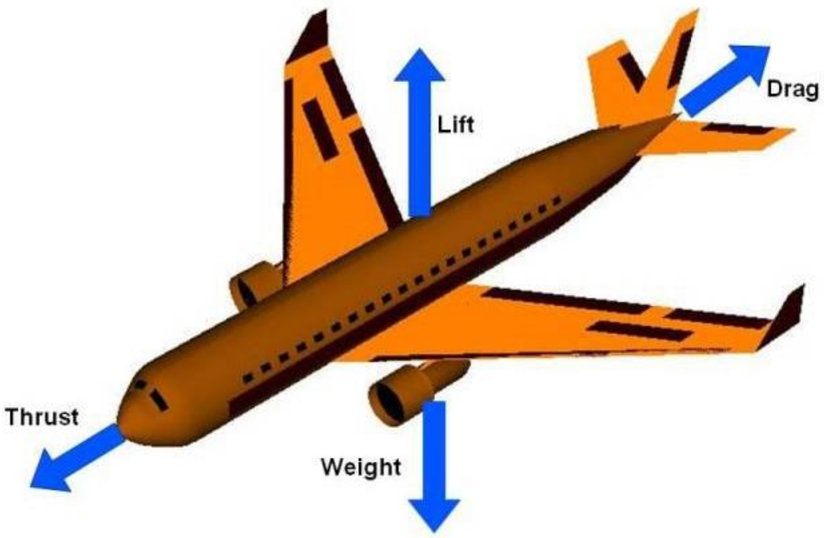


Figure 3.1. Forces acting on an aircraft [4]

Once an aircraft leaves the ground, it is acted upon by four aerodynamic forces; thrust, drag, lift and weight. Understanding how these forces work and knowing how to control them with the use of power and flight controls are essential to flight. [4]

They are defined as follows:

1. Thrust - the forward force produced by the power plant/propeller or rotor. It opposes or overcomes the force of drag. As a general rule, it acts parallel to the longitudinal axis.
2. Drag - a rearward, retarding force caused by disruption of airflow by the wing, rotor, fuselage, and other protruding objects. Drag opposes thrust and acts rearward parallel to the relative wind.

3. Weight - the combined load of the aircraft itself, the crew, the fuel, and the cargo or baggage. Weight pulls the aircraft downward because of the force of gravity. It opposes lift and acts vertically downward through the aircraft's center of gravity (CG).
4. Lift - opposes the downward force of weight, is produced by the dynamic effect of the air acting on the airfoil, and acts perpendicular to the flightpath through the center of lift.

Drag depends on the properties of the fluid and on the size, shape, and speed of the object. One way to express this is by means of the drag equation:

$$\boldsymbol{F_D = \frac{1}{2}\rho v^2 C_D A} \qquad \text{…(i)}$$

Where,

F_D = drag force (*N*)
ρ = density of the fluid (kg/m^3)
v = speed of the object relative to the fluid (*m/s)*
A = cross sectional area (m^2)
C_D = drag coefficient – a dimensionless number.

The drag coefficient depends on the shape of the object and on the Reynolds number.

If the value of coefficient of lift for a wing at a specified angle of attack is given, then the lift produced for specific flow conditions can be determined using the following equation:

$$\boldsymbol{F_L = \frac{1}{2}\rho v^2 C_L S} \qquad \text{...(ii)}$$

Where,

F_L = lift force (*N*)
ρ = density of the fluid (kg/m^3)
v = speed of the object relative to the fluid (*m/s)*
S = wing area (m^2)
C_L = lift coefficient – a dimensionless number.

The lift coefficient depends on the angle of attack, Mach number, and Reynolds number.

3.1.2 Aircraft rotation movements

Aircraft Rotations are also fundamental in understanding flight aerodynamics.

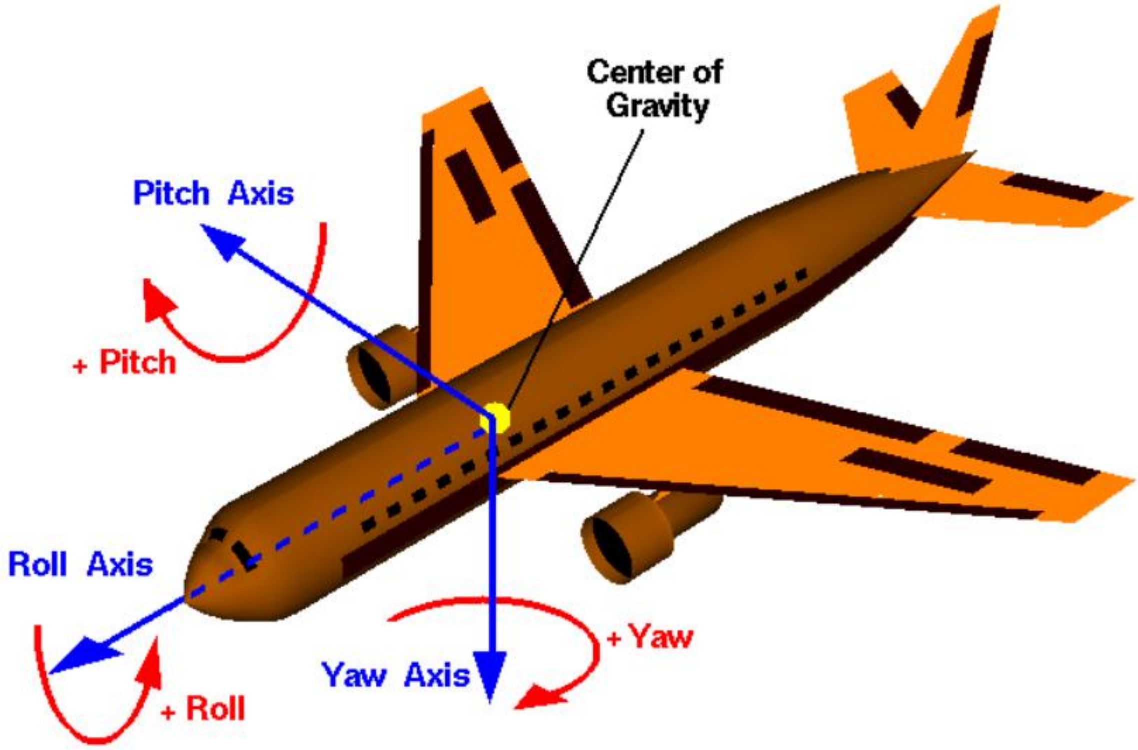


Figure 3.2. Aircraft rotation body axes [5]

We can define the orientation of the aircraft by the amount of rotation of the parts of the aircraft along these principal axes. [5]

The yaw axis is defined to be perpendicular to the plane of the wings with its origin at the center of gravity and directed towards the bottom of the aircraft. A yaw motion is a movement of the nose of the aircraft from side to side.

The pitch axis is perpendicular to the yaw axis and is parallel to the plane of the wings with its origin at the center of gravity and directed towards the right-wing tip. A pitch motion is an up or down movement of the nose of the aircraft.

The roll axis is perpendicular to the other two axes with its origin at the center of gravity, and is directed towards the nose of the aircraft. A rolling motion is an up and down movement of the wing tips of the aircraft.

3.1.3 Aerofoil wing

Any object with an angle of attack in a moving fluid, such as a flat plate, a building, or the deck of a bridge, will generate an aerodynamic force (called lift) perpendicular to the flow. Aerofoils are more efficient lifting shapes, able to generate more lift (up to a point), and to generate lift with less drag.

A lift and drag curve obtained in wind tunnel testing is shown on the right. The curve represents an aerofoil with a positive camber, so some lift is produced at zero angle of attack. With increased angle of attack, lift increases in a roughly linear relation, called the slope of the lift curve. At about 18 degrees this aerofoil stalls, and lift falls off quickly beyond that. [6]

The drop-in lift can be explained by the action of the upper-surface boundary layer, which separates and greatly thickens over the upper surface at and past the stall angle.

The thickened boundary layer's displacement thickness changes the aerofoil's effective shape, in particular it reduces its effective camber, which modifies the overall flow field so as to reduce the circulation and the lift. The thicker boundary layer also causes a large increase in pressure drag, so that the overall drag increases sharply near and past the stall point.

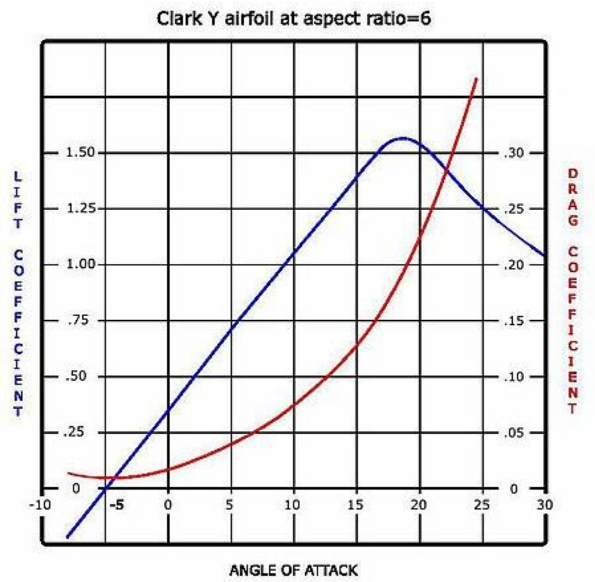


Figure 3.3. Lift and Drag curves for a typical aerofoil [6]

The various terms related to aerofoils are defined below:

1) The suction surface (a.k.a. upper surface) is generally associated with higher velocity and lower static pressure.
2) The pressure surface (a.k.a. lower surface) has a comparatively higher static pressure than the suction surface. The pressure gradient between these two surfaces contributes to the lift force generated for a given aerofoil.

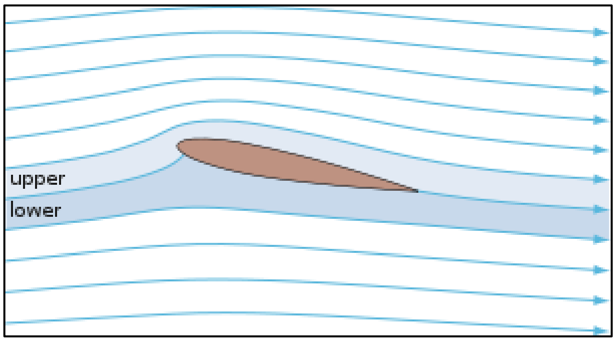


Figure 3.4. Streamlines around a NACA 0012 aerofoil at moderate angle of attack [6]

The geometry of the aerofoil is described with a variety of terms:

1) The leading edge is the point at the front of the aerofoil that has maximum curvature (minimum radius).
2) The trailing edge is defined similarly as the point of minimum curvature at the rear of the aerofoil.
3) The chord line is the straight line connecting leading and trailing edges. The chord length, or simply chord, c, is the length of the chord line. That is the reference dimension of the aerofoil section.

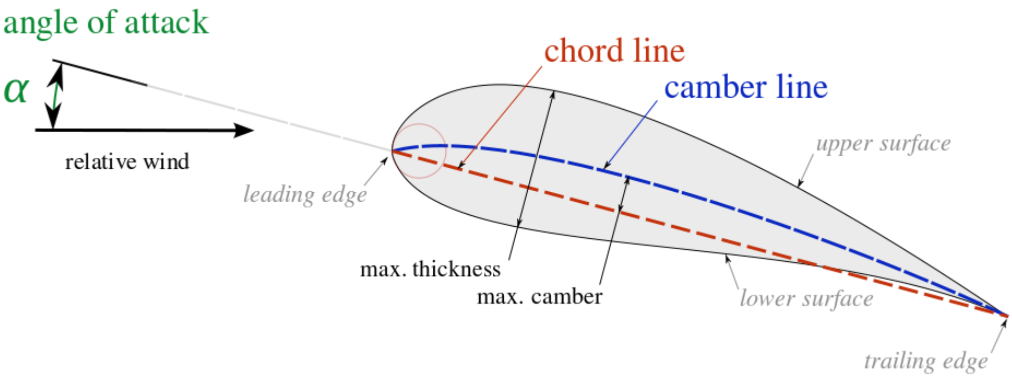


Figure 3.5. Aerofoil nomenclature [6]

The shape of the aerofoil is defined using the following geometrical parameters:

The mean camber line or mean line is the locus of points midway between the upper and lower surfaces. Its shape depends on the thickness distribution along the chord.

The thickness of an aerofoil varies along the chord. It may be measured in either of two ways:

Some important parameters to describe an aerofoil's shape are its camber and its thickness. For example, an aerofoil of the NACA 4-digit series such as the NACA 2415 (to be read as 2 – 4 – 15) describes an aerofoil with a camber of 0.02 chord located at 0.40 chord, with 0.15 chord of maximum thickness.

3.2 Bird Flight

3.2.1 Flapping strokes

A typical flapping cycle consists of two strokes: a downstroke where the wing flaps down in forward flight (or forward in hovering flight), and an upstroke. The wing produces both lift and thrust predominantly in the forward downstroke. During the upstroke, the wing still produces some lift, but little or no thrust. Note the bent outer segment in Fig 3.6: this is a consequence of a degree of passivity in its hinging at the root, i.e., where it is attached to the inner wing. This folding of the wing reduces the drag produced during the upstroke. For a small part of the upstroke, the wing tip does provide a small amount of propulsive force, presumably due to a delayed reversal of motion as compared to the inner wing.

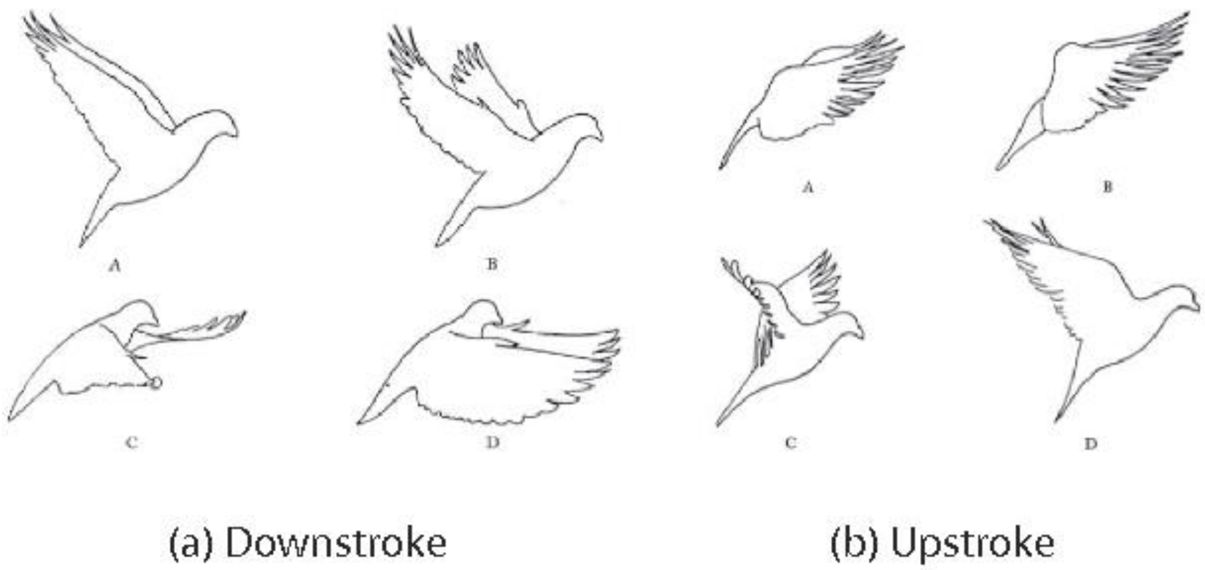


Figure 3.6. A typical flapping cycle of an avian in forward flight [7]

Figure 3.6. shows the downstroke and upstroke in slow flight (which is not exactly hovering, but a close analog). In slow flight, the role of upstroke and downstroke are reversed. A bulk of lift and thrust are obtained from the upstroke. On the other hand, the downstroke yields some lift, but no significant propulsive force. In particular, the propulsive force during the upstroke comes from the rapid, almost instantaneous, pronation and extension of the wing shown in Fig. 3.6. This discussion serves to illustrate a limitation of the discussion in the previous section where the kinematics of hovering were modelled using a first-principle approach. The effects of the rapid wing "flick" are nearly impossible to capture in that framework, but it provides a bulk of the propulsive force and therefore cannot be ignored in force and moment calculations. Such phenomena represent a challenge even to the general aerodynamic modelling of flapping flight. [7]

If the wing is inclined to the air stream at an angle of attack α, a large force appears on the wing F. This force is resolved into two components, the lift F_L (which is at right angles to the flow of air) and the drag F_D. Notice that, for a well-designed wing, the force F is not at right angles to the wing but is inclined forwards with respect to the wing chord. This is crucial to understanding how a flapping wing generates forward thrust. In fact, the angle between F and F_L – which is the reciprocal of the lift/drag ratio, is equal to $\alpha/2$. It is usual to express the lift F_L in terms of a dimensionless constant called the aerodynamic coefficient of lift C_L by dividing the force F_L by the term $0.5*S_w*\rho*v^2$. This takes into account the area S_w of the wing, the density ρ of the air (equal to 1.3 kg/m^3 at sea level) and the velocity of the wing through the air v.

Hence, $$F_L = 0.5 * C_L S_W \rho v^2 \qquad \text{...(ii)}$$

C_L varies critically with angle of attack. When a bird in cruising flight flaps its wings, the flow of air over the wing is no longer horizontal. On the downstroke, the relative velocity between the air and the wing is inclined upwards from below, while on the upstroke, the velocity of the air is angled from above. Now, assuming for the moment that the wing is symmetrical and has zero angle of attack, it can be seen from the diagram below that on both the downstroke and on the upstroke, the force of lift on the wing (which is, by definition, at right angles to the flow of air) is inclined forwards and has a significant forward component. This is the origin of the thrust produced by a flapping wing.

3.2.2 Gliding flight

During gliding flight, birds may manipulate both the lift coefficient and/or the surface area of the wing to create a force asymmetry between the two wings that will result in an angular acceleration around the roll axis. The angles of attack (α), and hence, the lift coefficients C_L, of the wings can be independently altered by pronation or supination. By pronating the wing on the inside of the intended turn, and supinating the wing on the outside of the turn, the bird respectively decreases and increases the angle of attack of each wing (and hence, the lift coefficients), creating a lift-force asymmetry that rolls the animal into a bank. This is probably the most common mechanism of creating force asymmetry employed by gliding birds.

Birds may also reduce the surface area of the wing on the inside of the intended turn by simply flexing at the wrist and elbow. In so doing, the bird can not only completely eliminate the aerodynamic force created by the inside wing, but also greatly reduce the inertia of that wing, thus greatly facilitating rolling acceleration. In addition, reducing or eliminating the force produced by the inside wing alters the centre of rotation of the roll. If no dorsally directed lift is created by the inside wing, either because of pronation to $\alpha = 0$, or flexion to $S = 0$, the body of the bird undergoes a purely ‘‘rotational roll’’ and only the inertia of the cross-section of the body and wings must be overcome to enter a bank. If lift continues to be produced on the inside wing, the centre of rotation is shifted laterally toward the inside wing, and the body is lifted against gravity, reducing roll rate. [8]

Pronation and supination are kinematically compact, and probably quicker than flexion, and certainly more quickly executed than producing a velocity asymmetry by flapping. Further, if the inside wing can be pronated to an angle of attack, 0, a ventrally directed aerodynamic force could be produced by this wing, which may more than compensate for the inertia of leaving the inside wing extended.

Birds can also use supination of a wing to manipulate drag rather than lift. Here, the wing on the inside of the intended turn is strongly supinated to beyond the critical angle of attack, stalling the wing and causing a substantial increase in drag on that wing. With this aerodynamic ‘anchor’ in place, the bird yaws strongly to the inside, which in turn, creates a greater velocity and lift on the outside wing, resulting in a bank. This mechanism is reported to be used by slowly flying gulls. [9]

3.2.3 Aerodynamic yawing moment and static stability

Due to absence of a vertical tail in birds similar to rudder in airplanes, yaw movement in birds is contributed by its tail. Gottfried [10] states that tails of birds can generate yawing moments in case of a sideslip disturbance and, thus, contribute to stability in the related axis. This holds for tails strictly in the horizontal plane without twisting such that there is no component in the vertical plane. The horizontal tail basically provides a positive contribution to yaw stability, which can be of significant magnitude when compared with the wing.

3.3 Existing flapping wing designs

3.3.1 FESTO SmartBird

The unusual feature of SmartBird is the active torsion of its wings without the use of additional lift devices. The objective of the SmartBird project was to achieve an overall structure that is efficient in terms of resource and energy consumption, with minimal overall weight, in conjunction with functional integration of propulsion and lift in the wings and a flight control unit in the torso and tail regions. Further requirements were excellent aerodynamics, high power density for propulsion and lift, and maximum agility for the flying craft. [11]

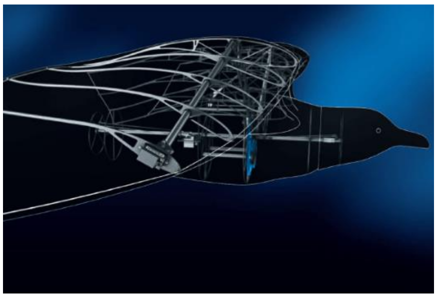


Figure 3.7. Wing structure of the SmartBird [11]

Flapping-wing flight comprises two principal movements. First, the wings beat up and down, whereby a lever mechanism causes the degree of deflection to increase from the torso to the wing tip. Second, the wing twists in such a way that its leading edge is directed upwards during the upward stroke, so that the wing adopts a positive angle of attack. If the rotation were solely due to the wing’s elasticity, passive torsion would result. If on the other hand the sequencing of the torsion and its magnitude are controlled by an actuator, the wing’s torsion is not passive, but active.

SmartBird's wings each consist of a two-part arm wing spar with an axle bearing located on the torso, a trapezoidal joint as is used in enlarged form on industrial excavators, and a hand wing spar. The trapezoidal joint has an amplitude ratio of 1:3. The arm wing generates lift, and the hand wing beyond the trapezoidal joint provide propulsion. Both the spars of the inner and the outer wing are torsionally resistant. The active torsion is achieved by a servomotor at the end of the outer wing which twists the wing against the spar via the outmost rib of the wing.

Table 3.1. Technical specifications of SmartBird [11]

Torso length	1.07 m
Wingspan	2.00 m
Weight	0.450 kg
Structure	lightweight carbon fibre structure
Lining	extruded polyurethane foam
Battery	lithium polymer accumulator, 2 cells, 7.4 V, 450 mA
Servo Drive	2x digital servo unit with 3.5 kg actuating force for control of head and tail sections. 2x digital servo units for wing torsion, with 45 degree travel in 0.03
Electrical Power Requirement	23 W
Motor	Compact 135, brushless
Sensors	Motor positioning 3x TLE4906 Hall sensors
Accelerometer	LIS302DLH
Power management	2 x LiPo accumulator cells with ACS715 voltage and current monitoring

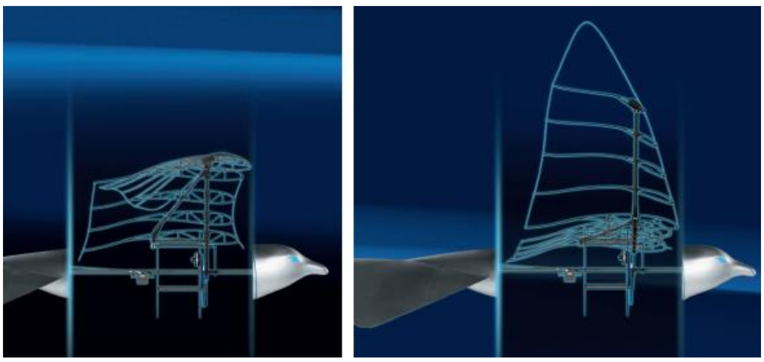


Figure 3.8. Wing flapping observed in the SmartBird structure [11]

3.3.2 Flapping UAV developed at University of Genova

The preliminary design of a biologically inspired small-sized flapping UAV is proposed. It summarizes some key technical issues of a flapping UAV, where the shape and size of the model were chosen in terms of the morphology of several birds. In table 1, the design specifications for the proposed flapping UAV are presented. One important design specification to highlight is that the vehicle is intended to be hand launched with a minimum velocity of 5.0 m/s [12]. The flapping frequency can be modulated, but shall not exceed 3.0 Hz; this constraint is imposed for structural reasons. A few design approximations used during this study:

1) The avian model is treated as a rigid body to simplify the equations that describe the dynamics
2) For the flapping flight simulations, the wings are considered to be made of two parts, one internal wing and one external wing, with a gap between the internal and external wings. This gap is where the wing is considered to be articulated.
3) The junction between the wing and the body of the avian model is also modelled through a gap.
4) The mass of the avian model is assumed to be distributed uniformly.
5) The fuselage is assumed to have a light shell making it look like a bird. This shell generates drag and lift, which are taken into account for the aerodynamic forces computations.

Table 3.2. Design specifications of Genova model [12]

Maximum weight	1.0 kg
Maximum flapping frequency	3.0 Hz
Minimum velocity (hand launch velocity)	5.0 m/s
Maximum velocity	14.0 m/s
Autonomy	20.0 min

Taking into account the design specifications and morphometrics/allometry of several birds, the initial form of the avian model is determined. The model shape, size, and flight conditions were chosen to approximate those of a seagull (Kelp Gull or Western Gull), which closely meets the design specifications.

Table 3.3. Avian model geometric data [12]

Wing projected area S_w (one wing)	0.314 m^2
Wing mean aerodynamic chord (MAC_w)	0.336 m
Wing semi-span (b)	1.0 m
Tail projected area (half the tail) S_h	0.087 m^2
Tail mean aerodynamic chord (MAC_h)	0.444 m
Fuselage maximum diameter	0.2 m
Fuselage length	1.0 m
Fuselage projected area (half the fuselage) S_f	0.066 m^2

The wing used in this study is a simplification of the actual wing of a seagull. they extracted the wing surface coordinates by using a 3D laser scanner. The simplified or engineered wing was used in order to parametrize the 3D model and to avoid potential surface modelling problems when conducting the parametric study.

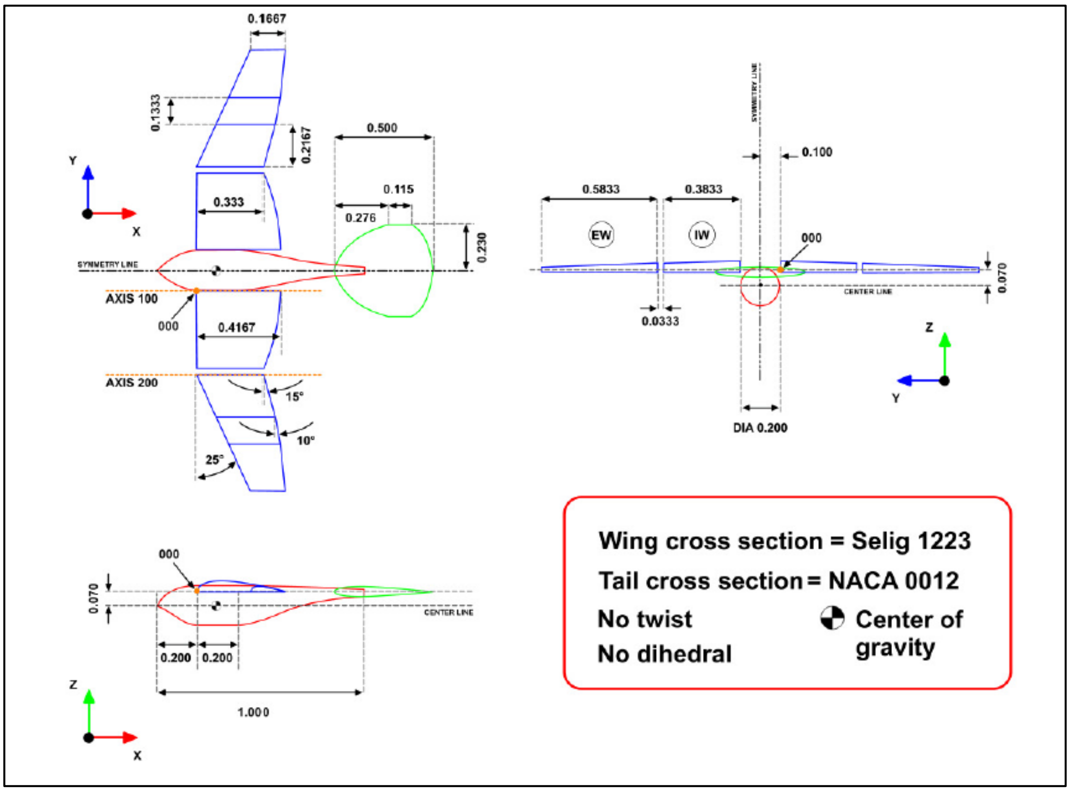


Figure 3.9. Design dimensions of Genova model [12]

The wing dimensions were chosen in such a way that they produce the lift needed to keep the avian model aloft at the design conditions of a forward velocity of 5.0 m/s and a flapping frequency of 3.0 Hz, that is, the model is designed at minimum flight velocity and maximum flapping frequency.

The fuselage is designed in such a way that it provides enough room to house the mechanisms and flight systems with no interference, it produces low drag, it has a low negative contribution to the overall stability of the model and resembles a seagull. Finally, a horizontal stabilizer or tail was added to the model and it was sized in such a way that it guarantees the stability of the avian model in flapping and gliding flight. It is important to mention that the whole tail is allowed to move.

In this figure, the point marked as 000 represents the junction between the fuselage and the internal wing and also serves as a reference point to define the wing kinematics, the position of the different components of the avian model, the position of the aerodynamic center of the wing and tail and the position of the center of gravity of the model. The axis 100 (which passes through the point 000), is the axis about which the internal wing oscillates or rolls, and the axis 200 is the axis about which the external wing is articulated and rolls. [12]

3.3.3 Phoenix by Jackowski at MIT

The wing design chosen for use for the Phoenix is a proven design by Sean Kinkade and is used throughout his line of ornithopter designs which shows that it scales well. Working from the specifications of the Kestrel ornithopter and the new payload capacity necessary an approximate size for the scaled-up0 wing was found based on the wing loading.

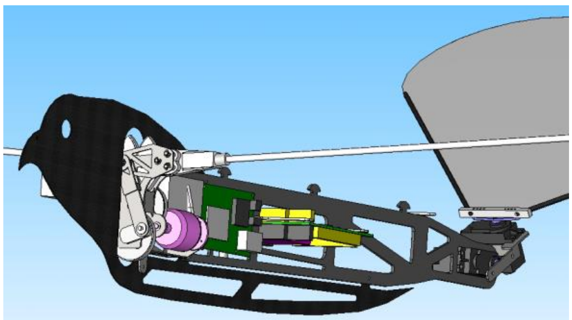


Figure 3.10. Software model of Phoenix [13]

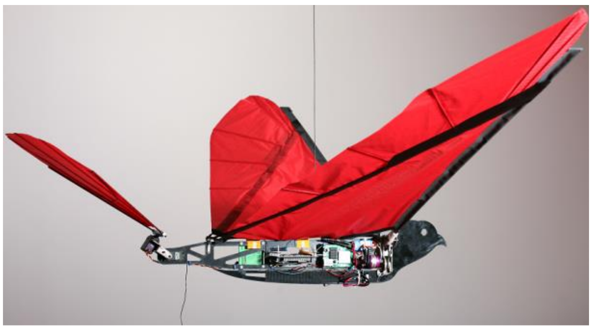


Figure 3.11. Final Phoenix prototype image [13]

With its 0.22 square meter wing area and overall weight of 395 grams the Kestrel has a wing loading of 1.78 kg/m^2. Scaling to a larger machine that even the size of is known is a pretty difficult proposition, but a few assumptions can be applied to clean up the situation. The payload fraction, or amount of payload divided by the overall weight of the ornithopter is assumed to be constant. For the Kestrel this number is 0.334 with a payload of 132 grams. The 132-gram payload was estimated by looking at the difference between the weights of onboard components like the batteries as equipped and the maximum weighs allowed (using lithium polymer batteries vs nickel metal hydride for example). The estimated required payload for the Phoenix is 400 grams which, using the same payload fraction, comes to a total weight of 1197 grams. With this weight in order keep the same wing loading as the Kestrel the Phoenix will need a wing area of 0.672 m^2. By scaling the original Kestrel wing the desired wingspan comes to about 2 meters. The actual wingspan used in the design was shortened to 1.8 meters in order to make the ornithopter easier to handle through the lab with the option left open to increase the wingspan with longer spars if necessary. [13]

4. Design and calculations

4.1 Motor selection

For the output flapping frequency of 4 Hz, the output angular speed of the crank is 240 Hz. Because of the large torque required at the transmission output a steep gear reduction will be required along with large strong gears in the stage close to the output. At the end a maximum of a 24:1 reduction was achieved which made motor selection very easy. The 240RPM output shaft speed through the 24:1 reduction becomes a target of 5760RPM at the motor shaft. [13]

The electric motor speed constant is inversely proportional to the motor's torque constant, a measure of the amount of torque produced per unit current. Because of this relationship it makes sense that the small lightweight motors desired for this application will have high speed constants.

Windings available on even the highest torque motors suitable start well above this speed constant because of their inability to produce a large amount of torque in such a small space. The law of conservation of energy when applied to this case shows that for the same energy output the speed of the motor must increase if the torque produced decreases. With these specifications the field of possible motors became very small. The selection of windings available in the brushless outrunner motors used in model aircraft is quite limited because of the specialized application but a motor that fit the desired specifications closely enough was found.

The weight of the ornithopter is 400 grams and the wing span is 1.5 metres.

So, the gravitational force = 0.400 x 9.81 = 3.924 N.

Now, considering that the half of the lift force is generated by one wing and the force acts on the centre of the wing, the torque at the shoulder of the wing is

T = F.r = (Lift force on one wing)*(Length of centre of the wing from fuselage)

(3.924/2) x (1.5/4) = 0.73575 N.m

Considering efficiency, torque by both the wings = (0.73575*2) = 2 N.m

Now, using a gear reduction of 20:1, the torque at the motor = (2/20) = 0.1 N.m

Speed constant required for the motor for 12 V supply is = (5760/12) = 480RPM/V.

The PJS 3D 1200 motor has a torque constant of 0.01126 N.m/A and a speed constant of 848RPM/V and can be used for the operation.

So, 10 A, 12 V battery is sufficient to provide the power to the motor.

4.2 Wing configuration and design

The wing design chosen for use is a proven design by Sean Kinkade and is used throughout his line of ornithopter designs which shows that it scales well. Working from the years of development on this wing design allows the focus of our project to be on the parts we have more experience in such as the gearbox, electronics, and controls.

The wings have a triangular support structure made from carbon rods. A main spar runs along the leading edge of the wing and a strut connects from the rear of the ornithopter's body to a point near the tip of the main spar. From this strut there are several smaller carbon rods that project to the edge of the wing which are somewhat free to move. This results in a fanning motion from the trailing edge of the wing that produces thrust while the leading edge is flapping up and down which directly contributes a part of the lift in addition to the conventional lift coming from airflow over the wing. [13]

Table 4.1. Wing measurements of the study species [14]

Species		Mass (kg)	Wing span (m)	Wing area (m^2)
Corvus corone	Hooded crow	0.553	0.925	0.147
Sturnus vulgaris	Starling	0.0884	0.384	0.0251
Fringilla coelebs	Chaffinch	0.0228	0.262	0.0130
Buteo buteo	Common buzzard	0.964	1.29	0.254
Accipiter nisus	Sparrowhawk	0.196	0.611	0.0642
Milvus milvus	Red kite	0.851	1.50	0.304
Ardea cinerea	Grey heron	1.21	1.60	0.358
Cygnus olor	Mute swan	9.01	2.31	0.682
Anas penelope	Wigeon	0.770	0.822	0.0829
Somateria mollissima	Eider	1.39	0.978	0.131
Phalacrocorax carbo	Cormorant	2.56	1.35	0.224
Columba palumbus	Wood pigeon	0.495	0.751	0.0797
Larus ridibundus	Black-headed gull	0.280	0.963	0.0985
Larus canus	Common gull	0.364	1.10	0.138
Larus argentatus	Herring gull	0.925	1.35	0.200
Larus marinus	Great black-backed gull	1.51	1.66	0.290

From the table, we can note down the data for a herring gull as follows,

Mass = 0.925 kg   Wing span = 1.35 m   Wing area = 0.2 m^2

Similarly, for a mass of 0.5 kg, we can roughly calculate its wing dimensions by ratio and proportions,

Wing span = 0.73 m   Wing area = 0.108 m^2

In order to calculate the wingspan for a certain mass, there also exists an alternate equation [15],

$$\boldsymbol{L_w = 2.43 * w^{0.3326}} \qquad \text{…(iii)}$$

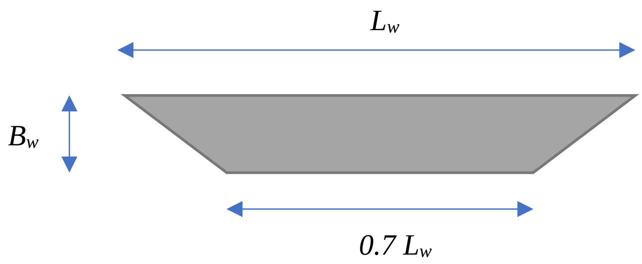
where,

L_w = wing span *(feet)*

w = weight *(lbs)*

Substituting, w = 1.1 lbs (0.5 kg), we get, L_w = 0.765 m   …from (iii)

To calculate the other dimensions of the wing, we have assumed it to be of the shape of a trapezium such that,



Area of trapezium = Area of the wing = $A_w = \frac{1}{2}(L_w + 0.7L_w)B_w$ …(iv)

We know that, A_w = 0.108 m^2

Hence, $B_w = \frac{2*A_w}{1.7*L_w}$ = 0.17 m   …from (iv)

Considering it is a flapping wing model, the wing dimensions should be multiplied by a factor to avoid any errors.

Hence, corrected wing span,   ***L**_w* **= 0.765*2 = 1.5 m**

corrected wing width, ***B**_w* **= 0.17*2 = 0.34 m**

4.3 Tail configuration and design

Perhaps the most influential design choice of a flapping wing MAV is its tail configuration. A tail damps the rotational dynamics, implying that around the nominal flight condition the flapping wing MAV has a passively stable attitude.

In addition, directional control can be achieved with parts of the tail, as is done with normal fixed wing aircraft. The wings do not have to be used for directional control and can be realized with relatively straightforward mechanisms.

The tail section of the ornithopter is responsible for both of the controllable degrees of freedom aside from the ability to throttle the drive motor. The tail of the Kestrel is set up with one servo directly connected to the tail at an angle and another further up the body which rocks it via a linkage. Mounting the rudder servo at an angle is important because with a single control surface the elevator and rudder are naturally coupled, moving the rudder servo makes the tail also move in the vertical direction unless it’s at zero angle where it doesn’t have any control authority anyway. With the tail at an angle to the rudder servo it allows the servo to held into the zero-angle position with respect to the ornithopter body and while the tail stays near the trimmed position for horizontal flight. This causes the tail to move in a bowl-shaped trajectory decoupled from the elevator action and is much easier to control by a human pilot. It does not solve the problem when the elevator servo moves the tail out of the trimmed horizontal position, but being able to exploit that is a big advantage where it applies. [13]

There are various forms of tails in birds: rectangular form, delta form and trapezoidal form.

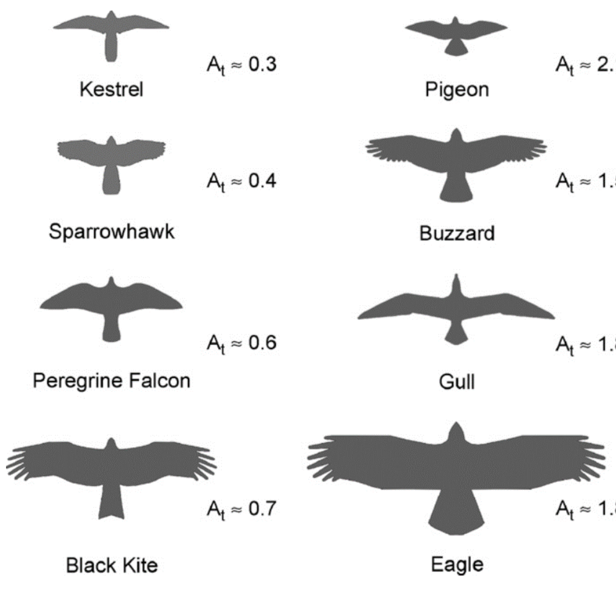


Figure 4.1. Bird tails similar to rectangle form (left) and to delta or trapezoid form (right) [10]

For tails forms similar to delta, aspect ratio can be expressed with [10],

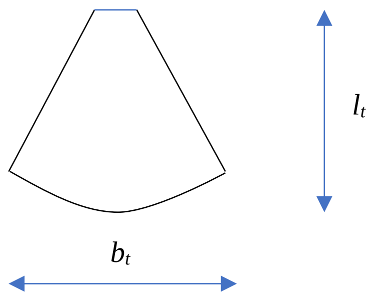
$$A_t = \frac{2b_t}{l_t} \qquad \text{...(v)}$$

where,

A_t = aspect ratio

b_t = tail breadth (m)

l_t = tail chord length (m)



For a herring gull, $A_t = 1.8$

Let, $l_t = b_w = 0.34$ m

Now, $2\, b_t / l_t = 1.8$ ...from (v)

$b_t = 0.9\, l_t = 0.305$ m

Hence, Tail chord length, $\boldsymbol{l_t = 0.34}$ **m**

Tail width, $\boldsymbol{b_t = 0.305}$ **m**

4.4 3D model

Based on the above preliminary designed parameters, *SolidWorks* was used to create a visual of the model.

4.4.1 Part drawings

The following figures show different parts of the model:

Figure 4.2. Isometric view of gearbox

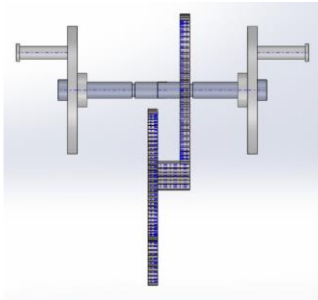


Figure 4.3. Top view of gearbox

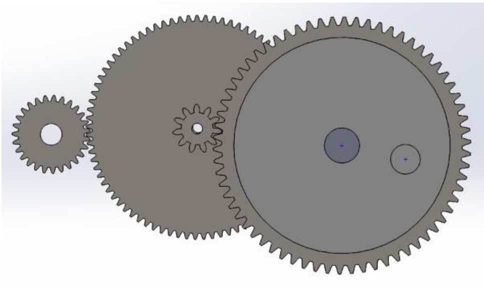


Figure 4.4. Side view of gearbox (shows meshing)

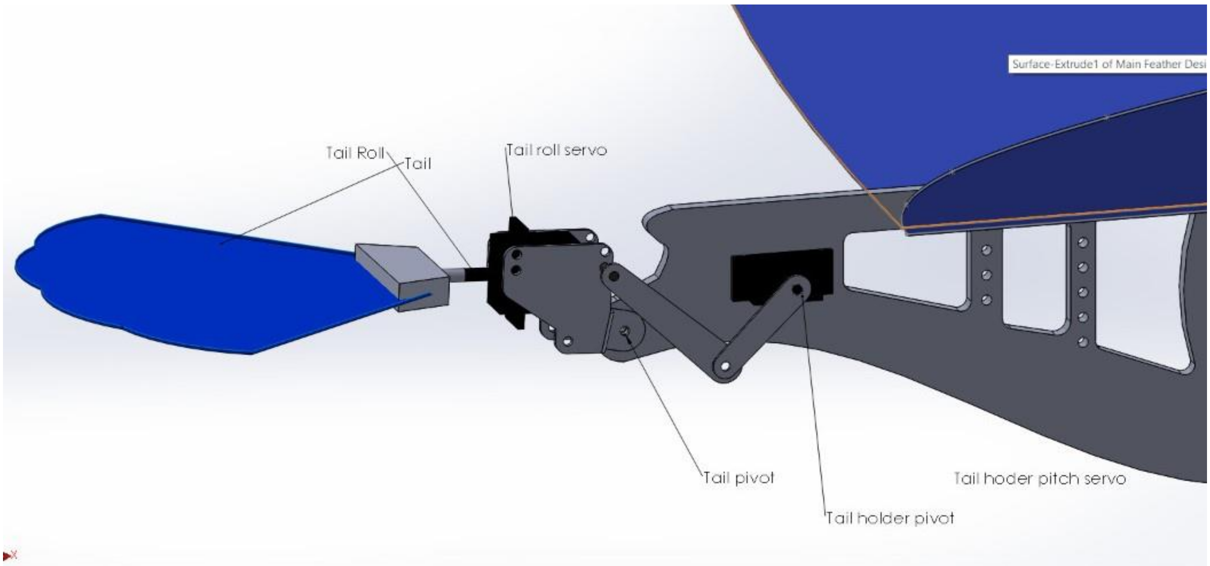


Figure 4.5. Components of the tail

The above images show the gearbox mechanism which help the wings flap.
The other image is a close-up snap of the tail showing its various components.

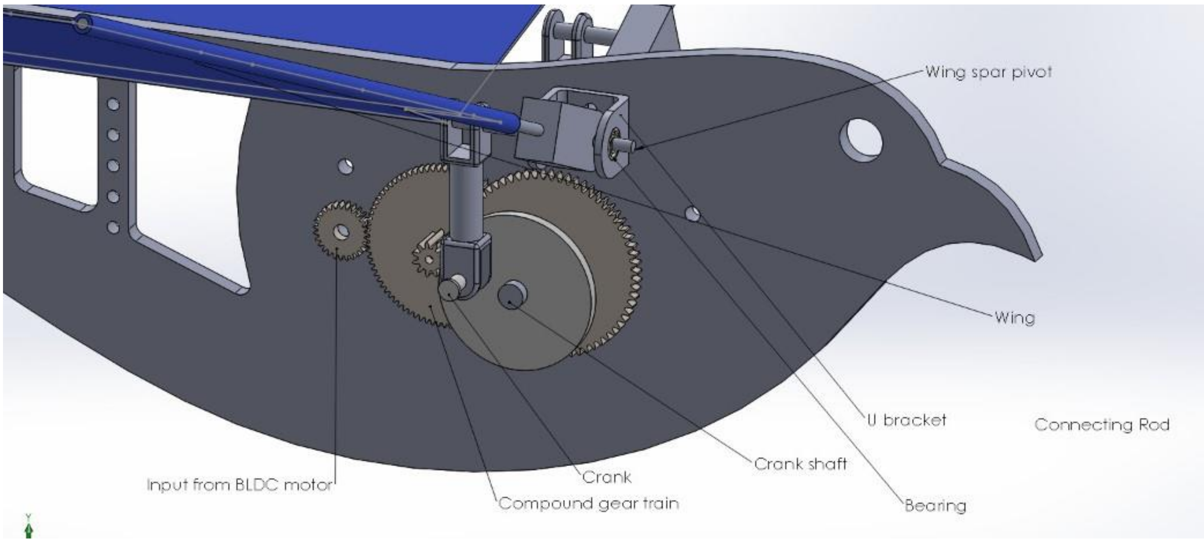


Figure 4.6. Components of the wing

4.4.2 Assembly drawing

The following images show the different views of the assembly modelled:

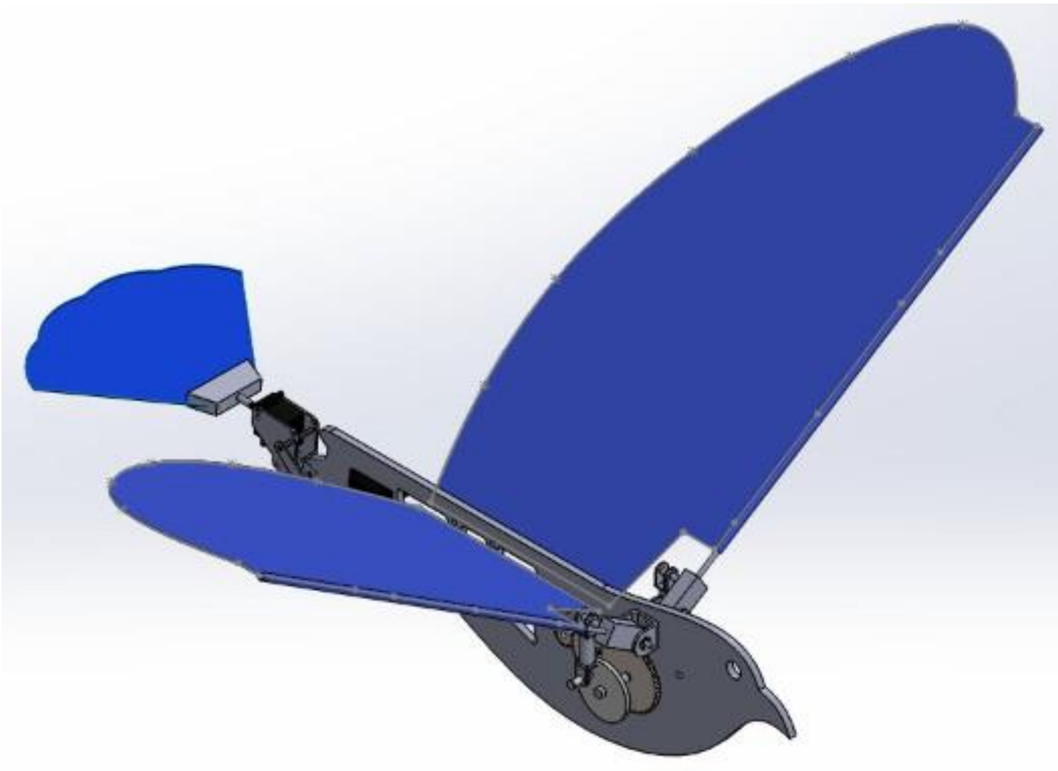


Figure 4.7. Isometric view of 3D model

The flapping movement in an ornithopter is executed with the help of a slider crank mechanism, where two cranks are connected to a single rotor. The rotor is connected via a two-stage gear reduction to attain higher torque output from the light weight compact brushless DC motor. The compound gear train was used to attain a gear ratio of 24:1.

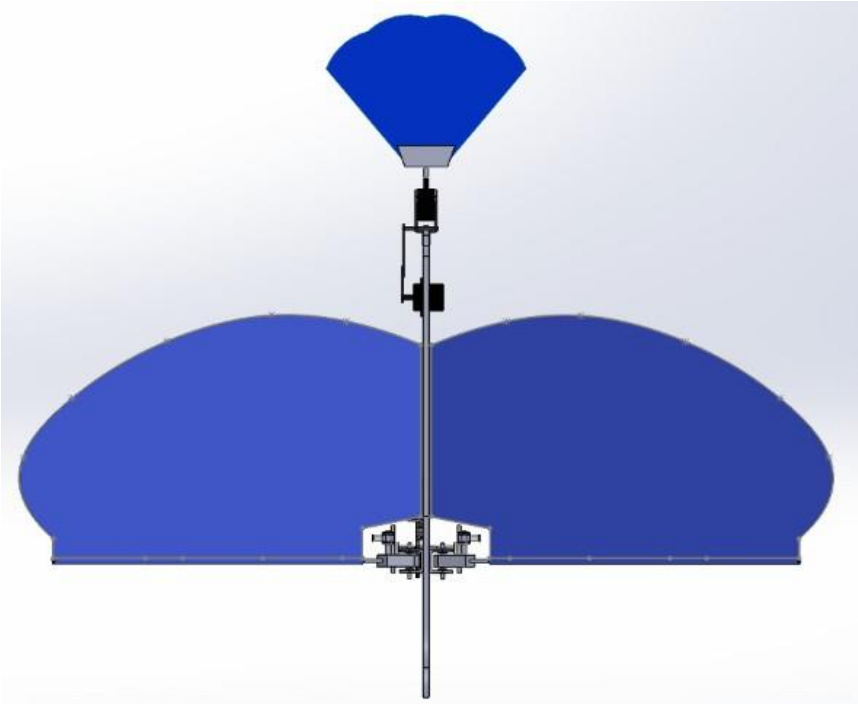


Figure 4.8. Top view of 3D model

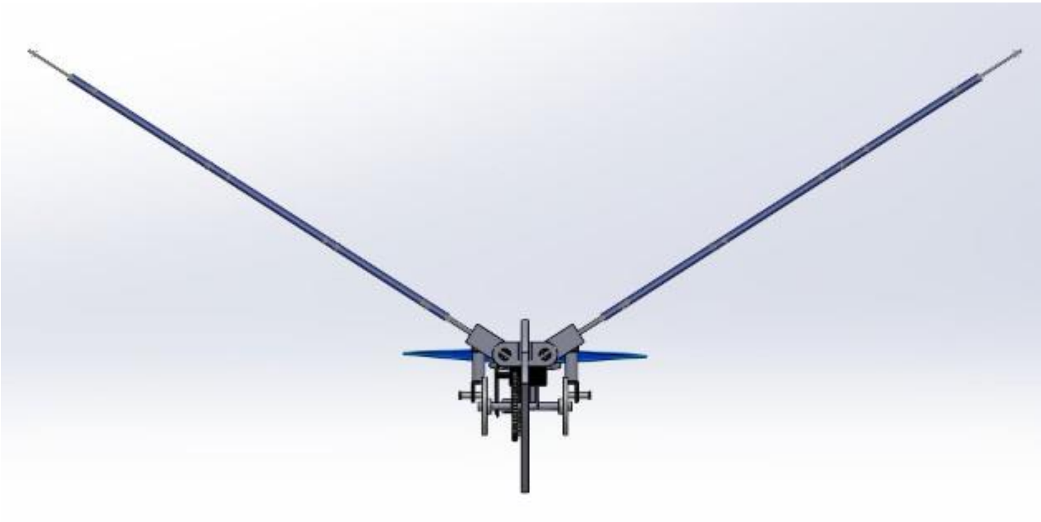


Figure 4.9. Front view of 3D model

The rotational motion of the motor and the compound gear train is converted into the translations motor with the help of the slider crank mechanism, where connecting rods are connected to the wing spars and the spars are hinged to the fuselage to provide flapping movement. The dihedral angle and the range flapping stroke is solely governed by the placement position of the hinge with respect to the rotor of the slider crank mechanism.

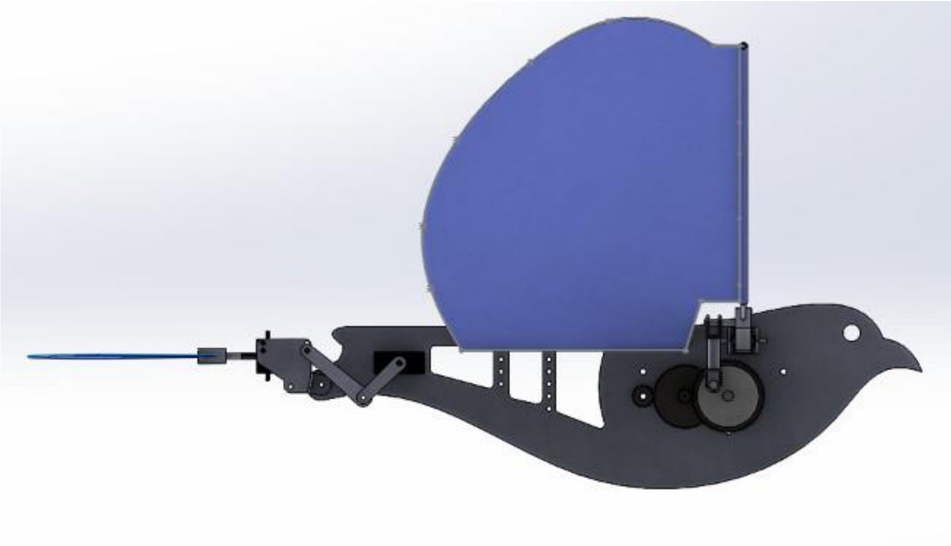


Figure 4.10. Left hand side view of 3D model

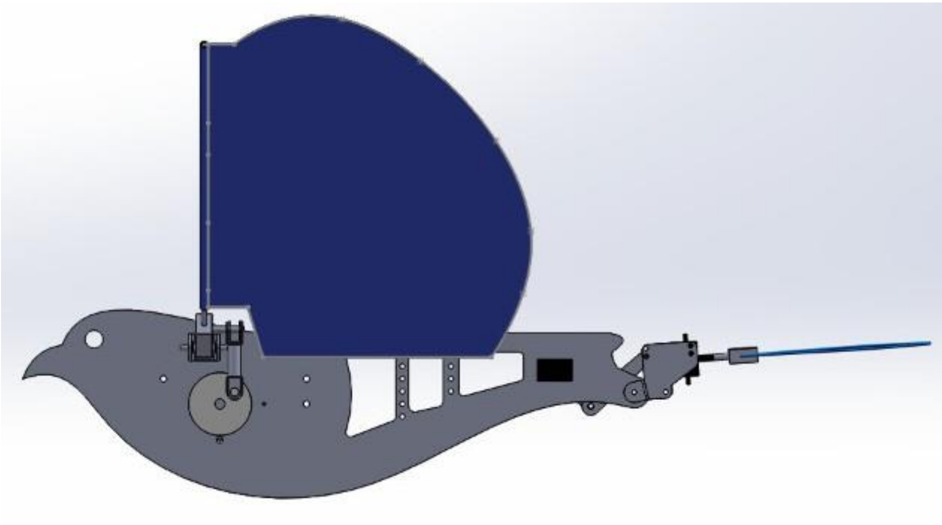


Figure 4.11. Right hand side view of 3D model

Tail holder is also hinged to the fuselage and the angular motion of the holder is governed by high precision servos, which are responsible for the pitching of the ornithopter. The tail holder is also mounted with another servo which is responsible for the angular movement in the lateral plane of the ornithopter. The combined motion of both the servos provides wide angular domain of operation to the tail which is essential for maneuverability of the ornithopter.

5. Cost estimation

The following table shows the estimation of funds needed at different phases of development of the final model to be achieved:

Table 5.1. Estimation of funds

Sr.no.	**Area**	**Particulars**	**Amount (Rs.)**
1.	Raw Material	1(a) Carbon Fibre Sheets (For body, frame and chassis) 1(b) ABS sheets	10000/-
2.	Motors	2(a) BLDC motor (For driving the main crank) 2(b) Digital servo motors (For the wing twist) 2(c) Servo motor (For the tail)	4000/- 1000/- 1000/-
3.	Mechanical Components	Bearing, Gears	1000/-
4.	Manufacturing	4(a) Cutting (Laser, Water jet) 4(b) Milling	4000/- 1000/-
5.	Electronics	5(a) Sensors (Position sensors) 5(b) Control Unit 5(c) Battery 5(d) Connector, Cables, Wire	2000/- 5000/- 1000/- 500/-
6.	Miscellaneous	On spot expenditure	2000/-
Total			32500/-

6. Conclusion

In this report, the case for the construction of a large scale ornithopter suitable for control systems research is motivated. Performance and weight constraints imposed by the computers and sensors desired onboard make it difficult to work with the smaller platforms currently available, let alone micro UAVs currently in development.

In order to work with the dynamics and controls of a flapping wing flying vehicle while these future targets are currently in development, a scaled-up version has been designed and constructed.

The ornithopter was designed from the ground up with the needs of research in mind. All components should be designed to be as lightweight and high performance as possible so as to maximize payload capacity and are intended to fail in predicable and field repairable ways.

This report will help invoke interest and promote others to work in this field as a lot of research is to be done in this field. Further research and development may also increase the availability of cheaper and lighter components which will further promote projects in this field.

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