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Design and kinematic analysis of flapping wing mechanism for common swift inspired micro aerial vehicle

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Abstract

The article presents a novel flapping wing mechanism for Micro Aerial Vehicle (MAV) inspired by one of the most efficient flyers of the aerial world, the Common swift (*Apus apus*). The flight characteristics such as wing beat frequency, wing beat amplitude, and fore and aft movements, as well as wing rotation of the bird at a flight speed 8 m /s, were studied. The common swift rotates its hand wing keeping the pitch of the arm wing constant during the entire wingbeat cycle. The hand wing undergoes forward rotation during the downstroke and backward rotation during the upstroke. This complex wing kinematics enables swift to generate various unsteady aerodynamic mechanisms. Using the geometric and kinematic details, a flapping wing mechanism that emulates the wing kinematics of the bird was designed. The flapping wing mechanism based on the epicyclic ellipsograph mechanism presented herein integrates flapping motion, fore and aft motion, and selective wing rotation. Importantly, this fully constrained mechanism allows performing all the key kinematic motions of the common swift with a single actuator. A kinematic model of the mechanism is presented to calculate the design parameters based on the scale of the MAV. Kinematic simulation of the mechanism is also presented to verify the design.

Keywords

Kinematics, flapping wing, common swift, biomimetic design, micro aerial vehicle

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Introduction

The small aerial vehicles whose largest dimensions are in the order of centimetres (15 cm to 1 m) are called Micro Air Vehicles (MAVs).[1] Apart from their small vehicle size, MAVs are characterized by low flight speed and low Reynolds number. The research on MAV is the intersection of several knowledge domains like mechanisms design, actuators, electronics, materials, and bioinspiration, which makes it highly complex and challenging. Researchers are keen on developing MAVs, as the small size will help these artificial flyers to fly closer to the ground and reach places that are inaccessible to larger Unmanned Aerial Vehicles (UAVs).[2,3]

MAVs are used for situational awareness (especially in urban environments), remote sensing, "over the hill" reconnaissance, precision payload delivery, and aid in rescue missions.[4] The reduced dimensions give a strategic advantage in providing an overview of the battlefield to military personnel without being exposed to danger. Additionally, they can carry onboard sensors to locate biological, nuclear, chemical, or other threats.[3] Though the MAVs were largely confined to assist military operations initially, they are being used nowadays in many civilian applications and are also considered prospective for space applications.[5]

Depending on the mechanism of lift production, MAVs are broadly classified into three configurations - fixed wing, rotary type and flapping wings. At small size scale, highly efficient flapping wing configuration can save up to 27% of the aerodynamic power compared to fixed wing with its optimized flapping motion.[6] From an energetics perspective, the propulsion efficiency of flapping flight can be even higher than 85%.[7] Moreover, flapping flight produces less

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noise, high collision recovery, agility, and manoeuvrability compared to MAVs with other configurations.[8] Flapping flight being the most preferred and highly evolved configuration found in nature, and the new demand for small and manoeuvrable UAVs, all collectively put animal flight recently into focus.[9] As birds, bats and insects have evolved under constraints and requirements that are very relevant to these small aircrafts,[10,11] many features of nature's flyers are highly promising, albeit their complexity, for implementation in small aerial vehicles. Many insects, birds, and bats make use of the enhanced aerodynamics of clap and fling,[12] wake capture,[13] leading-edge vortices[14,15] or wing rotation.[16] Bats, insects like dragonfly, wasp and bee, and birds like hummingbird, raven, sea gull, and eagle have been a source of bioinspiration for design of various MAVs.[8,17] It is interesting to note that, till date, no flapping wing MAV has been developed that emulates the flight of Common swift, the agile aerial insectivores that spend almost their entire lifetime on the wing. The swifts are unique both in terms of biology and body design. Evolution has favoured the swift with a specialized body and wing design; a streamlined body and long, relatively slender, aft-swept wings due to its extreme lifestyle. Due to the aforementioned reasons, we hypothesised that swifts being accomplished flyers could be the right choice for drawing inspiration from, especially for developing aerial vehicles.[18–20]

Birds' kinematics contains 3 degrees of freedom (DOF): stroke, deviation of stroke plane, and pitching or wing rotation. To realize the complex 3 D movements of a bird flight, novel flapping wing mechanism, arguably the cornerstone in the design of the whole MAV has to be realised. It is still unclear how to best design the flapping wing mechanism.[21] The mechanism has to have sufficient strength and with low weight and vibration.[22] A survey of mechanisms based on workspace, compliant or rigid body, type synthesis, mobility, and actuator type is presented elsewhere.[5,23–25] Based on the rigidity of the links used in the mechanisms, they can be compliant transmission or rigid transmission systems. Former has several advantages due to their lower number of parts, thereby reducing the total weight and being able to store and release mechanical power during the flapping cycle.[25] However, due to difficulty in analysing and designing compliant transmissions, rigid transmission mechanisms are still widely used. Based on the special configurations, the mechanism can be either planar or spatial. Due to simplicity in design, several planar flapping wing mechanisms were developed.[26–28] The commonly used mechanisms are four bar crank rocker mechanism, slider crank mechanism, and modified slider crank mechanisms.[24] However, these mechanisms have limitations in generating the complex 3 D kinematics observed in nature. Based on the type of wing rotation, the flapping wing mechanisms can be classified into two: active and passive. A passive mechanism utilises the natural stiffness of the wing spar to generate wing rotation.[29,30] In the active mechanism, rotation is generated by actively rotating the wing to generate different angle of attacks during the stroke.[31–33] Ideally, mechanisms that can actively control all the three DOF in a single kinematic chain are the most demanded, whereas the literature on them remain sparse, with the exception of a report on insect-flight inspired flapping mechanism based on slotted link mechanism.[34] On the contrary to insect flight, birds like Common swift selectively rotate different sections of the wings at different rates during the wing-stroke and hence offer considerable challenge for the designer attempting to mimic their flapping flight. To the best of our knowledge, there are no reported flapping wing MAVs till date, that generate all the three wing kinematics including selective wing rotation coupled to a single kinematic chain. A preliminary design towards this end has been presented earlier.[35]

To achieve the envisaged kinematics, various actuation techniques were developed for flapping wing mechanism that used smart materials like piezoelectrics, electroactive polymers and shape memory alloys, whereas brushless DC motors still remain the most energy efficient option.[36] Hence, the development of a drive mechanism that converts the continuous rotary motion of the motor into 3 D motion of the wings becomes a crucial step in the development of bird flight inspired MAVs.[26] Additionally, the drive mechanism should have low weight so as to maximize the i) payload and battery capacity along with high power transmission efficiency and ii) operational range and minimize the weight of the motor. Consequently, it is evident that the stringent size, weight, and power constraints imposed on flapping mechanisms make their design quite intricate and challenging.

In this article, we present the design of a novel flapping wing mechanism with the capabilities to execute complex kinematic features of the fast-forward flight of Common swift. The unique features of the mechanism include i) coupling of vertical flapping, stroke plane variation, and selective wing rotation in a single kinematic chain with a fixed trajectory and ii) exceptionally, driven by a single rotary actuator. A Kinematic model of the mechanism was also developed to calculate the design parameters. The simulation of the kinematics was also performed in SolidWorks Motion analysis and is presented herein.

Kinematics of common swift

Common swifts (*Apus apus*) are medium sized birds (measuring 15 to 20 cm from head to tail) which appear as quite large birds in flight, having a wingspan of often over 40 cm when in flight. The geometry, wing beat amplitude, fore and aft movement, and wing rotation of the bird are presented in this section.

Geometry: To design the flapping wing mechanism, it is essential to have an exact idea of the geometry as well as the expected mass of the system. Since the proposed MAV is mimicking the Common swift, the biometry of the bird was studied in detail.[37] In the present study, the geometry of the wings was scaled down to attain a wing span of 30 cm, in contrast to the wing span of around 40 cm of Common swift, in order to meet the MAV size specification of National Program for Micro Aerial Vehicle (NP MICAV) initiated by Government of India.[38] The geometry was modelled in SolidWorks[39] following details like body and wing outline[40] and cross-sectional profiles of the arm and hand wing[41] (Supplementary Material 1). All the morphological features like span, wing area, shoulder to wingtip length, and the frontal area were linearly scaled down. The total mass (m) of the system cannot be linearly scaled down as it shows an allometric relationship with wingspan (B) as shown in equation (1):[42]

$$B = 2.24m^{0.53} \tag{1}$$

All these features related to the Common swift-inspired bionic MAV were calculated and are tabulated in Table 1.

Wing beat amplitude: Henningsson et al.[40] extensively studied the kinematics of Common swift wherein wing beat kinematics were recorded by high-speed filming and was used for calculating frequency and amplitude of wing beat at different flight speeds. The basic kinematics of the bird was captured using a single camera setup filming at 60 frames per second, installed in the wind tunnel. Extracting data from the flight, in the present study, wing kinematics corresponding to 8 m/s was chosen for mimicking. At this velocity, the bird flies with an angular amplitude (2θ) of approximately 110 degrees (Figure 1).

Fore and Aft movement: During the flapping or wing stroke, the bird changes its stroke plane. The fore and aft movements of the wing were traced from the video of Common swift flying at 8 m/s in a wind tunnel (kindly provided by P. Henningsson, Lund University, on request). Frames from the video were extracted and the position of wingtip was marked. Every frame was overlaid so that the projected trajectory of the wing tip on the vertical plane was fitted by an ellipse. The ratio of minor to major axis of the ellipse was found to be 0.36 (Figure 2).

Table 1. Morphological features of Common swift and proposed MAV.

Sl. No.	Features	Common Swift	Proposed MAV
1	Span, B (m)	0.39	0.30
2	Total Mass, m (g)	38	22.5
3	Projected Wing Area, S_w (m^2)	0.015	0.012
4	Shoulder- wingtip, l (m)	0.178	0.137
5	Projected Frontal Area (m^2)	0.0017	0.0013

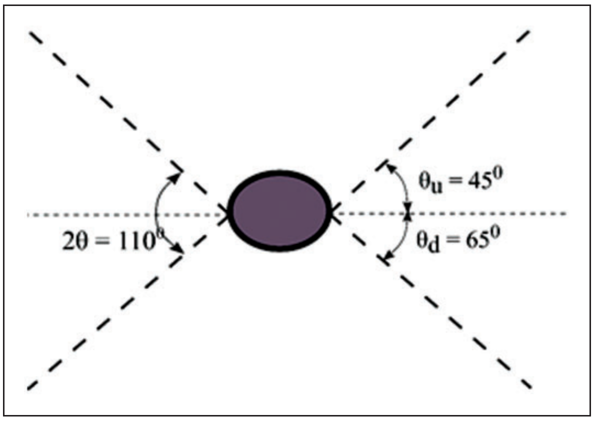

Figure 1. Amplitude of wingbeat: The Common swift has an unsymmetrical wing beat about horizontal plane, where the total wingbeat amplitude is 110°.

Wing rotation: It is notable that the skeleton of Common swift wing is different from that of other birds. The hand wing of Common swift is extremely long covering 75% of the total wing length. Moreover, the humeral joint allows normal vertical flapping motion and the angle at the elbow of the bird is virtually fixed (Figure 3(a)). The quantitative details regarding wing rotation in Common swift, to the best of our knowledge, is not available in the literature. Hence, as a design consideration, we assumed the rotation of arm part of the wing which is proximal to the body as almost equal to zero with respect to the body and that the hand part which is distant from the body rotates with respect to arm wing (Figure 3(b)). The approximate value of relative rotation between hand part and arm part was calculated using the frames extracted from the video of Common swift flying at 8 m/s in wind tunnel. Angles were calculated between hand wing and the body for the two frames: i) at the instant when the wing tip was at the level of the body during upstroke (ω_u) and ii) during downstroke (ω_d). It was found that the hand wing made an angle of 21.1 degrees with the body during the downstroke and −17.6 degrees during upstroke (Figure 4). With these geometric and kinematic details, a Common swift inspired flapping wing mechanism was developed.

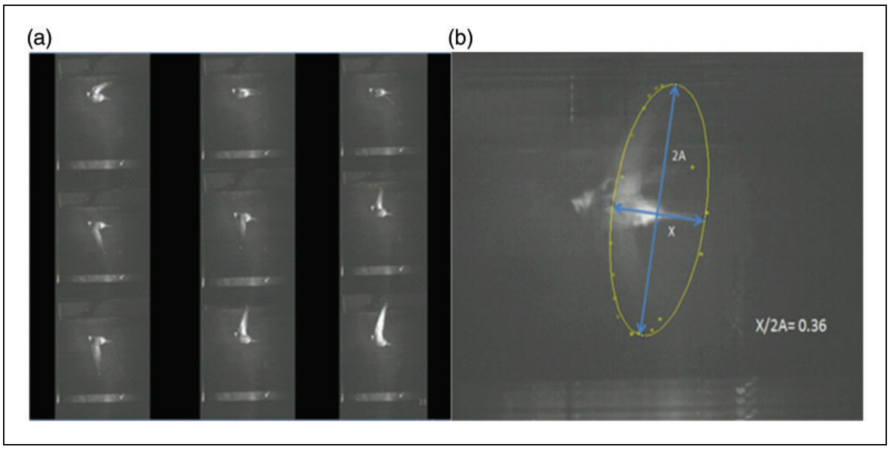

Figure 2. (a) Extracted frames with the wing tip position marked (b) Wing tip movement traced by compiling the frames and marking the trajectory.

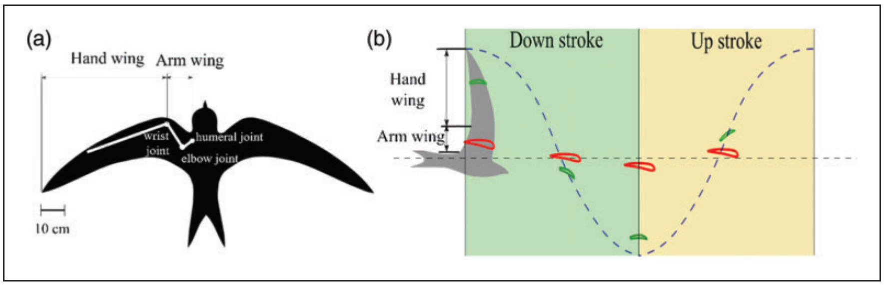

Figure 3. (a) Anatomy of the Common swift wing b) Rotation of distant part of the wing (hand) with respect to proximal part (arm) for one wing beat cycle. The dotted curve shows the trajectory of the wingtip. The red and green curves are the wing profile of the arm and hand, respectively, at different instances in a wing beat.

Results and discussion

Design of flapping wing mechanism

From flight kinematics of the Common swift, we formulated the design considerations for a novel flapping wing mechanism with the following features:

- *Flapping or vertical stroke*: The angular amplitude was assumed to be symmetric with respect to the horizontal plane with an equal duration for the upstroke and downstroke for the simplicity of the design.
- *Fore and aft movement or varying stroke plane*: Together with the flapping motion, the mechanism should facilitate fore and aft movement of the wing. Ideally, the wingtip should project an ellipse on the vertical plane.
- *Wing rotation or pitching*: The wing constitutes of two parts: arm and hand. The arm part closer to the body does not rotate with respect to the body during flapping. However, the hand which is distant from the body will rotate with respect to the arm – in the forward direction during the downstroke and in the backward direction during upstroke. The rotation was assumed to be symmetric in both downstroke and upstroke.

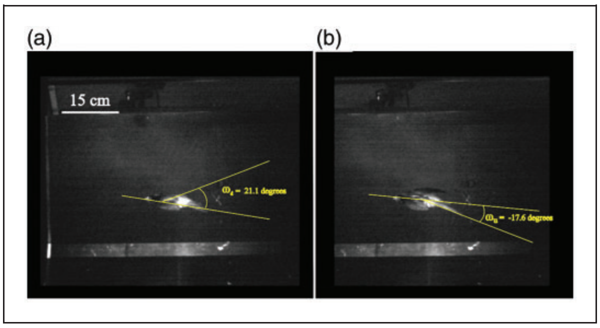

Figure 4. The inclination of the hand wing with respect to body when the wings are in the horizontal plane during a) downstroke and b) upstroke. This was measured using ImageJ software.

- *Single actuator*: Considering the strict weight constraints on MAV designs, the flapping motion, fore and aft motion, and the wing rotation were proposed to be coupled and happen through the transformation of rotary motion from a single motor.

With these considerations in mind, a new mechanism was proposed (Figure 5 and Supplementary Material 2). The mechanism consisted of two units: the driving unit and the flapping unit.

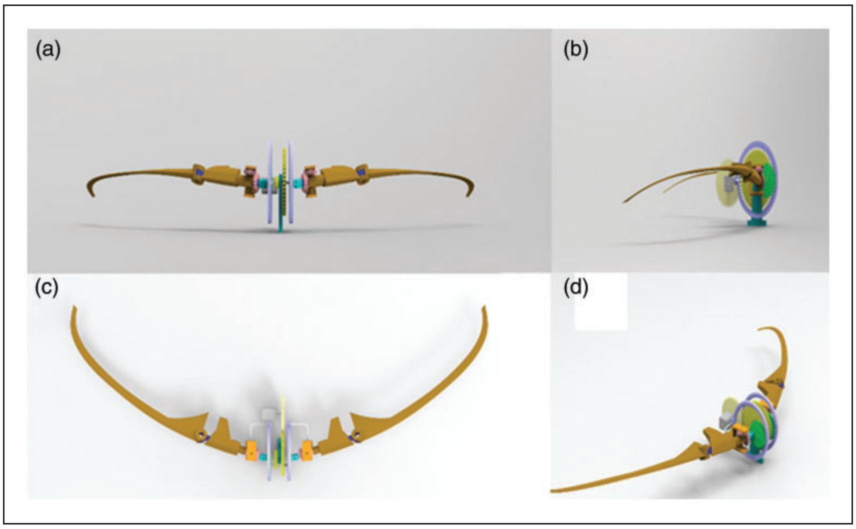

Figure 5. a) Front view b) side view c) top view and d) isometric view of the mechanism modelled in SolidWorks.

The driving unit discussed here was derived from an ellipsograph mechanism, i.e., one that generates an elliptical path. Among several ellipsograph mechanisms in the literature like elliptical trammel (trammel of Archimedes), Kleiber's ellipsograph, and the like, a simple ellipsograph in which ellipse is generated by the three-link mechanism is shown in Figure 6. This epicyclic mechanism, comprising gears G1 and G2 with radii r_1 and r_2 respectively, satisfies the condition $r_2/r_1 = 1/2$. Any point D such that $O_2D < r_2$, generates an elliptical path.[43]

The driving unit shown in Figure 7(a) consisted of a gear crank *C1*, spur gear *G2* and grounded internal spur gear *G1*. *C1* and *G1* were concentric about point O_1. *C1*, driven by a motor M through gear transmission, rotates about the revolute joint at O_1. The gear *G2* was hinged at its centre to *C1* at O_2. The length $O_1O_2 = d$ and the radius of gears *G1* and *G2* are r_1 and r_2, respectively. The relationship between d, r_1, and r_2 are as shown in equations (2) and (3):

$$d = r_2 \tag{2}$$

$$r_1 = 2r_2 \tag{3}$$

The point D on gear *G2* traced an ellipse as mentioned in Figures 6 and 7(a). The flapping unit was hinged at Q to grounded link *L3* which was fixed to the internal gear *G1* as shown in Figure 7(b). The flapping unit was connected to the driving unit through a clevis joint. Clevis eye, *L1* was connected to *G2* at D by a revolute joint. The clevis fork, *L2* was connected to the eye through the pin joint at P (Figure 7(c)). The shaft fixed on to the *L2*, slides concentrically inside the link *W* which was a hollow tube. The elliptical motion was transmitted from link *L2* in the driving unit to the link *W* in the flapping unit. The flapping unit assembly comprised of an

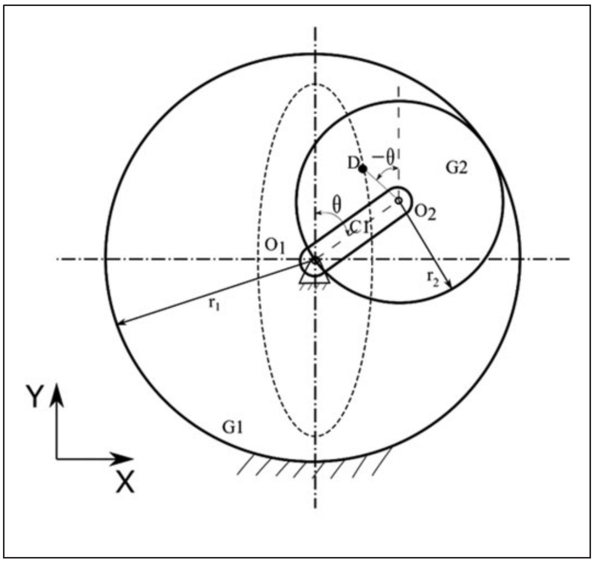

Figure 6. The schematic of epicyclic ellipsograph mechanism.

arm part; *A* and hand part; *H*. Arm part was connected to link *U* via revolute joint at R as shown in Figure 7(b). The bevel gears *B1* and *B2* were fixed onto links *U* and W respectively in order to attain a controlled rotation of *W* inside *A* which was placed coaxially. *W* and *H* were fixed together at S as in Figure 7(c). *H* was connected to *W* and they rotate together, allowing the rotation of hand part with respect to arm part.

All the components were mirrored about the vertical plane for the opposite wing except that the link *C2* was used instead of a gear crank *C1*. *C1* and *C2* were fixed to a same shaft and connected to the grounded revolute joint which rotated about *g-g* axis which pass through O_1, i.e., through the centres of *C1* and *G1* as shown in Figure 7(b).

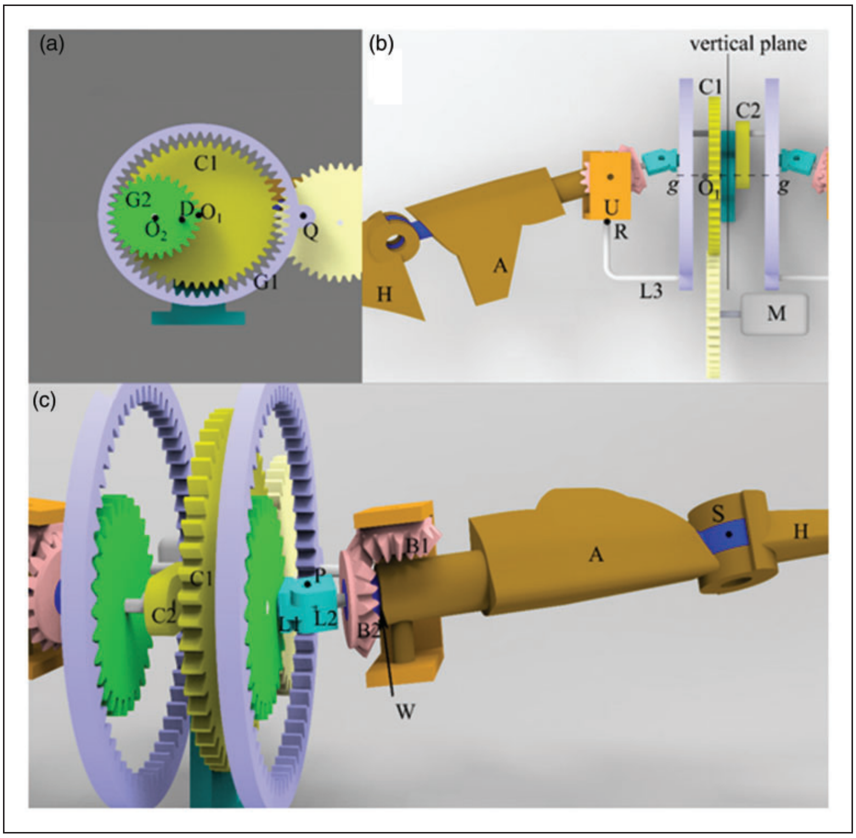

Figure 7. Working of Flapping Wing Mechanism: a) epicyclic driving unit b) flapping unit hinged at Q on a grounded link L3 c) connection of driving unit and flapping unit through a hinge and arrangement of bevel gears for the rotation of hand wing. The gears were designed according to the ones in ISO 54.[44]

Kinematic model

For the kinematic analysis and thereby choosing the design parameters, a kinematic model was developed. The gear ratio of the epicyclic system is as in equation (4)

$$\frac{\omega_2 - \omega_a}{\omega_1 - \omega_a} = \frac{T_1}{T_2} \tag{4}$$

where, ω_1, ω_2, and ω_a are the angular velocities of gear *G1* with T1 teeth, *G2* with T2 teeth, and crank *C1*, respectively. The gear ratio between *G1* and *G2* (T2/T1) is 0.5 and the value of ω_1 is 0 (gear *G1* is fixed). Hence, the relationship between ω_2 and ω_a is as in equation (5);

$$\omega_2 = -\omega_a \tag{5}$$

The trajectory of ellipse traced by the point D in x and y co-ordinates with O_1 as origin is given by the equations (6) and (7):

$$x_D(t) = r_2 sin(\theta) + O_2 D sin(-\theta) \tag{6}$$

$$y_D(t) = r_2 \cos(\theta) + O_2 D cos(-\theta) \tag{7}$$

where, θ is the angle of rotation of crank *C1* (Figure 6). Differentiating $x_D\ (t)$ and $y_D\ (t)$ with respect to time, the velocity of D in x ($u_D\ (t)$) and y ($v_D\ (t)$) directions were obtained as given by equations (8) and (9).

$$u_D(t) = r_2\omega_a \cos(\omega_a t) - O_2 D\omega_a \cos(\omega_a t) \tag{8}$$

$$u_D(t) = -r_2\omega_a sin(\omega_a t) - O_2 D\omega_a sin(\omega_a t) \tag{9}$$

When the point D moves in the elliptical path, the wing oscillates in vertical (flapping) and horizontal (fore and aft) directions. For any instantaneous position of D, the wing makes an angle about point R in vertical (θ_V) and horizontal (θ_H) directions (Figure 8). The geometric relationship between the trajectory of the point D and these angles are given by the equations (10) and (11):

$$\frac{x_D(t)}{k} = tan(\omega_H t) \tag{10}$$

$$\frac{y_D(t)}{k} = tan(\omega_V t) \tag{11}$$

where, k is the perpendicular distance from the face of the gears (*G1* and *G2*) to the revolute joint R. The ω_V

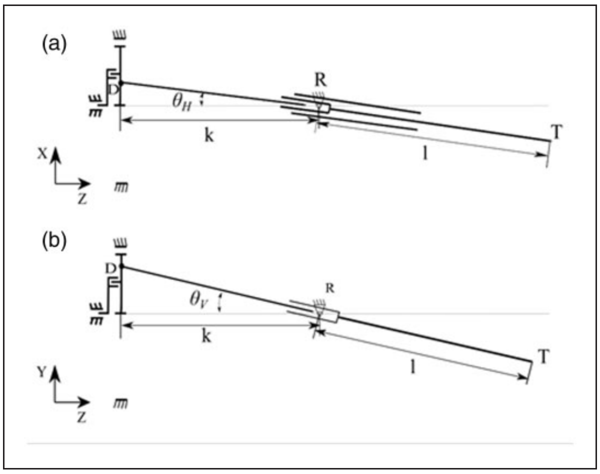

Figure 8. The schematic of the mechanism in XZ and YZ plane.

and ω_H are the angular velocity of wing stroke (flapping) and variation in stroke plane (fore and aft), respectively. Here, angles θ_V and θ_H are related to angular velocities by the relations $\theta_V = \omega_V t$ and $\theta_H = \omega_H t$, where t is the time.

The x and y coordinates of the wing tip are given by the following equations (12) and (13):

$$x_T = l sin(\omega_H t) \tag{12}$$

$$y_T = l sin(\omega_V t) \tag{13}$$

where l is the shoulder to wing tip length (Figure 8). Differentiating x_T and y_T with respect to time, the velocity of the wing tip in these directions were obtained as given by the equations (14) and (15).

$$u_T = l\omega_H cos(\omega_H t) \tag{14}$$

$$v_T = l\omega_V cos(\omega_V t) \tag{15}$$

In any mechanism, there are design and control parameters. In this mechanism, angular velocity of the crank was the control parameter. In order to flap the wings with predefined geometry and trajectory, few design parameters have to defined. These parameters are k, O_2D, r_2, and the gear ratio of the bevel gears. By choosing their proper values, we could achieve the desired kinematics. These parameters were calculated using the following two relations given by equations (16) and (17).

$$\tan^{-1}\left(\frac{r_2 + O_2D}{k}\right) = sin^{-1}\left(\frac{A}{l}\right) \tag{16}$$

$$\tan^{-1}\left(\frac{r_2 - O_2D}{k}\right) = sin^{-1}\left(\frac{X/2}{l}\right) \tag{17}$$

Table 2. The geometric and design parameter values.

Geometric parameters (cm)		Design parameters	
X	8.1	r_2 (cm)	0.70
A	11.2	OD_2 (cm)	0.46
l	13.7	k (cm)	0.81
		T_{B1}/T_{B2}	1

where A is the amplitude of wing stroke and X/2 is the amplitude in variation in wing stroke plane (Figure 2). Since there are three unknowns in two equations, we could fix a plausible value for r_2 and solve for k and O_2D. The rotation of the hand part depends on θ_H and the gear ratio of bevel gears *B1* and *B2*. The relationship between wing rotation (θ_W), $\theta_{H,}$ and gear ratio is as in equation (18).

$$\theta_W = \frac{T_{B1}}{T_{B2}}\theta_H \tag{18}$$

where, T_{B1} and T_{B2} are number of teeth in gears *B1* and *B2*, respectively. Desired wing rotation was achieved by selecting appropriate gear ratio (T_{B1}/T_{B2}). The geometric parameters *X, A,* and *l* were chosen as in Table 2. The values of other geometric and design parameters were calculated and are shown in Table 2. The design parameters were calculated using the equations (16) to (18).

Kinematic simulation

The mechanism was simulated using SolidWorks Motion solver, using the option *Motion Analysis*.[39] The variation of wing beat angle, fore and aft movement and hand wing rotation are shown in the Figure 9. They are shown from the beginning of the down stroke with one complete wingbeat cycle. The path of the wing tip was traced and is shown in the Figure 10.

Wing kinematics can describe the force production of the flapping wings. Figure 11 shows the position of the hand and arm wing in the global coordinate system with qualitative force production at mid-downstroke and mid-upstroke. Assuming the MAV to be horizontal to the global X-Z coordinates, the angle of attack is zero for arm wing during downstroke and upstroke since it does rotate with respect to the body. Therefore, the arm wing generates lift throughout the wingbeat cycle due to its aerofoil profile.[41] The angle of attack is positive for the hand wing during downstroke. Along with the lift, a component of the force is also used to generate thrust. The angle of attack of the hand wing is negative at upstroke, and the overall force on the section points downward and forward. This kind of force production is similar to that of hummingbird and swift, whose advance ratio (the ratio of flight speed to the wing tip velocity) is close to one and with constant span throughout the

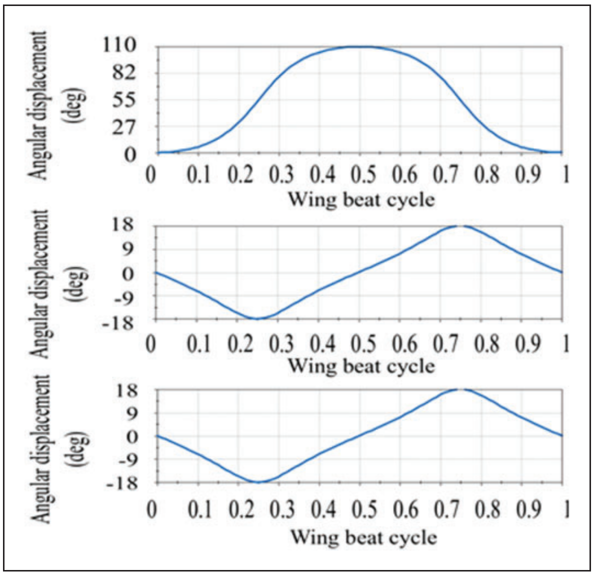

Figure 9. The variation of key kinematic parameters in one wingbeat cycle a) wing beat amplitude b) fore and aft angular displacement, c) and wing rotation.

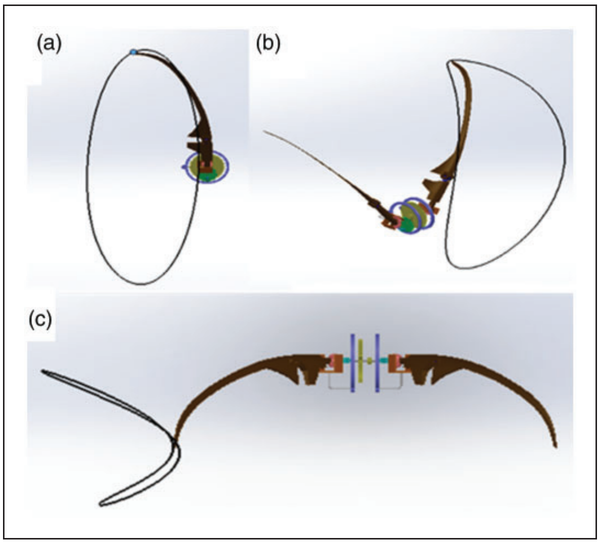

Figure 10. The trajectory of the wing tip a) side view b) isometric view, and c) top view.

wing beat cycle.[45] In addition to this, sharp leading edge of the hand wing can generate lift due to vortex generation.[37]

Discussion

The proposed mechanism is capable of mimicking all the key aspects in the kinematics of Common swift flight i.e. fore and aft movement, wing rotation, and elliptical trajectory of the wingtip. There are several advantages for the mechanism in terms of complexity (control input, number of links, mechanical joints) and performance (kinematics like wing trajectory, wing rotation, and varying stroke plane).

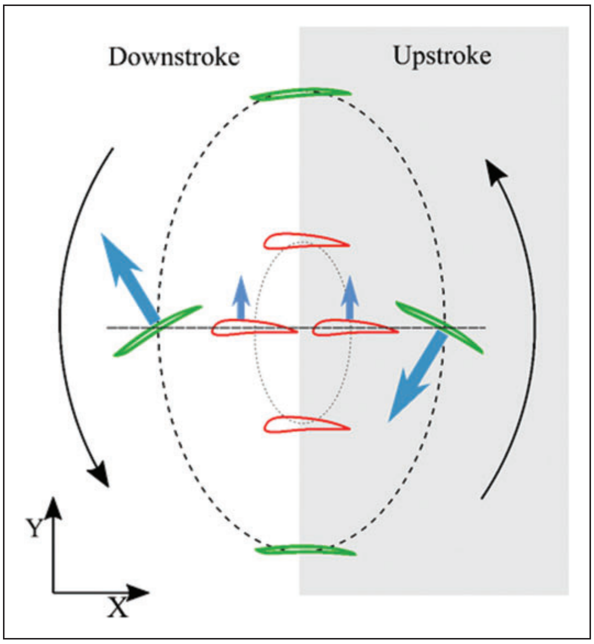

Figure 11. The force production at mid-downstroke and mid-upstroke at different wing section. The profile of hand wing and arm wing are described in green and red colour along the path traced (dashed ellipse) by them.

A fully constrained mechanism offers a reduction in control complexities. The mechanism has to be driven by a single rotary actuator, preferably a miniaturised DC brushless motor. Fully constrained mechanisms often lead to complexities in mechanical design.[31] In the fully constrained mechanism we designed, with an epicyclic ellipsograph mechanism as the drive unit, both flapping and fore and aft movements were achieved by a simple three link mechanism. With the proposed design, we were able to produce the desired kinematics with 2 pairs of bevel gears, 2 pairs of epicyclic gears, 2 prismatic joints, and 15 revolute joints. The planar motion of the driving unit was converted to the spatial motion of the flapping unit with a slider joint that connects both. Using bevel gears for transmitting rotation to the wings helped to confine the mechanism to small space. The three-dimensional motion of the mechanism was achieved only by using revolute and prismatic joints as well as spur and bevel gears.

The active rotation can be achieved either by using a separate actuator or by a kinematic chain to transfer the motion. Using two actuators, one for rotation and another for flapping, is a definite disadvantage considering the strict size and weight constraints on an MAV. The Common swift rotates only its hand wing keeping the pitching of the arm wing constant during the entire wingbeat cycle. This selective rotation/pitching of a section of the wing coupled with flapping, as seen in the proposed mechanism was not reported in the literature before. There are several mechanisms that combine flapping motion with

Table 3. Comparison of the proposed mechanism with slider crank and modified slider crack mechanism.

Features	Slider crank mechanism	Modified slider crank mechanism	Proposed flapping wing mechanism
Number of actuators	1	1	1
Spatial configuration	2D	3D	3D
Wing rotation	Passive	Active	Active with selective wing rotation
Stroke plane	Fixed	Fixed	Varying within each stroke

pitching motion. In the proposed mechanism, we effectively combined flapping motion with selective wing rotation as well as fore and aft movements. A comparison of kinematic features of the proposed flapping wing mechanism with slider crank and modified slider crack mechanism[24,46] is presented in Table 3.

With a fixed wing trajectory, the mechanism could perform all the desired movements with the proposed novel kinematic chain. Hence, the only control parameter in the mechanism is the wingbeat frequency. The amplitude and wing rotation/pitching can be modified by changing the design parameters r_2, O_2D, k, and T_{B1}/T_{B2}. The trajectory of the wing tip (Figure 10) could be also controlled in real time with an additional linear actuator changing the length of link $L3$ which with change the value of design parameter, k. In the present analysis, we chose $T_{B1}/T_{B2} = 1$, which resulted in the variation of stroke plane and the wing rotation to be equal. With different gear ratios (T_{B1}/T_{B2}), various wing rotations (rotation of hand with respect arm) can be achieved.

The kinematic and aerodynamic studies of free-flying birds are limited. The aerodynamic consequences of various kinematics seen in birds are still unclear. A bioinspired MAV can contribute back to biology in the fields such as biomechanics, neuroscience, and aerodynamics. It can be used to test hypotheses about the underlying interactions of body, control, and environment.[47]

Conclusion

The present article describes the efforts targeted at the design of a novel flapping wing mechanism towards the objective of developing bionic MAV whose capabilities will more closely resemble that of Common swift. Kinematic and morphological features for the study were collected from the literature as well as extracted from the video of the bird flight in the wind tunnel. These provided the design specification for the flapping wing mechanism. A novel flapping wing mechanism based on epicyclic ellipsograph mechanism was designed and simulation of motion analysis was performed. The simulated results matched with expected kinematics of the mechanism. The proposed kinematic model was used to calculate design parameters in the mechanism and offers the advantage of scalability in MAV design. To its credit, this fully constrained mechanism used the minimum control effort by just using single actuator without compromising on the kinematic performance. Adding further to its uniqueness, with the novel kinematic chain, the mechanism was able to perform all the three basic kinematics: vertical stroke (flapping), varying stroke plane (fore and aft movement), and pitching (wing rotation), where all the movements were coupled to a single kinematic chain. These results constitute the first steppingstones in the long term goal towards fully manoeuvrable bionic MAV. Successful design and simulation have set a strong premise for further studies on dynamic analysis and fabrication of the mechanism.

Article highlights

- Design of flapping wing mechanism inspired from the kinematics of Common swift
- Integrates flapping motion, fore and aft motion and selective wing rotation.
- Fully constrained mechanism allows performing all the key kinematic motions of the common swift with a single actuator.

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Supplemental material

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