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Design and Development of a Bio-Inspired Flapping Wing Type Micro Air Vehicle

Sachin Mishra[a,*], Dr. Brajesh Tripathi[a], Sahil Garg[a], Ajay Kumar[a], Pradeep Kumar[a]

[a]*School of Engineering, Gautam Buddha University, Greater Noida -201312, Uttar Pradesh, India*

Abstract

This paper presents the design and development of a bio-inspired flapping wing type Micro Air Vehicle (MAV). Bio-inspiration is implicated to design a flapping wing aerodynamic ornithopter, controlled using a micro scale integrated on- board electronic circuits and communication device. The study of flapping flight from an experimental standpoint brought insight into the lift-generating mechanisms produced during flapping. These vehicles are meant to address a large number of civilian and military applications including intelligence, surveillance and reconnaissance. A First Person View (FPV) approach is utilized to wirelessly pilot the vehicle and for surveillance. The integrated system concludes to present a multidimensional approach to design, develop and control a micro scale aerial vehicle for deployment.

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Keywords: Aerodynamics; Bio-Inspiration; Ornithopter; Surveillance.

1. Introduction

An Unmanned Aerial Vehicle (UAV), colloquially known as a drone, is an aerial vehicle without a human pilot on board, having flight controlled either autonomously by computers in the vehicle, or under the remote control of a pilot on the ground or in another vehicle [Lian et al. (2008)]. The MAV is defined as a vehicle with a maximal dimension of 150 mm or less, comparable to the size of small birds, and a flight speed of 10–20 m/s [McMichael et al. (1997)]. Flapping wing MAVs are latest research hotspot as a result of bio –inspiration. The design of MAV in Fig. 1, named as Falcon, as presented in this research, is a 24.0 gram ornithopter. Falcon MAV is designed and developed as bio-robotic surveillance equipment with integrated communication and control devices.

* Corresponding author. Tel.: +91-9910891068.
E-mail address: sachinmishra92me@gmail.com

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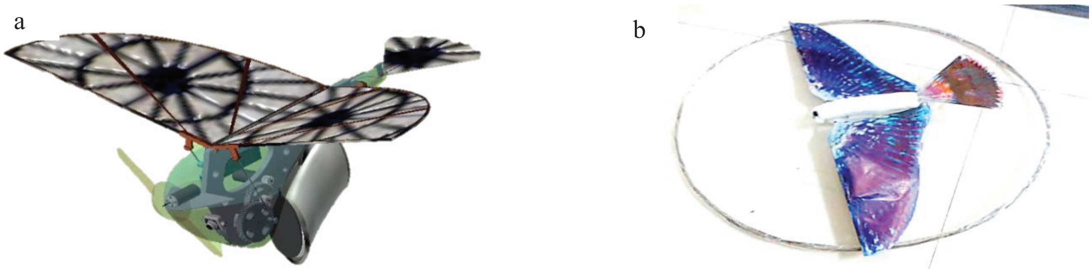

Fig. 1. (a) Falcon MAV Design; (b) Falcon MAV Prototype

These vehicles present various civilian and military applications in the field of surveillance and reconnaissance with a video camera and sensors equipped on it. Scaling, flapping flight and aerodynamic behaviours are studied as bio-inspiration and envisaged in the design of MAV Falcon. With an interdisciplinary approach, the integrated output of structural and material engineering, aerodynamics, control system and electronics are utilized to design and develop the discussed aerial vehicle. Essentially, there are two main approaches to create small autonomous ornithopter: bottom-up and top-down. The design of Falcon resembles bottom- up approach. It is modelled as a collection of three rigid bodies (a central body, two wings and a tail). The wings and tail have prescribed motions relative to the central body, i.e., they are kinematically driven. The numerical integration of all the governing equations, which are differential-algebraic, is performed simultaneously and interactively in the time domain.

Nomenclature

K_L	aspect ratio coefficient
S_W	area of wing
ρ	density of air
σ	Strouhal number
v	velocity of the wing through the air
β	positive angle of attack
f	flapping frequency
μ	Kinematic viscosity
L	dimensional length
F_L	lift force
C_L	coefficient of lift
α	angle of attack
A	aspect ratio of the wing

2. System Design

For designing Falcon MAV, the inspiration was taken from birds which creates lift by flapping its wing and navigates through its tail. For this, intensive study of birds was done for design and aerodynamics [Lian et al. (2008)]. Weight reduction was done for optimized flight with strength to fulfill the surveillance requirement.

Two existing ornithopter concepts were studied. The first concept was a simple monoplane with one set of wings. The second was a biplane concept where two sets of wings were placed above each other. These wings moved in counter phase on a common rotational axle. Both concepts were studied with respect to the flight speed, the power consumption, and the stability of the ornithopter body during flight. Since Falcon was to be designed for hovering and gliding also, the monoplane concept was selected for low weight and dimension. But due to high rocking amplitude of monoplane in fuselage, it is less suitable for camera platform.

2.1. Flapping Flight

The structural movement and the resulting unsteady fluid dynamics of flapping flight present a more complicated situation in design. The flapping mechanism produces both, lift and thrust [Linton (2007)] as shown in Fig. 2. During flapping, in down stroke, 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. The thrust is produced as a forward component of inclined force of wing lift during upstroke and down stroke.

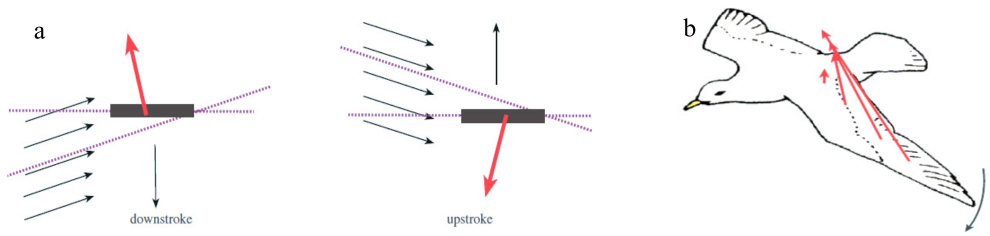

Fig. 2. (a) Flapping Wing Thrust (b) Flapping Wing Lift in down stroke

By considering the non-flexible characteristics of wing motion to be designed, the mean lift force calculation [Linton (2007)] is based on eq. (1) as

$$Thrust = \frac{1}{3} K_L S_W \rho \sigma^2 v^2 \tag{1}$$

In order to keep the vehicle in flight, lift force is required to be created by flapping. It is done by using a positive angle of attack, β. The mean lift force calculation is based on eq. (2) as

$$Lift = \frac{1}{2} K_L S_W \beta \rho v^2 \tag{2}$$

Strouhal number plays an important role in flapping flight which should be in the range of 0.2–0.4, and for birds in cruising flight it is almost always nearly equal to 0.2 [Linton (2007)]. For our design, the value of 0.2 was selected for calculations with the Strouhal angle [Taylor et al. (2003)] of 22°. The work done in pushing the bird through the air is simply the thrust multiplied by speed given in eq. (3) as

$$Power = \frac{1}{6} K_L S_W \sigma^2 v^3 \tag{3}$$

By putting the values for a speed of 15 m/s and calculating for an expected weight of 25 gram with K_L as 5, the thrust is coming out to be 0.48N, lift is 31grams and power is 2.80W for the design.

The effects of different parameters, such as wing area and wingspan, on the flight characteristics, based on dimensional analysis is done for scaling of aerial vehicle. First, the balance between lift and weight during steady state flight is considered for calculation. The flapping frequency scaling is done based on eq. (4) obtained by comparing Reynolds number and Strouhal number calculations [George et al. (2012)].

$$f_{scale} = \left(\frac{\mu_{scale}}{\mu_{bird}}\right)\left(\frac{L_{bird}}{L_{scale}}\right)^2 f_{bird} \tag{4}$$

For a bird like falcon, the values in the above equations were put and the scaling was done to fit with size of a Micro air vehicle of 300mm maximum dimension to be designed.

2.2. Aerodynamics

The MAV is designed to be highly aerodynamic, optimizing the lift and drag force thus providing high endurance. The CFD approach is followed through analysis in Autodesk Simulation CFD Software. During flapping flight, the wing moves forward through still air and thus the air exerts a force on the wing. The force generated on wing due to this have further two components, lift force and drag force [Lian et al. (2008)] as shown in Fig. 3(a).

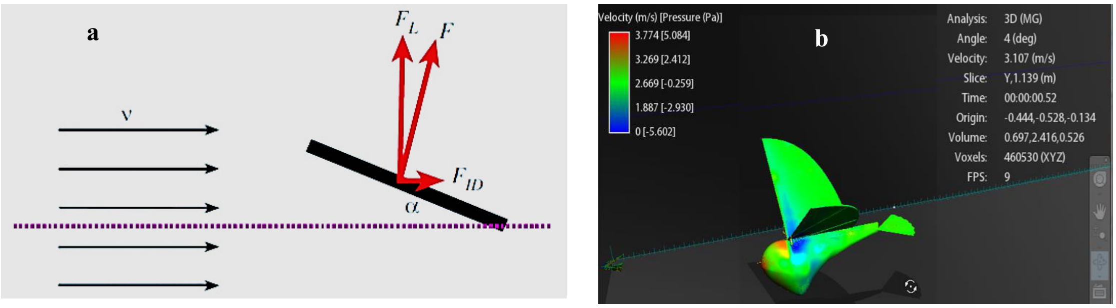

Fig. 3. (a) Force on wings in flight; (b) CFD flow analysis of design

The value of lift force is given by eq. (5) and coefficient of lift as shown in eq. (6). Also the value of coefficient of lift varies with angle of attack.

$$F_L = \frac{1}{2} C_L S_W \rho v^2 \tag{5}$$

$$C_L = \frac{2\pi\alpha}{(1+2/A)} \tag{6}$$

The aerodynamic coefficients was calculated using the equations and the flow over CAD model of the design was analyzed using Autodesk Falcon software as shown in Fig 3(b).

2.3. Structure and Powertrain

The fuselage as shown in Fig. 4(a) is the base frame which supports other parts. It is made of carbon fiber reinforced plastic. The flapping mechanism gears and motors are mounted on the bottom side. Wings are hinged on the top side. In the front, camera and other sensors and the propeller motor is attached. Slots are cut in the frame to reduce the weight from unwanted area. The frame is supposed to be of constant layup and thickness throughout the entire area. The modeling of frame is done in Autodesk Inventor software.

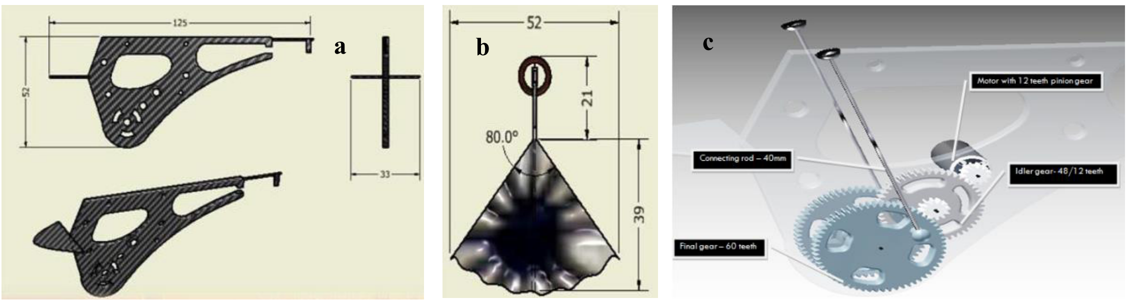

Fig. 4. (a) Fuselage design; (b) tail design; (c) drivetrain design

For analyzing the composite frame, the Composite Layup Manager Tool of Abaqus Software is used. The tail as shown in Fig. 4(b) is designed to be actuated by magnetic actuator to control the navigation of vehicle. To generate effective lift and thrust, powertrain as shown in Fig. 4(c) is designed with gears driving a crank mechanism. The mechanism uses gear train of pinion gear to achieve desired rpm and thus the flapping frequency. A BLDC motor of diameter 6mm and length is used which provide up to 50000 rpm. The module of the gear is 0.3.

2.4. Electronics and Control

Falcon is a light weight MAV which is possible only by using light weight electronics component. The control loop, shown in Fig. 5(a), starts with collecting all the sensor and video data, and they are streamed back to the ground station from on-board computer. After these data are processed, control commands are sent back to the MAV by a custom interface and the trainer function on Xbee Transreciever which allows switching between computer and human control instantaneously.

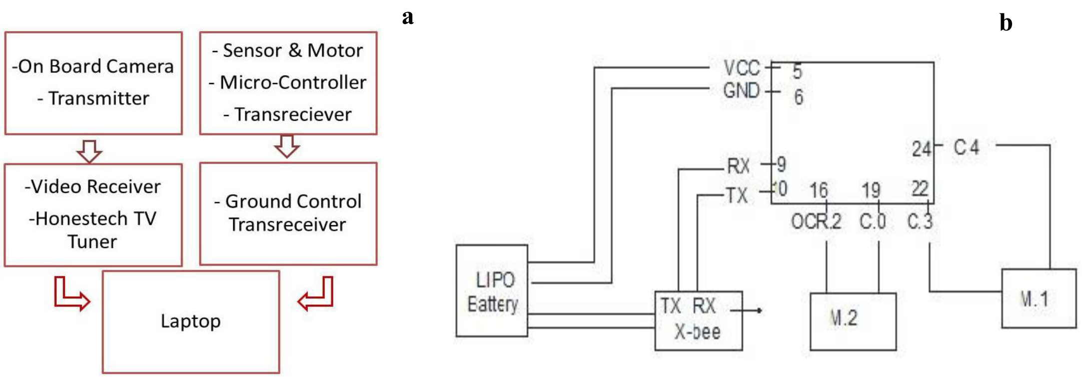

Fig. 5. (a) Control loop diagram; (b) on-board circuit diagram

Falcon's flapping mechanism is achieved by using a Nano DC Brushless motor from Precision Microdrive's which is connected to the pinion gear. The motor is of high torque and high RPM such that creating a flapping frequency of 17Hz which is adequate for the Falcon to fly. The direction control of the MAV is governed by the Nano DC coreless motor. The Microcontroller placed as in Fig. 5(b), used to control these Nano DC Coreless motors is Atmel's Atmega 16L for its small size and inbuilt PWM Ports hence eliminating the use of motor controlling IC, reducing the weight of falcon MAV.

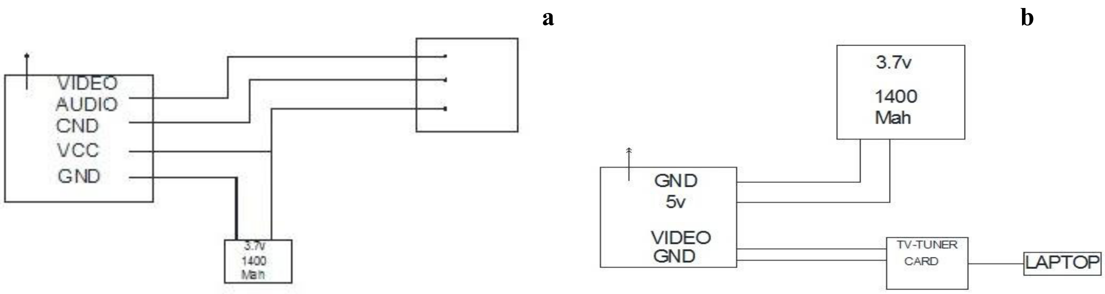

Fig. 6. (a) MAV FPV system; (b) base station receiver circuit

Since the MAV is used for surveillance, camera of 5.8 GHz with inbuilt microphone is present for FPV communication as in Fig. 6(a). To meet the power consumption of the electronic system on MAV, LiPo batteries are used as they have a long life and better power to mass ratio. TV Tuner card is used which is using Honestech TVR 2.5 Software on Ground Control Station for receiving the video and audio as in Fig. 6(b). The Wireless module is being controlled by X-CTU Software on the laptop.

3. Prototype Development

The design was developed for testing and further use through micro scale manufacturing techniques and system integration to reduce weight of the aerial vehicle. The development of prototype is achieved by structural development, actuation and control system development and system integration.

3.1. Structural Development

The base frame, as shown in Fig. 7(a) supports the other parts. It is made of carbon fiber reinforced composite. The flapping mechanism gearbox and motors are mounted on the top front side. Wings are hinged with the gearbox and frame. In the front, camera and other sensors are attached. Slots are cut in the frame to reduce the weight from unwanted area. The frame was made using computer laser cutter and then after that finalized on milling machine. The overall weight of the frame is 3gram. The frame is made compact to accommodate all the components.

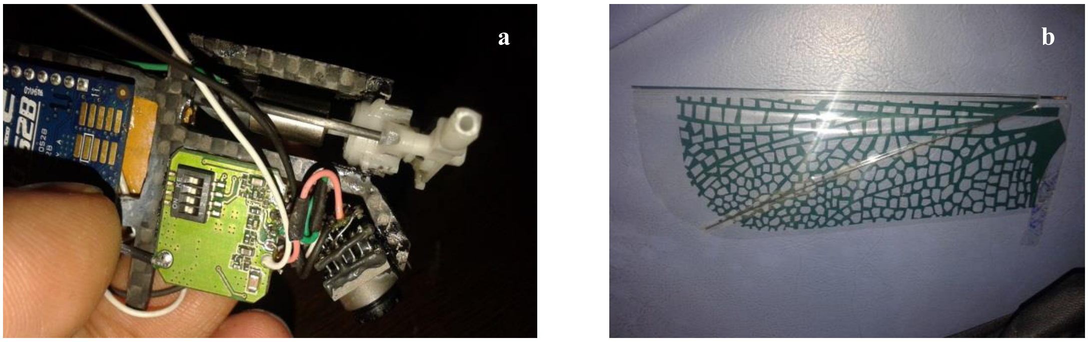

Fig. 7. (a) Base frame with integrated systems; (b) Mylar foil wings

With a total wingspan of 300mm, the two flapping wings as shown in Fig. 7(b) provide maximum lift force to uplift falcon with payload. The material consisted of 6 microns Mylar foil which is biaxial- oriented polyethylene terephthalate polyester film. This material is high strength and very easy to process, light weight and very strong and stiff. The wings are provided with carbon fiber ribs in order to provide stiffness and create appropriate lift. The outer body of the MAV is made of polystyrene to provide rigidity and aerodynamic behavior.

3.2. Actuation and control system development

There are two main components for the flight control system, the ground station and the on board circuit. The ground station receives and transmits visual and control data to and from the MAV. It consists of a transceiver, a 15-inch laptop, a Honestech TV Tuner Card with receiver, and a USB converter. The custom on board computer, modified from an Atmel microcontroller, provides all of the data communication with the ground station as shown in Fig. 8(a). It is only 2 x 1.5 x 0.5 cm in dimension and weights 5 grams.

There is a 2.4GHz Xbee transceiver as shown in Fig. 8(b) interfaced to the Micro-controller to provide data link to the ground station at up to 250kbps data rate. The entire system is controlled by X-Bee Pro S2B wireless module which provides a wireless range of approximate 1600m. The PAN ID is 23 for the wireless module that is used for Falcon. Thus this wireless module will not cause any interference with any other frequencies persisting in the area, making it a secured wireless communication.

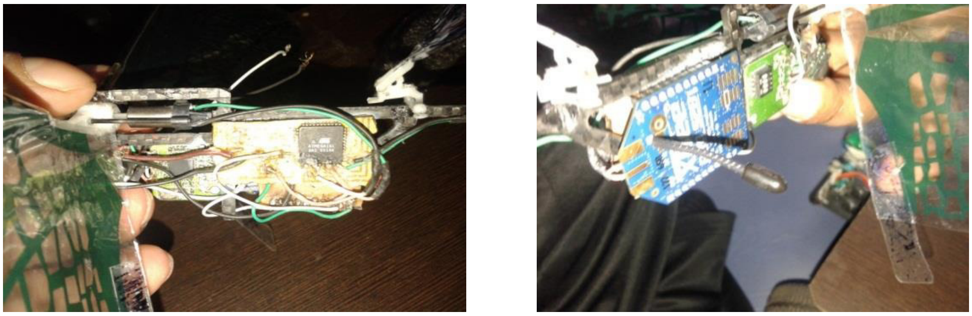

Fig. 8. (a) Circuit board on MAV; (b) Transreciever on MAV

The MAV is equipped with a 5.8 GHz wireless camera which has a range of about 1.5 km as shown in Fig 9(a). This camera has an overall weight of 1gram and with video transmitter, as in Fig. 9(b), the total weight is 4 gm. This camera is compatible with a microphone which also exhibits the range of 1.5km. Camera is equipped with night vision lens to have clear video transmission during low light also. At the ground control station the video receiver as shown in Fig. 9(c) is interfaced with the Honestech TV tuner card. The programming of the microcontroller has been carried out on BASCOM software. Further this programming has been burnt on the microcontroller with the help of AVR Dude Software. Table 1 shows the final design and performance specification of developed prototype.

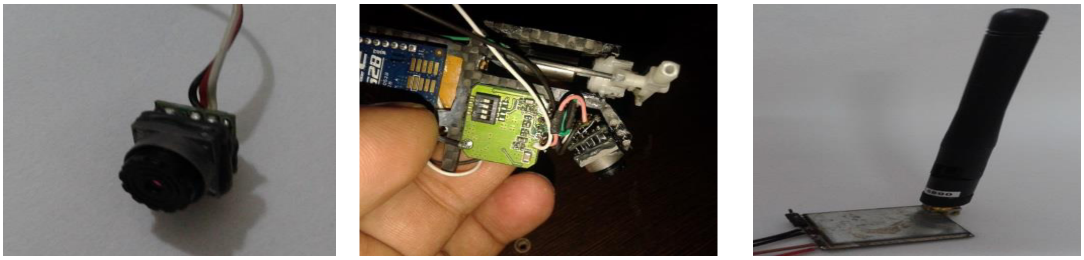

Fig. 9. (a) On-board camera; (b) FPV transmitter board; (c) FPV receiver board

Table 1. Design and Performance specification of developed prototype

Characteristics	Description
Type	Flapping Wing
Dimension (L*B)	131mm * 320mm
Overall weight	24 g
Wing Span	300mm
Flapping Frequency	17 Flap / Sec
Wing amplitude angle	55°
Material Selection	Carbon Fiber Frame of 2mm Thickness
Flight Mechanism	Gear Box with Flapping Output
Processing and Controlling	Atmega 16L with built-in PWM ports
Communication Details	X-bee Pro Wireless Module With 1600 m Range
Telemetry	5.8 GHz Camera with inbuilt Microphone
Power House	Li-Po Battery of 3.7 Volt and 1000 mAh
Endurance	15 Minutes

4. Conclusions

With a discussion on design and development of Falcon MAV, it can be seen that enhancement in the capabilities of micro air vehicle will always remain an area of thirst. The technology development in this field is drastically increasing which will further increase the surveillance capabilities. It can be concluded that the present design and development of micro air vehicle is a result of Bio- Inspiration and micro-scale electronics integration technology. The design and developed prototype on one hand offers flapping type bio-robotic surveillance equipment and on the other hand, provide a micro scale integrated on- board electronic circuits and communication device for piloting the aerial vehicle. Future works will include implementation of hovering capabilities and autonomous flight.

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