Research Progress on Control of Bioinspired Flapping-wing Micro Air Vehicles

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***Abstract*—The Bioinspired Flapping-wing Micro Air Vehicle (FMAV) has been attracting many research institutions due to the advantages they present, such as greater maneuverability, greater efficiency, and lower energy consumption. Compared with the fixed and rotary airfoils, maneuvering characteristics of FMAV depends much upon efficient control of flight attitude. So, an effective model of flight control is of utmost importance. The developments of bioinspired FMAV in recent years is firstly highlighted in the paper, and we specifically discuss the different mechanisms for bioinspired FMAV flight control as well as model-based control and the model-free control. We conjointly define the challenges related to making associate degree integrated bioinspired FMAV.**

Keywords—bionics; flapping-wing; flapping-wing micro air vehicle (FMAV); flight control

I. INTRODUCTION

The concept of micro air vehicle (MAV) was proposed within nineteen nineties, since then a major quantity of analysis into MAV has been conducted [1]. For vehicles applied on a small scale, flapping-wing structures can be more efficient than conventional aircraft structures, because it is difficult for fixed-wing aircraft/rotorcraft to generate enough lift to overcome their gravity to take off when the Reynolds number decreases as the scale shrinks, but at the same time flapping-wing results in highly unstable fluid forces [2]. Due to the wings movement, the complexity of flight mechanism and the influence of unsteady aerodynamic force, control of the vehicles is a difficult problem in the field of FMAV. Wood et al. [3] designed the lightest FMAV thus far to achieve sustained untethered flight. Xinyan Deng et al. [4] presented a full non-linear dynamic model and a geometric flight controller to achieve globally stable and exponential attractive properties. By adjusting the position of wing-root in a hovering insect-scale FMAV, H.V. Phan [5] investigated the effect of wing-root position modulation on the generation of aerodynamic force. And DelFly prototype [6] is based on two pairs of wings combined tail control mode, successfully realized the airborne camera autonomous flight. *Science* presented a FMAV designer by DelFly team [7], the power efficiency of the FMAV enables to hover for five minutes or fly for more than a kilometer after a single battery charge. Though it's fifty times larger than the fruit fly, it can accurately simulate the flies' amazing maneuverability.

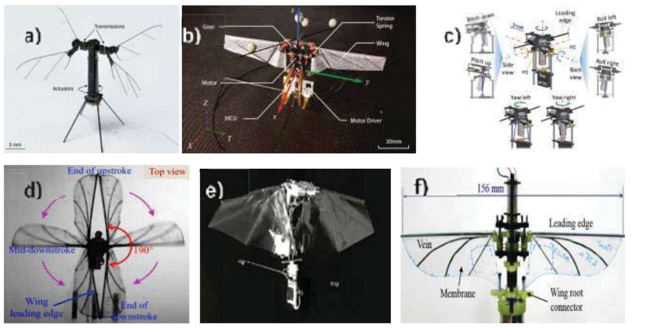

Fig. 1. a)The RoboBee X-Wing using solar [3] , b) Hummingbird size FMAV drirven by motor [4]. c) Design of the attitude control mechanism for FMAV [8], d) The position of KUBbeetle's wing when flaps [9], e) FMAV in hover [7] , f) Assembly of FMAV mechanism [10].

The nonlinear unsteady FMAV is a complex system. With the structure becomes small and flexible, the influence of disturbance is more vulnerable, and the performance of sensors and actuators sharply drops with the decrease of the size, FMAV requires a better control strategy to achieve the stability of the vehicle. The traditional PID control algorithm cannot meet the higher control requirements, so researchers combine artificial intelligence and other advanced technologies with traditional control method to solve this problem, and apply such new effective algorithm to the automatic control of flight vehicle.

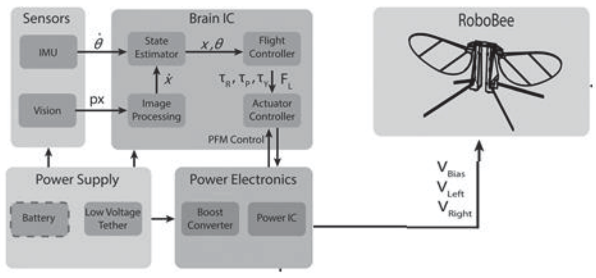

Fig. 2. The control and power supply diagram of a typical FMAV - RoboBee. The brain IC reads signals from IMU and sensors which measure aircraft speed. Then the brain uses series of sensors to determine FMAV's

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status and the vehicle state datas are taken, calculated by the flight controller. These torques then are employed by the actuator controller to control the power IC and booster converter, then the control signal is sent to the vehicle [11] .

The most critical and widely studied aspect of flight control of flapping-wing aircraft is flight attitude control. That is to say, the controller is designed to control FMAV attitude angle (pitch angle, yaw angle, rolling angle) and flapping wing angle, to realize attitude adjustment.

Also, vibration control is an important link that determines the performance of the FMAV. During the flight, the wing and fuselage are susceptible to external disturbances and vibrations caused by the motion of the motor and wing structure. It is of the great necessary to design the special controller to suppress the vibration [12].

II. Mechanisms for Flight Control

To realize the free flight of the biomimetic FMAV in the air, researchers put forward different mechanism design schemes to meet the control requirements. At present, most of the bionic FMAV uses two main types of wing beating: the wing beating with a tail (or aileron) and the wing beating without a tail, corresponding to tail actuation structure of control and wing actuation structure of control respectively.

A. Tail Actuation Structure of Control

The way of flapping with a tail (or aileron) to generate lift adopts "clap and flying" mechanism, and to rely on the tail (or aileron) to adjust the direction of the flight, such as series of DelFly prototype (DelFly - Ⅰ, Ⅱ [6], Micro [13] and Explorer [14]), which is based on two pairs of wings combined tail control mode, successfully realized the airborne camera autonomous flight. FMAV based on this flapping mode has few degrees of freedom, generally can only realize pitch, forward and turn flight, and the flight control is relatively simple.

B. Wing Actuation Structure of Control

Hummingbirds and most dipteran use the tailless flapping mode, which can achieve six degrees of freedom of position and attitude adjustment. This flapping mode works at a large angle of attack, and the lifting mechanism is relatively complex, including delay stall mechanism, rotation loop mechanism, wake capture mechanism and virtual mass effect, etc. Based on this flapping pattern, the researchers designed a variety of insect FMAVs, which can be classified into three forms according to the angle of attack: active control, passive control, and semi-passive control. And in terms of semi-active control, the main scheme at present is to adjust the angle of attack by controlling the trailing edge of wings. Specifically, the nano hummingbird robot controls the angle of attack by relying on the rope transmission and positioning device and can realize a controllable flight of six degrees of freedom.

The KUBeetle of Konkuk university of Korea [15] and the Colibri flapping aircraft of free university of Brussels [16] adopt the tailless structure form. By controlling the steering engine, the controllable position adjustment of the trailing edge can be achieved, also the angle of attack during the flapping process is controlled, the control torque can be generated to control the attitude of the aircraft and the successful suspension can be also achieved. DelFly Nimble [7], the latest achievement of DelFly University, adopts the structure form of tailless two-wing, and uses the steering engine to control the trailing edge and adjust the Angle of attack, thus generating the tilting and turning moments, and at the same time uses the coupling of both moments to generate yaw moments, showing the maneuverability equal to that of natural fruit flies in turning at rotational speed.

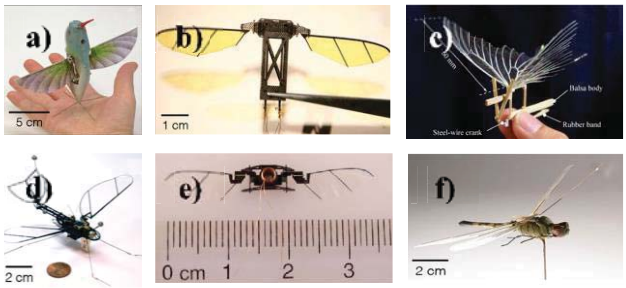
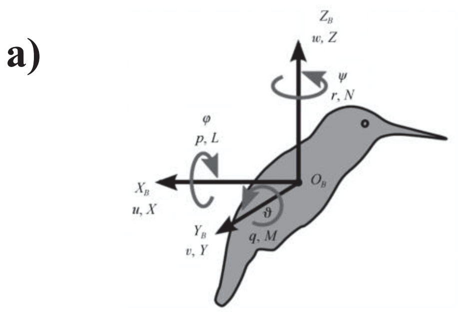


Fig. 3. Typical bioinspired FMAVs. a) Nanohummingbird robot [11], b) AFRL Piezo-driven FMAV [17], c) Butterfly-inspired FMAV [18], d) Harvard Robot Moth [19], e) Electromagnetic FMAV [20], f) Central Intelligence Agency insectothopter [21].

III. Control Strategies

The FMAV has a high degree of flexibility and adaptability, which can be used in various complex environments, but its flight mechanism which is the most complicated, need to lift to overcome gravity, thrust to overcome resistance, and wings flap also needs energy supply.

To explain yaw acceleration observed during the vehicle robots operation, Matěj Karásek et al. [7] developed a functional aerodynamic yaw moment model. Wood [3] estimate neglects any aerodynamic wing interactions and change two wings to four. Xinyan Deng et al. [4] derived the full nonlinear model of the system to capture the unstable dynamics of FMAV. In H.V. Phan’s study [5], the results of force modulation by wing mechanics in the process of hovering FMAV are studied by dynamical the wing-root offset, which proves that the calculation of wing mechanics is reasonable and feasible.



$$\dot{u} = -(wq - vr) + \frac{X}{m} + g\sin\vartheta$$

$$\dot{v} = -(ur - wp) + \frac{Y}{m} - g\cos\vartheta\sin\varphi$$

$$\dot{w} = -(vp - uq) + \frac{Z}{m} - g\cos\vartheta\cos\varphi$$

$$I_{xx}\dot{p} = (I_{yy} - I_{zz})qr + I_{xz}(\dot{r} + pq) + L$$

$$I_{yy}\dot{q} = (I_{zz} - I_{xx})pr + I_{xz}(r^2 - p^2) + M$$

$$I_{zz}\dot{r} = (I_{xx} - I_{yy})pq + I_{xz}(\dot{p} + qr) + N$$

$$\dot{\varphi} = p + q\sin\varphi\tan\vartheta + r\cos\varphi\tan\vartheta$$

$$\dot{\vartheta} = q\cos\varphi - r\sin\varphi \qquad (1)$$

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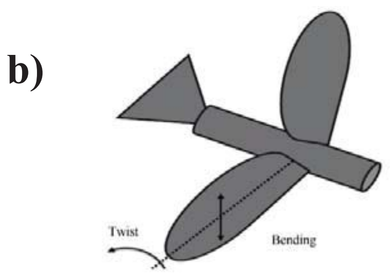

$$
\begin{aligned}
& m\ddot{w}(x,t) - mx_e c\ddot{\theta}(x,t) + \eta EI_b \dot{w}''''(x,t) + \\
& \qquad EI_b w''''(x,t) = F_b(x,t) \\
& I_p\ddot{\theta}(x,t) - mx_e c\ddot{w}(x,t) - \eta GJ\dot{\theta}''(x,t) - \\
& \qquad GJ\theta''(x,t) = -x_a c F_b(x,t) \\
& w(0,t) = w'(0,t) = w''(L,t) = \theta(0,t) = 0 \\
& EIw'''(L,t) = F(t) \\
& GJ\theta'(L,t) = M(t) \qquad (2)
\end{aligned}
$$

Fig. 4. a) Body dynamics, when it is considered a rigid strcture and dynamic analysis is performed by using the euler equation of motion, and in equation 1, m is mass, I_{XX}, I_{YY} and I_{ZZ} are inertial non-zero moment of fuselage, aerodynamic X,Y,Z, torque L, M, N [22]; b) Dynamics analysis of wing, and in equation 2, $L, m, I_p, EI_b, GJ, x_e c, x_a c, F(t)$ and $m\,(t)$ respectively represent wing length, mass of each wing, moment of inertia of polar distance, flexural stiffness, torsional stiffness, distance from shear center of wing to center of gravity, distance from dynamic center to shear center, external force on top, and torsion momentum [24].

In the study of flight dynamics, people often get flight motion parameters by aerodynamic analysis [22]. Through wind tunnel test [23], the aerodynamic performance of insect bird aircraft at low speed and low Reynolds number can be obtained. Theoretical analysis is carried out by employing numerical simulation, and mechanism analysis of flapping-wing flight is performed by combining several methods [24].

Up to this point most of the strategies to model and control the FMAV depend on first principle procedures because the exact numerical model can assist to design an accurate control schemes and well improve the FMAV control performance. But actually, lots of different vulnerabilities cause FMAV to become a profoundly over-actuated and nonlinear system. Building an exact numerical model of FMAVs that considering all these characteristics is a challenging task [39]. To better solve such a problem, the reseachers present a solution named model-free knowledge-based data-driven techniques, because no mathematical model is required for data-driven modeling and control so that better control becomes possible [25].

A. Model-based controller design

1) Feedforward Control: Without sensors, the feed-forward controller can effectively control the FMAV [25], which is important because reducing the number of sensors can effectively reduce the weight of the FMAV and reduce energy consumption. However, this simple control method is not suitable for FMAV systems with disturbances, uncertainties and load changes, and nonlinearity cannot be ignored. Since 1998 UC Berkeley has been developing The Micromechanical Flying Insect(MFI), and now the MFI can use feedforward control to achieve 506μN lift at 160 Hz [12] .

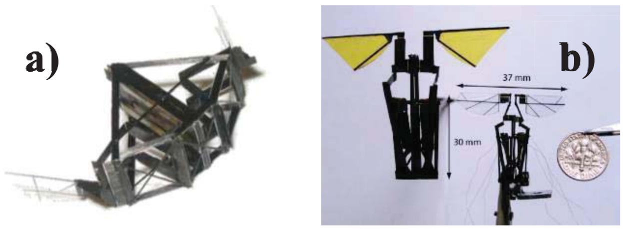

Fig. 5. a) Current two wings, 4DOF MFI [12]; b) CMU Piezo-driven FMAV [18].

2) Boundary Control: Many scholars are paying attention to FMAVs with flexible structure, especially the flexible wings, to be more like natural real creatures. But when dynamic analysis is carried out on the flexible wing, it will constitute a distributed system with infinite dimensional state space [26], so boundary control is needed to solve this problem and it can effectively deal with the disturbance and vibration of the system.

In the NPS flapping-wing MAV [27], K. D. Jones made the model to be tested in the wind-tunnel and using a smoke wire to observe the flow visualization on the edge of wings.

3) Predictive Control: For FMAV, the time delay problem of non-minimum phase system needs to be solved and the problem of feedback delay and nonlinear system constraints should be dealt with effectively.

Martin Saska et al. [28] proposed a unique model protective control-based method for guiding the formation, and also the methodology can be used to unravel the flight coming up with and management into a target region. Mina Kamel et al. [29] conferred a Linear-nonlinear Model Prophetic Controllers (NMPC). In the case of lower external disturbances, a detailed comparison was made of the whole FMAV parameters. Each controller exhibits similar behavior, while NMPC exhibits higher performance.

B. Model-free active control

1) PID Control: The advantages of PID based mostly autopilot management include: straightforward and simple to style and perceive, Higher level management ways are often engineered on prime of it, tiny memory and process resources needed. However, PID primarily based autopilot controls even have some disadvantages: hardiness (the PID parameters have to be compelled to be re-tuned if the payload is modified), unstability (under some interference conditions, the nominal working point of PID control may be unstable), difficult for parameter adjustment.

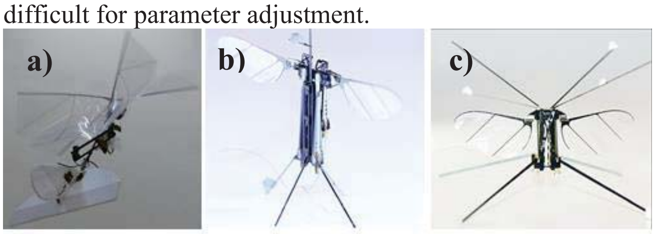

Fig. 6. PID control. a) The DelFly [30] contains a PID-controller that operates the motor and controls the frequency of wing beat. b) PID control is used in the "quad actuator bee" [11], c) "Big Bee" Robot [31].

2) Active (Passive) Position Feedback: This control method effectively suppress the vibration and can improves the adaptability, in the meantime, the stability of systems will not be reduced. But the frequency cannot change in time,

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coping with multiple system models is difficult and a high-order controller is formed.

Bilal Ahmed and Hemanshu R. Pota presented a dynamic compensation method which essentially use positive position feedback (PPF) to suppress the first resonance peak of the lightly damped coupling fuselage. Fig. 7 shows the block diagram of the closed-loop system. An internal-loop negative virtual controller and an external-loop low-bandwidth controller form the two-level control structure. The coupling frame rotor mode will be suppressed to get a higher bandwidth [32].

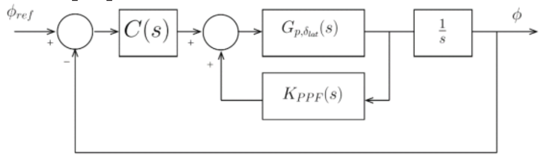

Fig. 7. The control scheme of two-level hierarchical attitude [32]

3) Linear Speed Feedback: When the FMAV is required to be fully autonomous and all calculations are done on robots, without human interaction beyond external infrastructure, communications, or advanced commands, it is difficult to maintain the unconditional stability of the closed-loop system, an effective solution is to use the linear speed feedback system.

Shaojie Shen et al. [33] pursued a system design and method for autonomous navigation and real-time performance on mobile processors using onboard sensors only, so the flight vehicle can fly autonomously in complex environments with multiple floors.

4) Fractional Derivative Control: The general time derivative of integral order can be generalized by the derivative of fractional order constitutive relationships for viscoelastic material, that is important for FMAV because the air with which wings beat is a complex viscoelastic material. One particular advantage of constitutive relations involving fractional derivatives, as presented in the paper, is that they can cause an arbitrary responses at zero time [26] and it is robust for different loads, the influence of disturbance also can be eliminated. Therefore, the convolution method with structural damping has obvious advantages..

5) Singular Perturbation Control: A nonlinear unsteady flapping-wing flight vehicle is a complex system and its aerodynamic model must be a complex system of a higher order. The singular perturbation control JAMES [34] mentioned can divide high order items of a complex system into simple low order subsystems, but when considering higher-order terms, the solution of adding terms will become very complicated and the uncertainty of the model will be reflected in the slowly changing dynamic performance.

C. Model-Free Passive Control:

The flexible structures of FMAV are inherently infinite-dimensional systems, and model-free passive control method is simple and robust to dynamic performance changes. A model-free passive control system [35] can be characterised by an unreasonable transfer function of the infinite model or its truncated rational transfer function. For non-co-interrupted passive transfer functions, the PD controller is sufficient to stabilize the entire system.

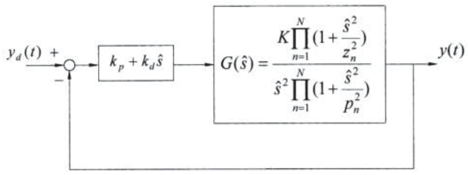

Fig. 8. Passivity-based PD control structure [35]

D. Model-free adaptive/intelligent control

1) Sliding Mode Control: FMAV is a kind of uncertain high order system, and the linear sliding mode method can be used to design the controller of FMAV because it can reduce order to deal with systems with unknown or uncertain models, also maintains the system stability and consistency.

Pu Ming et al. [36] proposed a solution of hierarchical sliding mode: a sliding mode surface was designed for each subsystem, and to make sure the trajectory can enter the sliding surface, a controller was designed accordingly. Next the trajectory converges successively on each sliding mode surface until the control purpose was achieved. Such sliding mode control can be used to deal with systems with unknown or uncertain models, effectively maintain the stability and consistency of the system and reduce order, but it may cause vibration, energy loss, equipment damage of the model-free system.

2) Adaptive Control: Due to the complex aerodynamic model, FMAV is an uncertain continuous-time random controlled object.

The closed-loop stability of robust multi-model adaptive control system (RMMAC, as shown in Fig. 9.) for continuous-time linear time-invariant random controlled objects is proved by ZHANG Wei-Cun et al. [37]. Adaptive Control can cope with variable load and position disturbance of the system but may lead to the adaptive factors independent of the process and require additional adjustment.

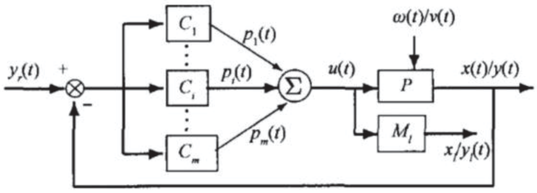

Fig. 9. Structure block diagram of a general RMMAC [37].

3) Neural Network Control: Compared to the model-based control, the accurate mathematical model is not necessary for adaptive neural network (NN) controllers when be used in FMAV control. Aiming at the uncertainty of complex nonlinear FMAV dynamic systems, Wei He et al. [38] designed a neural network controller with full state output feedback to improve the system robustness.

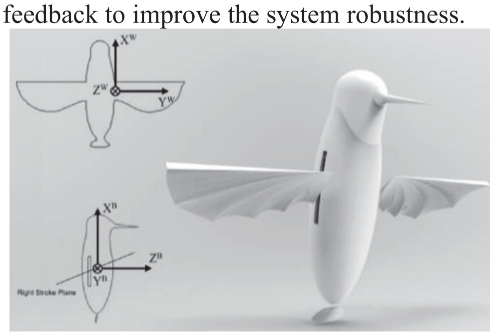

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Fig. 10. 3-D model of FWMAV analyzed in NN control [38].

4) Fuzzy Control: FMAV can adapt to environmental disturbances by tuning the antecedent and consequent parameters of the fuzzy system. A fuzzy system doesn't need an accurate physical model or real physical system, is easy to design and nonlinearity can be effectively handled by adjusting parameters.

An adaptive fuzzy controller was developed on a simulated nature-inspired insect robot with four wings by Md Meftahul Ferdaus' team [39], which outperforms the PID controller in all cases.

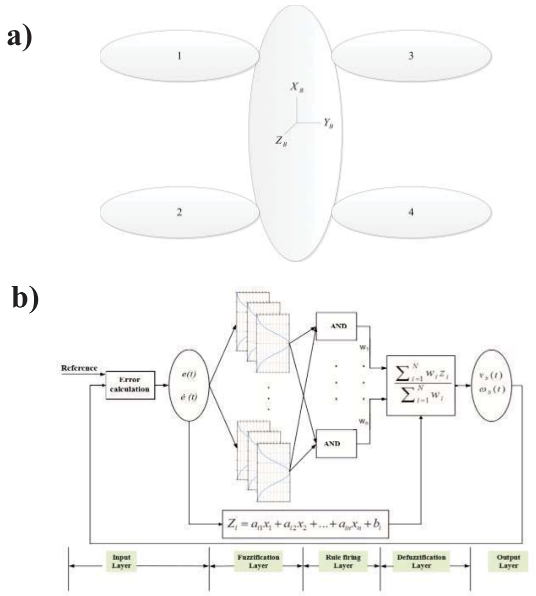

Fig. 11. a) The body of an FMAV. The numbers represent the actuator number; b) The schematic diagram of a fuzzy adaptive control system [39].

IV. Conclusion

In a word, in the past two decades, extensive and rich research achievements have been made in the field of bioinspired FMAV worldwide, and there is still plenty of room for innovation in driving technology, structural design, manufacturing technology, independent high-maneuvering flight control, and practical application. Besides, due to the small size of the imitated insect flapping-wing micro aircraft, most of them are subject to the existing relevant technical level.

In the future, the combination of active control and passive control, the combination of aerodynamic modeling and data-driven modeling, and the use of neural network and other new control algorithms will further solve the problem of FMAV control, and promote the introduction of FMAV into people's lives as soon as possible.

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