

Bio-inspired Flapping UAV Design: A University Perspective

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ABSTRACT

Bio-inspired design to make artificial flappers fly does not just imitate biological systems as closely as possible, but also transferring the flappers' own functionalities to engineering solutions. This paper summarizes some key technical issues and the states-of-art of bio-inspired design of flapping UAVs with an introduction to authors' recent research results in this field.

Keywords: Bio-inspired, Flapping-wing, Aerodynamic Model, Fluid-Structure Interaction, Flight Dynamics

1. INTRODUCTION

The flapping flight of birds, bats, and insects has fascinated many researchers in various fields such as biology, zoology, aerodynamics, and electronics because of their highly efficient maneuverability and aerodynamic benefits especially in a low Reynolds number flight regime. For many centuries, numerous efforts have been made to mimic nature's fliers in order to make artificial flapping-wing vehicles. It is well known that most of the early trials for "flying machines" adopted flapping mechanism for generating thrust and/or lift; typical examples of the early design of flapping vehicles can be seen in the sketches of da Vinci and Cayley. It seemed that the flapping vehicles were being forgotten with the great success of fixed wing aviation. However, we now see the rebirth of flapping flying machines in much smaller devices, namely flapping unmanned aerial vehicles (UAV). Equipped with a small video camera and various sensors, they can be used for surveillance and reconnaissance missions with quite perfect camouflage due to their inherent natural like shapes. More difficult or complicated technology issues are involved in the development of flapping UAV compared with their fixed or rotary wing type counterparts. In terms of payload carrying capacity and flight controls, the current flapping UAV need to be further improved. Birds and insects are the most efficient and outstanding flying objects, resulting from over 150 million years of evolutionary processes. However, bio-inspired design to make artificial flappers fly does not just imitate biological systems as closely as possible, but also transfers their own functionalities to engineering solutions.

This paper summarizes some key technical issues and the state-of-art of bio-inspired design of flapping UAV with the introduction of the author's recent results in this field. As with all other engineering, the development of integrated system engineering is essential for the development of successful flapping UAV, and the following items should be considered: 1.) an efficient aerodynamic model for low Reynolds number flow, 2.) design considering fluid-structure interaction, 3.) a bio-inspired design of flapping-wing motion mechanism, 4.) robust flight navigation and control, and 5.) miniaturized electronics and a micro power source. These items are in many cases tightly linked to each other. One typical example is the structural flexibility of a flapping-wing. Actually, biological flyers, especially insects, have spanwise-chordwise anisotropic flexible wings, and use complicated wing motions, such as flapping, twisting, folding, or rotating motions. The artificial flyers also have very thin and flexible wings structurally similar to those of the nature's flyers, but they use mainly the flapping and passive twisting motions generated by the wing flexibility. The deformation of these flapping wings is strongly coupled with aerodynamic forces generated by the wing motion. At the same time, the structural deformation and the resulting flexible wing aerodynamics strongly influence the flight stability and controllability of flapping UAV.

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2. KEY TECHNICAL ISSUES TOWARD A FLAPPING UAV

The preliminary design of flapping UAVs is quite different from those of fixed- and rotary-wing aircrafts. For conventional aircrafts, we started design with the assumption of cruising flights or trimmed flight conditions which require an aircraft to satisfy “the forces and moments equilibriums” without any continuous control efforts. For example, the weight of an aircraft is equal to the lift of the main wing, and the lift is determined by $L=W=1/2\rho V^2 SC_L$. Here C_L , V , and S represent the lift coefficient of the wing section (airfoil), the operating flight speed, and the wing area, respectively. The lift coefficient of a fixed-wing aircraft is proportional to the angle of attack, and theoretically it is known as $2\pi\alpha$ for a small angle of attack. Many aerodynamic researchers have designed various airfoils for specific mission requirements and tested them in wind tunnels to get the precise coefficients of lift, drag, and moments up to the stall boundary. These values are sensitive to the changes of the Reynolds number, airfoil, aspect ratio, etc. In addition, the wing motions such as plunging and pitching significantly affect the aerodynamic coefficients.

Helicopters rotate their rigid (or moderately flexible) and high aspect ratio wing with high rotational speed to generate enough force. Blade element theory or blade element momentum theory (much more complicated than thin airfoil theory for fixed-wing aircrafts) are very useful to predict such aerodynamic forces under a helicopter’s rotational motion. However, research interests in helicopter aerodynamics have focused on a high Reynolds number regime, unsteady flow, and the suppression of undesired wing motion.

A flapping UAV is a flight vehicle which generates aerodynamic forces and moments to fly and maintain its stability by a complex multi degree of freedom wing motion: flapping, pitching, twisting, and lagging. One of the combined wing motions is the “figure-of-eight” motion of some insect flights. In addition, the flexibility of wings causes elastic deformations of wings, which seem to contribute to gaining sufficient lift and thrust. Even for the design of small flapping UAV, there are too many design parameters including wing geometry (span, aspect ratio, and thickness), wing kinematics (amplitude, frequency, phase, and DOF), and wing structural dynamics (flexibility, vibration, and resonance). The main difficulty during the design comes from the fact that we do not exactly know how each parameter affects the characteristics of the flapping UAV system, especially its aerodynamics.

Commercially available toy flappers can barely fly, and it is difficult for them to carry additional payloads, such as cameras and chemical sensors, as in typical UAV missions. For example, we installed additional mass (5% of the entire system mass) onto a toy flapper at the center of gravity so that the flapper’s longitudinal dynamics were changed as little as possible. Then, we gradually increased the wing area until the modified flappers could fly. However, those modified flappers proved ineffective; if the wing area was enlarged, much higher torque and power were required. Moreover, the wing is not rigid, so structural properties such as mode shapes and natural frequencies should be tuned for an enlarged wing. This made us replace motor, transmissions, and the discharge rate of the battery to match the flapping frequency, which increased the system weight. In these kinds of iterative works, we felt the necessity of a performance index representing the flight capability and stability of flapping vehicles, even the system has highly nonlinear, time-varying, and uncertain dynamics.

Table 1 represents the specification of the commercial toy flappers shown in Fig. 1. It is interesting that the *Cybird-P1* is the scaled-down model of the *Cybird-P2*; they share the same motor, transmission, and power. But nearly 30% reductions of weight and wingspan make the *Cybird-P1* flyable with a slight increase of flapping frequency. “Scaling-down” seems to somehow work, in this case, due to the sufficient power level of the baseline model. In case of the *Dragonfly*, the wingspan and weight are much smaller than those of *Cybird* (40% wing span and 8.4% weight). The amount of power is just 10% of baseline model, *Cybird-P2*. This is the reason why the maximum take-off weight is dramatically decreased. Even we try to increase the power level of the *Dragonfly* for more weight, it requires a higher flapping frequency and very stiff wing structures to conserve the structural properties connected to aerodynamic characteristics such as wing camber, twist angle, etc.



Fig. 1. Commercial Toy Flappers: (Left) *Cybird-P2*, Neuros Co. Ltd, (Middle) *i-Fly VAMP*, Interactive Toy Concepts Ltd, (Right) *Dragonfly*, WowWee Group Ltd. (adopted from the company websites)

Table 1. Specification of Commercial Toy Flappers

	Wing Span [cm]	Length [cm]	Max. Flapping Frequency [Hz]	Weight [gf]	Endurance [min]	Operating Radius w/o barrier[m]	Etc
<i>Cybird-P1</i>	73.6	40	10	201.2	< 10	< 450	Flapping angle -10 deg to 20 deg
<i>Cybird-P2</i>	99.1	60	9	283.5	< 10	< 450	CG at 42% of chord
<i>Dragonfly</i>	40	30	10	24	3~4(< 8)	< 45	-
<i>i-Fly VAMP</i>	30.48	25.4	10	23.5	< 8	< 45	Control easier than Dragonfly

In general, the typical design of new air vehicles refers to existing baseline models. In the case of flapping air vehicles, the base line model can be found in nature so that the initial design parameters can be adopted from nature's morphology and scaling law [1-2]. We have made continuous efforts to collect those data in nature and interpolate or extrapolate the data, including successful artificial flappers. Based on those empirical laws dealing with the relationships of wing geometry, kinematics, weight, and flight speed, we could define design parameters. In the case of nature's flyers, the whole flight system as well as its constituting subsystems (wing skin, muscles, and so on) seems to be well optimized and harmonized. Because the current engineering technology cannot provide all the subsystems that have comparable performances, artificial flapper design requires a series of trade-offs and compromises.

2.1 An Efficient Aerodynamic Model for Low Reynolds Number

Flapping UAV designs can be categorized into bird types and insect types according to the wing actuation mechanisms (motor-mechanical linkage vs. PZT implemented vibro-actuation) and aerodynamic mechanisms (quasi-steady vs. unsteady aerodynamics). Quasi-steady aerodynamics can be applied to the flights of birds that have high aspect ratio wings and slow flapping motions. In quasi-steady aerodynamics, aerodynamic characteristics of wing sections, which are represented by resultant angles of attack due to the dynamic wing motion, correspond to the conventional aerodynamic characteristics. The quasi-steady wing will not have larger maximum lift coefficient than the stationary wing. However, in the flight of nature's flyers, the relative angle of attack is much higher than the stall angle, and the maximum lift coefficient is 2~3 times larger than common airfoils. For example, at the end of the downstroke, the wing is twisted quickly due to the flexibility of the wing, and it generates a very large peak of lift. Those unconventional aerodynamic mechanisms have been introduced by many researchers in terms of dynamic stall due to the leading-edge vortices, rotational lift, wake recapture, and Weis-fogh's clap-and-fling. A detailed explanation can be found in [3-7]. Without a sound understanding of those unsteady aerodynamic mechanisms, the systematic design of flapping UAVs will not be possible.

Up to now, the research trends of flapping-wing aerodynamics have focused on the principles of insect-wing aerodynamic enhancements, the relationship between propulsion efficiency and vortical patterns, wing-wake interactive dynamics, and leading-edge formation and stabilization. Flow visualization by using the particle image velocimetry (PIV) techniques and numerical analysis based on the computational fluid mechanics (CFD) are powerful tools to understand the detailed flow characteristic of flapping aerodynamics [8-13]. Nevertheless it seems that we do not have a simple explanation on the formation and stabilization of unsteady aerodynamic mechanisms of the flapping-wing. In addition, those unsteady aerodynamic mechanisms are not fully utilized for flapping UAV design. In particular, a simpler or reduced-order unsteady aerodynamic model, whether it is theoretically derived or experimentally obtained, is required since it can be effectively used for multi-disciplinary design, such as the analysis of flight dynamics and control considering wing flexibility. It is well-known that flapping-wing motion disturbs the flow field and generates a complex vortex structure [14]. If we successfully build such a vortex model, we can directly calculate the aerodynamic forces from a well-known Kutta-Joukowski theorem, $\mathbf{F} = \rho \mathbf{V} \times \mathbf{\Gamma} = 1/2 \rho V^2 SC_F$, where the force coefficient, C_F is a function of time, the Reynolds number, wing kinematics, and wing geometry. Then, four pre-described unconventional aerodynamic mechanisms can be expressed by the corresponding vortex dynamic model. However, the circulation, $\mathbf{\Gamma}$ is governed by unsteady low Reynolds number flow, and it has not yet been fully investigated, as shown in Fig. 2. That is the reason why most flapping-wing aerodynamic models rely on how we model such circulations. For example, Van den Berg and Ellington [25] established a quantitative circulation model of the hovering *Hawkmoth* based on a series of experimental observations.

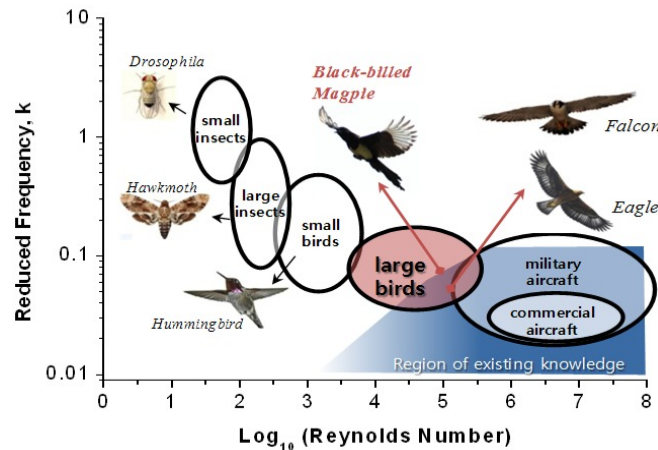


Fig. 2. Flapping-wing aerodynamic characteristics, Reynolds number vs. reduced frequency, k for nature's flyers (adopted from [16], and modified in this paper, including similarity to nature's flyers)

Modified strip theory (MST) [17-18] is a semi-empirical nonlinear flapping-wing aerodynamic model based on Theodorsen theory, dynamic stall analogies, and the wind tunnel testing data of the stationary wing. Low Reynolds number characteristics are considered by six experimentally extracted parameters: the static angle of attack, zero-lift angle of attack, cross-flow coefficient based on slender-wing theory, zero-lift drag coefficient, Polhamus' leading-edge suction coefficients, span efficiency factor, and large unsteady wing motion are taken into account by modified Theodorsen function, which was originally introduced by Theodorsen[19], extended to the finite-wing[20], and validated by water tunnel experiments under large plunging and pitching wing motion [21]. Moreover, the MST represents the cruising flight aerodynamics of high aspect ratio wings which have relatively large wing motions. We have specified the model validity of the modified strip theory, and now we are quite convinced that it can be a very promising tool for flapping UAV design [22-23]. The original dynamic stall model by DeLaurier reflects pitching motion only; it was further extended to include both plunging and pitching motions which are the most effective motion of flapping flight. Our improved theory was accompanied by the experimental validation. As shown in Fig. 3, we designed and developed the plunging and pitching motion generator with the load cell for aerodynamic loads measurements. The main difficulty of flapping-wing aerodynamic measurements was how we would compensate for the inertial forces due to the dynamic wing motion. We introduced dummy masses to model lift and thrust directional accelerations with precise modal testing of the load cell assembly. Our modification of the dynamic stall models under the large plunging and pitching motion at a low Reynolds number regime needed to be somehow explained by using unsteady aerodynamic characteristics. We performed several PIV (Particle Image Velocimetry) tests for our smart flapping wing model, and the leading-edge vortices were observed during the flapping-wing motion at low advance ratio, as shown in Fig. 4.

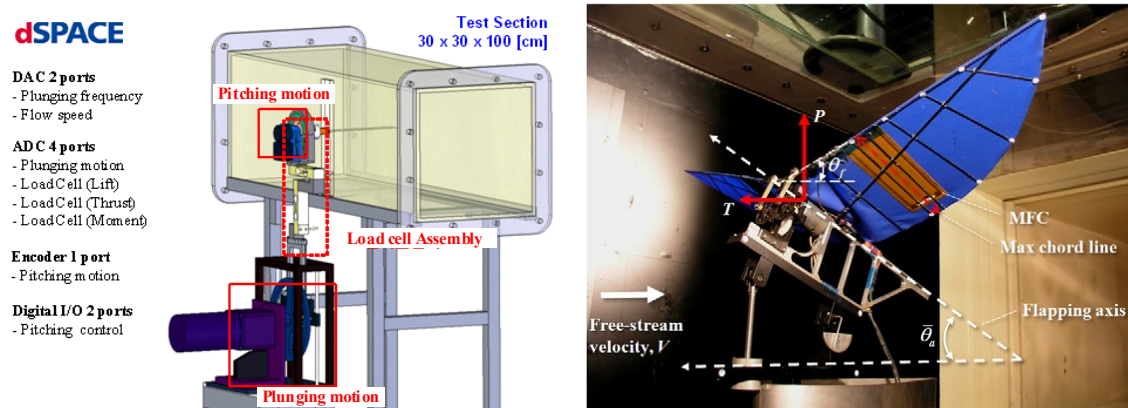


Fig. 3. Experimental set-up for the wind tunnel testing under plunging and pitching motions for MST validation (left), and PIV test model of smart flapping wing with macro-fiber composite actuator [13,22-23]

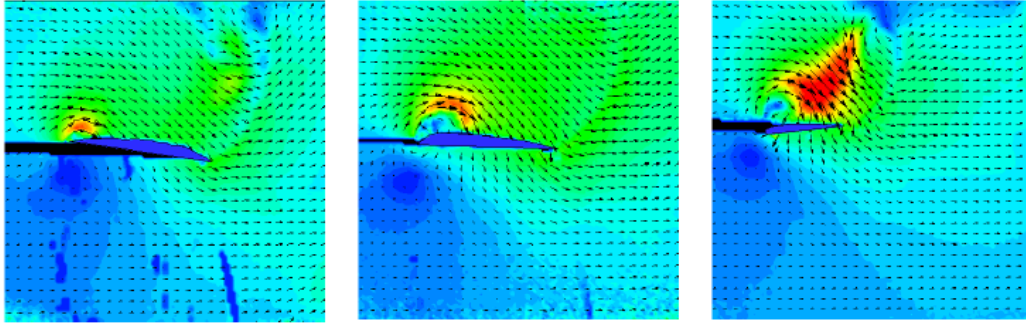


Fig. 4. Particle image velocimetry experimental results of our smart flapping wing, as shown in Fig. 3 (right), Leading-edge vortices observed at advance ratio, $J=0.53$ [13]

2.2 Design Considering Fluid-Structures Interaction

A typical flapping UAV has a flexible membrane structure that is easily deformed. While aerodynamic damping affects the natural frequency of structure, the added mass or apparent mass of fluid is augmented to the mass property of the wing structure, resulting in changes of its structural properties. Modern aeroelastic design of the helicopter rotor blade or the high-speed aircraft wing mainly aims at the prevention and suppression of fluid-induced vibrations, namely flutter. However, an aeroelastic design of the flapping-wing makes use of the fluid-structure interaction phenomena. The flow-induced deformation of wing structures can provide higher lifts and thrusts compared with rigid counterparts. In the case of artificial flapping UAV, the fluid-structure interaction or the passive wing deformation is quite essential to generate proper pitching motion that is closely related to aerodynamic loads of each section.

To achieve a successful prediction of fluid-structure interaction of flapping wings, we need to mutually consider the following three items: structural deformation (finite element structural model of a flexible wing), kinematic motion (flexible multibody dynamics), and flapping-wing aerodynamics. DeLaurier [24] investigated the optimal aeroelastic design of an engine-driven ornithopter. The modified strip theory was used to describe the flapping-wing aerodynamics, and a simple box beam was introduced to model the structural characteristics of the elastic wing. Some refined works on wing structure modeling are also available. In [25-26], finite element formulations of the flexible flapping wing were performed based on the Lagrangian methods to derive the equation of motion; further improvement considering the nonlinear deformation is described in [27] and a compliant membrane wing of a bat had been studied [28]. A more realistic structural model can be established by using experimental modal testing, which is used to extract structural properties such as generalized mass, stiffness matrices, mode shapes, and natural frequencies. Combes and Daniel [29-30] experimentally measured the wing flexibility of six different species of real insects and derived an empirical formula about the relationship between spanwise flexibility and chordwise flexibility, and they constructed a finite element model of a membrane and rigid vane to match the structural properties. Modal approaches of flapping-wing modeling reduce the computation costs and easily extend to flexible multibody dynamics to assign the kinematic motions [25,27]. However, those refined structural models have not been coupled with aerodynamics, yet.



Fig. 5. Sound understanding of the anisotropic flexible flapping-wing structure is necessary to build an efficient flapping-wing (Left) Similarity of rigid vane of insects [31], (Right) *Hawkmoth's* flexible wing FEM model and material properties obtained from the experiments in [30].

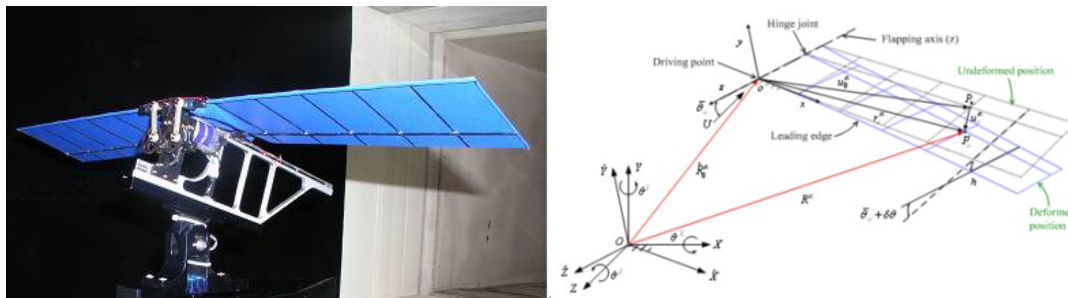


Fig. 6. Rectangular flapping wing model for wind tunnel verification; coordinate definition of flexible multibody dynamics [32].

Because of excessive computational cost, computational fluid dynamics has not been used often for fluid-structure interaction analysis. It is wise to use a reduced-order aerodynamic model instead of massive wind tunnel data or time-consuming computational fluid dynamics results. Smith [33] compared various aerodynamic models: momentum, blade-element and hybrid momentum methods, the lifting-line method, a two-dimensional method using thin airfoil theory, lifting surface/vortex lattice method, and unsteady panel methods. No matter what aerodynamic model is used, it is necessary to take into account the large resultant angle of attack, and the unsteady, low Reynolds number flow.

We performed fluid-structure interaction analysis for a rectangular flapping wing shown in Fig. 6 and found the importance of appropriate flexibility of wings [32]. The analysis used the generalized mass and stiffness matrices of the finite element model extracted from commercial finite element analysis software (MSC.NASTRAN), a flexible multibody dynamics based on the modal approach, the Craig-Bampton method, and our improved modified strip theory as an efficient flapping-wing aerodynamic model. Structural and kinematic models were validated by the modal testing, the wind tunnel testing, and commercial flexible multibody dynamics software (MSC.ADAMS).

2.3 Bio-inspired Design of the Flapping-wing Motion Mechanism

Flying insects and hummingbirds utilize an unconventional aerodynamic mechanism (advance ratio, $J < 1$) to get 2~3 times larger lift coefficients than can be obtained from stationary wings [34]. This unconventional mechanism provides a high lift to weight ratio, but in the case of birds that have a muscular-skeleton actuating system, it is not possible to use those honorable aerodynamic characteristics. The flapping frequency of insects is greater than 100Hz, and they use the structural resonance of muscular-exoskeleton vibration to make proper wing deformations and motion, known as the figure-of-eight. A hummingbird belongs to birds, but its flying behavior is very similar to that of insects, particularly its heart beat frequency of 1220 times/min and its muscle power of 133W/kg (c.f. human: ~100times/min, 15W/kg). Just like hummingbirds, flapping UAVs are also located between bird and insects. The actuation mechanisms of the flapping vehicle are similar to birds, as shown in Fig. 8, but in the sense of passive wing pitching motion, anisotropic insect wing types can be helpful to reduce the burden of motor torque and to conserve the energy of the battery. Active wing shape control of flapping-wing such as variable camber may enhance the aerodynamic characteristics [35].



Fig. 7. Flapping and passive pitching is not enough for energy efficient flight. A high or low aspect ratio wing has different degrees of freedoms; of course, it also depends on flight modes, such as hovering, cruising, and turning [36-38].

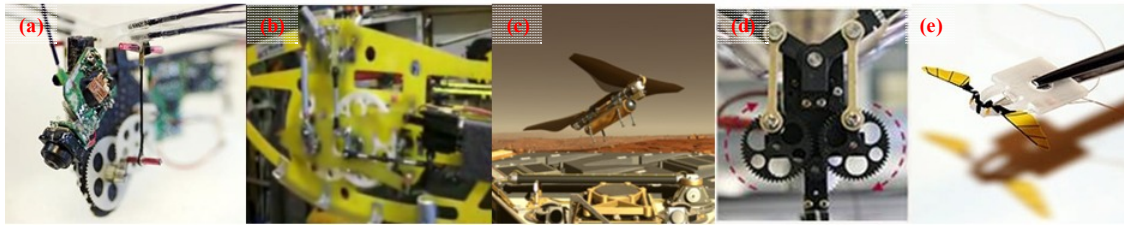


Fig. 8. Various types of widely used flapping-wing mechanisms, (a) X-wing of Delfly, near hovering maneuver is possible, utilizing the clap-and-fling mechanism [39], (b) Slowhawk's abirk system, a stroke plane can be inclined to control the rolling moment [40], (c) Entomopter's two pair flapping wing design [41], (d) Havard microrobotic fly, PZT actuation [42], (e) Cybird's famous crank-rocker mechanism [35].

There are many kinematic parameters for wing motions such as stroke angle, frequency, motion profiles (sinusoidal, triangular, etc), phase differences between the right and left wing or fore and hind wing, etc. It is worthwhile to identify the effects of certain kinematic parameter on the flight performance such as obtainable lift and thrusts, and maneuverability and controllability. This is the reason why we observe the flight behavior of nature's flyers and get some inspiration from them. Many zoologists and biologists have used PIV techniques and high-speed video cameras to quantitatively acquire the kinematic parameters during the various flight modes of nature's flyers [36-38]. For example, female bats in pregnancy or birds holding their prey are experiencing weight increments. Because they are already fully grown, there can be no additional changes of wing area or flexibility of lifting surfaces (feathers). In this case, nature's flyers adjust their kinematical parameters to new environments; they usually increase their stroke angle and incline their stroke plane like the Abirk system shown in Fig. 8.

The current design of the flapping-wing motion mechanism mostly utilizes a four-bar linkage and single electric motor, or simply the crank-rocker mechanism. There are not many independent kinematic parameters of the wing motion. For example, the left and right wing motions are synchronized and each wing stroke angle is also fixed. In many cases, the flapping frequency is the only control parameter to tune the aerodynamic characteristics. The mechanically manipulated multi degree of the freedom wing motion leads to complex transmission design, and it directly increases the weight of the vehicle. Therefore, finding a way to increase the degree of freedom for better performance without a major penalty is an open issue for flapping UAV design.

2.4 Robust Flight Navigation and Control

The current unmanned technology of flight system seems to target the development of the autopilot based on the well-posed numerical model of the system. The system models for various fixed- and rotary-wing vehicles have been obtained either by using analytical modeling or flight test data. The flight vehicle system identification methodologies in the time domain or frequency domain are well-documented in [43-44]. Some researchers insist that the numerical system model is not necessary for flight control because they can use model-less control theories, such as neural networks, genetic algorithms, and reinforce learning. However, those controllers are not widely used because of high computational burden and unguaranteed reliability.

Compared with other types of flight vehicle systems, the flight dynamics characteristics of flapping UAV is much more complex. Basically it shows highly nonlinear time varying behaviors so that the linearization of nonlinear function does not work well [45]. Because of complex behaviors and many kinematical parameters, we need more measurements for system identification. In contrast, the typical payload affordability of flapping UAV limits the installation of many sensors and high performance data acquisition systems on it.

Taylor et al. [46-47] introduced new experimental approaches to the biology of flight control systems and reviewed the flight data acquisition of nature's flyer, such as *Aquila Nipalensis*. They installed a camera to measure the control input of the tail-wing and an on-board GPS-INS module to acquire the flight states. The Stepp Eagle or *Aquila Nipalensis* is a bird large enough to carry few hundred grams of prey or payloads instead. Once we get the flight data with control inputs and flight speeds, we could build a state-space equation and apply our well-accumulated knowledge of controller design for the known system model. There is another interesting approach that was conducted by Dickinson et al. [48-50], as shown in Fig. 9. Dickson studied the unsteady aerodynamics of *Drosophila* for more than 10 years, and that background was used to integrate the flight simulation model including the flight controller, sensory systems, rigid-body dynamics, aerodynamics, and environment model. The optic flow flight arena stimulates live *Drosophila*, which is attached to MEMS force sensor to monitor the change of resultant forces. Such a "hardware-in-the-loop" method can replace the

flight test without any heavy flight data acquisition system, so let us discover the control strategies and structures of the controller. However, this kind of approach could not be used directly to develop a flapping UAV because our targeted UAV dimension is much larger than that of *Drosophila*.

We performed some preliminary research on flight simulation shown in Fig. 10 using our flapping-wing aerodynamic model to find the trim condition. It was assumed that the longitudinal dynamics were decoupled from lateral dynamics, but the complex flapping-wing aerodynamics and wing kinematics were taken into account. We found that slight variations in the system parameters such as the location of wings and tail wing angle caused unstable behaviors. Therefore, efficient control methodologies that might be learned from nature's flyers seem to be indispensable for the practical operation of artificial flappers.

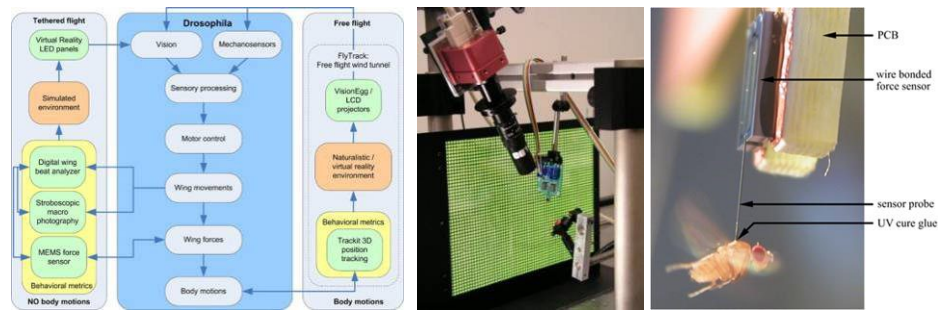


Fig. 9. *Drosophila* flight identification by using the optic flow flight arena, and the MEMS force sensor [50]

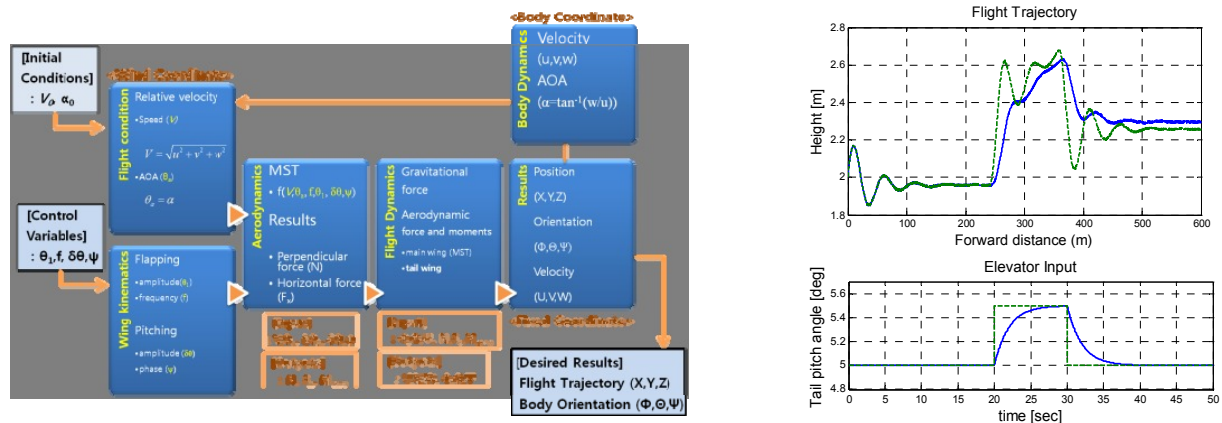


Fig. 10. Flowchart of the longitudinal dynamic simulation and time history of the level-up command of our flapping UAV model [51-52].

2.5 Miniaturized Electronics and Micro Power Source

In 1997, DARPA launched the first micro air vehicle (MAV) project, 'Toward a New Dimension in Flight' [53]. One of the main research drivers was the development of miniaturized radio control (RC) electric parts, such as motors, speed controllers, receivers, etc. Lighter and smaller electronics are one of the most important solutions to make MAVs fly. For fixed-wing MAVs, the static aerodynamic characteristic is not good due to the low Reynolds number regime, which requires the lightness of constituting components [54].

Because there have been many more active developments in fixed or rotary type MAVs than flapping MAVs, the electronic components have also been developed according to the requirements for fixed or rotary type MAVs. Many researchers in university have tried to build new types of MAVs by using the commercially available electric parts and payloads of fixed-wing MAVs [39,55-56]. Fig. 12 shows some representative commercially available electric parts. However, the current flapping-wing mechanism uses a four-bar linkage and single electric motor with reduction gears. It requires a large amount of torque and power capacity to generate proper wing motion during targeted mission time; however the motors and batteries in the market seem to be insufficient for flapping UAVs.

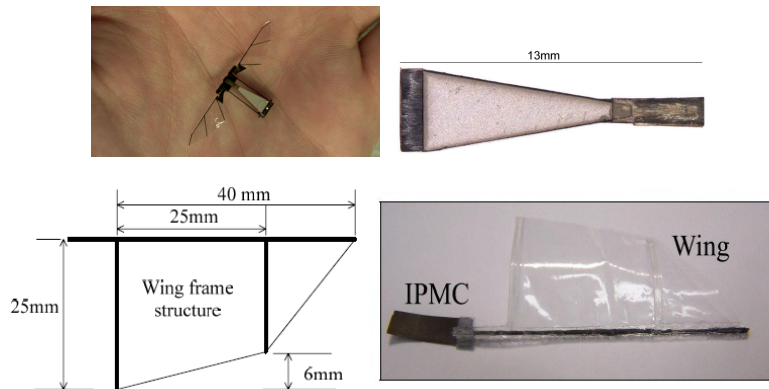


Fig. 11. New flapping-wing actuation modules using smart materials (Top) PZT [42], (Bottom) IPMC [57]

Most of miniaturized high efficiency and high power motors have the strongest magnet, neodymium ($\text{Nd}_2\text{Fe}_{14}\text{B}$), and switching power electronics. An attempt to further reduce the mass and size of the motor makes the performance worse. The power density of the electromagnetic motor at the flapping frequency is quite limited [58]. Wood [42] successfully developed a flapping-wing mechanism made of piezoelectric material (PZT) operating at a high actuation frequency, and artificial muscle composed of smart materials such as ionic polymer-metal composites (IPMC) were suggested as a breakthrough for flapping-wing actuation [57], as shown in Fig. 11. Since PZT actuator requires high voltages $O(10^2)$ [V], new types of actuators should be accompanied with corresponding light-weight power electronics for flapping UAV applications [59].

Moreover, flapping-wing type air vehicles as a promising UAV system should have micro power which has compact size, high efficiency, and large capacity. PEM fuel cells and CIS thin-membrane solar cells are the most up-and-coming candidates for flapping UAV power systems. Besides the inherently flexible structure of flapping UAV wings, the energy source utilizes the energy harvesting concepts by piezoelectric materials [60].

Toward a flapping UAV system, it is necessary to measure and feedback the system states such as translational and rotational velocities or accelerations, vehicle location or orientation, as much as possible. Fig. 13 shows the status of cutting-edge technology of on-board flight control systems. These are designed for fixed-wing air vehicles not flapping-wing ones.



Fig. 12. Commercially available RC electronic parts, (From left to right) SmartServo RC-1 (mass 0.8 g, output torque 15 gf-cm), YGE4-BL (mass 1.3g, smallest brushless motor speed controller), Micro D1811-2000 (Smallest brushless motor), R4P-JST (mass 3.8g, max. range 150m) (adopted from the company websites)

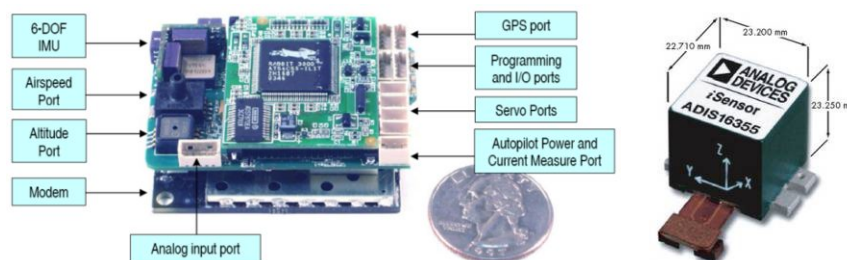


Fig. 13. Payload for a flapping UAV system (Left) Kestrel 2.2x autopilot (mass 16.7g) with Aerocomm AC4490 modem (mass 20g, range 6.4km – 32km) attached (adopted from the datasheet of Kestrel 2.2x autopilot [61]) (Right) High precision inertial sensor ADIS16355 (mass 16g) Analog Device, Inc. [62]

3. CONCLUSIONS

Five key technical issues were addressed for the systematic design of bio-inspired flapping UAV, and our research experiences were summarized. Flapping-wing aerodynamic modeling and the fluid-structure interaction approach are important tools to develop new flapping UAV systems and an autonomous flight controller. The design of flapping UAV is difficult because of the inherent multidisciplinary nature during the design. Further investigations should focus on a more precise flapping UAV system definition, utilization of unsteady aerodynamic mechanisms, and the estimation of power consumption.

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