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RESEARCH ISSUES IN BIOLOGICAL INSPIRED FLYING ROBOTS

Manuel F. Silva and J. A. Tenreiro Machado
Department of Electrical Engineering, Institute of Engineering of Porto,
Rua Dr. António Bernardino de Almeida, 4200-072 Porto
Portugal
Email: {mss,jtm}@isep.ipp.pt

ABSTRACT

Biological inspired locomotion robotics is an area revealing an increasing research and development. In spite of all the recent engineering advances, robots lack capabilities with respect to agility, adaptability, intelligent sensing, fault-tolerance, stealth, and utilization of in-situ power resources compared to some of the simplest biological organisms. The general premise of bio-inspired engineering is to distill the principles incorporated in successful, nature-tested mechanisms, capturing the biomechatronic designs and minimalist operation principles from nature's success strategies. Based on these concepts, several robots that adopt the same locomotion principles as animals, like legs for walking, fins for swimming, segmented body for creeping and peristaltic movements for worm like locomotion, were developed in the last years. Recently, flapping wings robots are also stating to make their debut but there are several problems that need to be solved before they may fly autonomously. This paper analyses the major developments in this area and the directions towards future research.

KEY WORDS

Flying, robot, biological inspiration, modelling, simulation, control

1. Introduction

The natural world contains some of the most elegant and robust solution principles and strategies. In the last decades the interest in biological inspired locomotion has rise a lot of interest in the research community. Several robots have been developed that try to mimic the way biological creatures move, adopting legs, crawling, and swimming fins [1]. Recently, there has been much interest in micro air vehicles (MAVs) for applications where maneuverability in confined spaces is necessary. Applications for MAVs have been identified including operations in hazardous environments, search-and-rescue and exploration around rubble in collapsed buildings, internal inspection of pipes, reconnaissance and surveillance of indoor environments, etc. The U.S. Air Force, for example, is interested in using MAVs for precisely delivering tiny bombs to destroy a single computer [2].

Flying indoors or in confined spaces is, nevertheless, tricky. Such a vehicle must fly with agility at low speeds without smashing into walls, ceilings, and other objects, hover for sustained periods, take off and land vertically, and have low power consumption. Several groups worked on MAVs based on fixed and rotary wings, but simply miniaturizing conventional aircraft technology to achieve this goal is not viable. Fixed-wing flyers are not ideal to undertake these missions because they can not hover and have to fly relatively fast to generate lift. Rotary-wing MAVs can hover, but they require a lot of power. However, they can not fly close to walls since the air pushed down by the rotor bounces off the wall and interrupts the downward flow of air through the rotor [2]. Therefore, many researchers are pursuing biomimetic aerial vehicles which use flapping wings as the most viable option to solve this problem, allowing for micro and nano air vehicles that fly at Reynolds numbers (the ratio of inertia to viscous friction) infeasible with fixed-wing flight [3]. It is also clear that flapping flight provides superior maneuverability that would be beneficial in obstacle avoidance and for navigation in small spaces.

Bearing these facts in mind, the paper is organized as follows. Section two presents some historical aspects of biological inspired flight. Section three introduces the research that is being developed in the areas of modelling and simulation of animal flight. Sections four and five present several biological inspired flying robots, and the concepts that are being considered for the control of these machines flight, respectively. Section six presents the research directions that are open in this area and, finally, section seven outlines the main conclusions.

2. Historical Aspects of Flapping Wing Fly

The first concepts in the area of biological inspired flying locomotion are quite old. Man's desire to fly goes back as far as the legend of Icarus. Since at least 500 BC, in ancient Greece, humans have been fascinated with birds and other flapping wing creatures. Fascination has spawned not only myths and fairy tales, but also the imagination of designers and engineers to mimic biology. The first ideas to implement biological inspired flying vehicles date from the XV century. Leonardo da Vinci, convinced that "Man forcing his big artificial wings against the resistance air, winning, rule and rise above it", began to work on a machine, powered by muscular activity alone, which would allow a man to hover in the air by moving its wings like birds do. There are drawings which show the various kinds of "ornitotteri", the flying machines designed by Leonardo (Figure 1). The "ornitotteri" was a significant outgrowth of Leonardo's studies on the anatomy of bird's wings and on the analysis of the function and distribution of its feathers [4], but it took until 1870 for the first successful ornithopter to be flown 70 meters by its builder Gustave Trouvé [5].

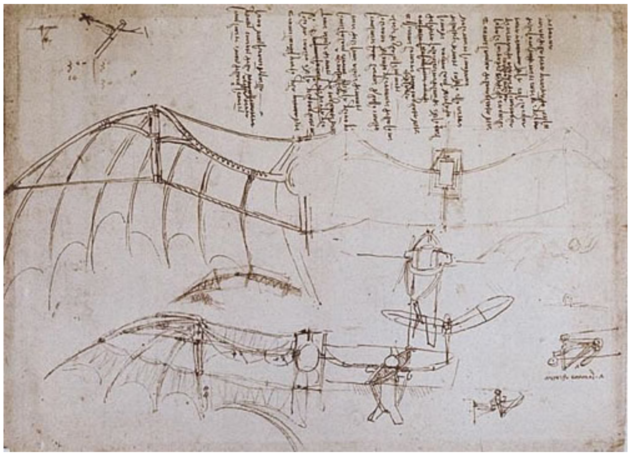

Figure 1. Drawings of Leonardo da Vinci studies for an human powered "ornitotteri"

However, sometimes, engineered technologies are unable to implement the physical principles used in the biological system. Prior to the initial flight by the Wright brothers with fixed-wing flight, articulated-wing flight was attempted but failed. At the time, fixed-wing flight proved more feasible. However, articulated-wing flight is now possible and today, biomimicry of flapping flight continues to fascinate engineers and designers who continue to try to fully capture the efficiency of the natural world.

Insect flight has been a subject of academic interest for at least half a century, but serious attempts to emulate it are more recent [2]. Regarding birds flight, aircraft designers have long been interested in morphing capabilities. The field got a big boost in 1996, when the U.S. Defense Advanced Research Projects Agency (DARPA) launched a three-year MAV program with the goal of creating a flyer less than 15 centimeters long for military surveillance and reconnaissance. A few fixed-wing designs were successfully demonstrated, most notably the Black Widow, from AeroVironment Inc. [6]. Several rotary-type MAVs were also put forward. But no group managed to get an insectlike flapping-wing design flying off the ground. Recently, a number of groups have also been working on morphing wing concepts [7]. Based on these biomimetic ideas some modern examples of ornithopters are under development [5]. A team at the University of Toronto, for example, developed a flapping plane, powered by an internal combustion engine that carries a pilot on board (Figure 2).

Figure 2. University of Toronto flapping plane

However, in order to achieve autonomy for a flapping micro air vehicle, there is the need to a deeper understanding of animal's flight, and the machines to be built will need actuators to drive the wings, sensors to provide measurements of both internal and external parameters, and a controller that processes these measurements to determine what signals to send to the actuators.

3. Modelling and Simulation of Flight

Flight dynamics of flapping animals is still an open area of research. This is primarily due to the difficulties in measuring aerodynamic forces on real animals, and in experimentally validating proposed theoretical models. For example, wing shape is instrumental in getting the bird aloft and keeping it there. In this respect, birds and traditional airplanes are similar. Both rely on Bernoulli's principle in order to create a lifting force. Insects, by contrast, flap their wings at high speed and rely on different lift mechanisms [7]. But birds and planes control their flight very differently. Conventional airplanes maneuver by means of moving surfaces: flaps and ailerons on the wings, elevators on the tail, and also the rudder. Birds, on the other hand, can bend, twist, and deform their wings and bodies to turn, change their speed, and adapt to unforeseen conditions such as wind gusts. If planes could do the same, they would have more lift and less drag, gaining agility and consuming less fuel [7]. These are just some of the aspects of animal's flight that researchers try to understand better.

3.1 Insect's Flight

The range of Reynolds number in insect flight is about 10 to 10^4, which lies in between the two limits that are convenient for theories: inviscid steady flows around an airfoil and Stokes flow experienced by a swimming bacterium. For this reason, this intermediate range is not well understood. On the other hand, it is perhaps the most ubiquitous regime among the things we see. Falling leaves and seeds, fishes, and birds all encounter unsteady flows similar to that seen around an insect.

The main questions in this area are “How do insects flap their wings?” and “What force does an insect wing generate?”. As the wing flaps, it creates swirls of air and generates aerodynamic forces that allow insects to dart forward, to turn, and to hover. Measuring the instantaneous aerodynamics forces on a live insect remains a challenge. To deduce the force on a single wing, all four (or two) wings are presumed to behave in the same way, which is approximately true in special cases, and the wing inertia and forces on the body must be subtracted. These effects all contribute to the uncertainty in the measurements. Most theoretical predictions of aerodynamic forces in an insect wing are based on the similarity and differences between an insect wing and a classical airfoil. In parallel, computer codes were developed to solve the Navier-Stokes equation around a moving wing. Several methods lead to prescriptions of complex and feasible geometries. The trade-off is that they are relatively expensive and it is difficult to achieve high-order accuracy. Improvements of these methods remain a challenge in computation fluid dynamics [8].

Zang [8] presents a review of recent experimental, computational and theoretical progress in “taking the insects apart” to scrutinize the forces and flows around a flapping wing. Hamamoto *et al.* [9] have been studying real dragonfly flight and have investigated a design for an artificial actuated wing using numerical analysis and finite element simulation based on the arbitrary Lagrange-Euler method. These authors use the simulation model developed to study several parameters important for the correct design of actuated wings (whose shape is based on the wings of real dragonflies), namely the lift force, the properties of the motors needed to generate the required lift force, the stress on plates and hinges, and the effect of backlash in the hinges on wing motion. Schenato *et al.* [10] model the dynamics of a flying insect as a rigid body subject to external forces. Although wings do move relative to the insect body and they can give rise to nonholonomic dynamics, recent experimental results on *Drosophila* flight seem to exclude this effect. Therefore, they assume that the insect body motion evolves according to the rigid body-motion equations subject to external forces relative to its center of mass. The external forces acting on an insect are the aerodynamic forces generated by the wings, the gravity force, and the body viscous drag. Also, since only slow body rotations are considered, angular viscous forces are neglected. Finally, these authors assume that the aerodynamic torques can be controlled exactly and continuously. In reality, the aerodynamic forces generated by flapping wings are highly time varying within a single wing beat, and they can not be controlled instantaneously. These researchers plan to employ more realistic insect body dynamics, which can account for the viscous torques resulting from body rotation, and to consider limiting factors such as input torque saturation and control of the torques only on a wingbeat-by-wingbeat basis. Deng *et al.* [11] present the modeling of the Micromechanical Flying Insect (MFI). The mathematical models are developed based on biological principles, analytical models, and experimental data. These models include the wing-thorax dynamics, the flapping flight aerodynamics at low Reynolds number regime, the body dynamics and the sensory system. These models are presented in the Virtual Insect Flight Simulator (VIFS) and are integrated together to give a realistic simulation for MFI and insect flight. VIFS is a software tool intended for modeling flapping flight mechanisms and for testing and evaluating the performance of different flight control algorithms [12].

3.2 Bird’s Flight

Birds are one of the sources of man’s inspiration to fly. They are extremely agile fliers, controlling their flight by changing their wings’ cross section, length, area, sweep, and inclination (Figure 3) [7]. However, very little of their morphology is manifested by modern aircraft. It is known that different wing shapes, either in planes or in birds, yield different types of flight [7]. Birds morph their wings and tails in very complex, yet fluid ways, in contrast to the very discrete control surfaces found on today's aircraft. Birds can change their wing area and shape radically to suit high speed attack and low speed loiter, as well as large variations in maneuverability [13].

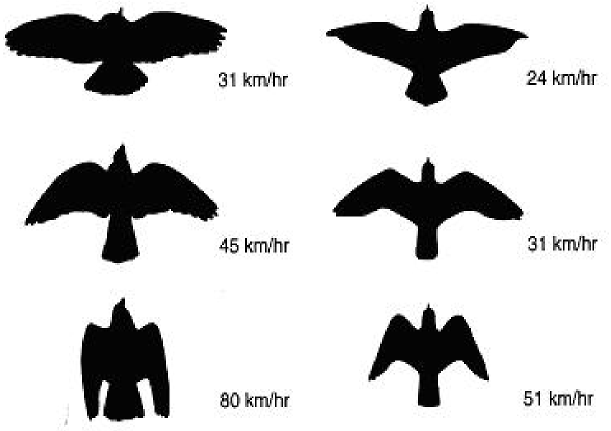

Figure 3. Wing morphologies for hawks (left) and pigeons (right)

Colozza describes an ongoing study into bio-inspired morphing flight to analyze the extent that birds "morph" their bodies in flight, to discover how they benefit aerodynamically from these changes, and to develop technology to be applied to unmanned aerial vehicles (UAV's) [7]. His project on designing a morphing wing solid-state aircraft begun by considering two basic aspects of bird flight: the shape of the wings and how they flap. His group studied the wings of various birds in search of an appropriate model for the aircraft and what grabbed their attention was the pteranodon, a carnivorous pterosaur that lived more than 75 million years ago [7]. Hou *et al.* [14]

present a method for capturing the effects existing in highly nonlinear flow movements generated by bird's wings. These nonlinear effects arise in general from changes in wind shape and from finite deviations in wing trajectory from a rectilinear course. The former effect is local, bearing instantaneous effects, whereas the latter is due to wing-wake interactions. These nonlinear effects are very important in cases involving irregular movements such as highly curved paths (e.g. quick U-turns). The main difficulty arises when analysing the fluid properties near the trailing edge of a wing, as well as the behaviour of the flow with complicated distributions of vortices, both bound to the wing and free after being shed.

4. Biological Inspired Flying Robots

Based in these ideas, several robots are already under development adopting biological inspired wings for flying. MAVs used for military reconnaissance, being considerably smaller than previously designed ornithopters, have spawned interest in the biomimicry of common houseflies. Researchers are interested in gaining an understanding of the sensory and mobility aspects that would be required to mimic nature's design with engineering solutions [15]. Therefore, three of the following biological inspired robots examples are based in flies.

4.1 Micromechanical Flying Insect

The Micromechanical Flying Insect (MFI) project aims to create a biologically inspired, autonomous, flapping-wing MAV robot, approximately 25 mm in size (wingtip to wingtip), capable of sustained autonomous flight [10, 16], and complex behaviors, mimicking a blowfly *Calliphora* [11]. The project started in May 1998, inspired by early work by Dickinson *et al.* [17] who quantified the precise lift mechanisms fruit flies rely upon to fly. In 2001, this team produced a 25-millimeter-long proof-of-principle demonstrator based on MEMS technology. Originally the MFI was envisioned to incorporate unimorph piezoelectric bending actuators combined with stainless steel joints and flexures along with an accordion style wing to achieve flight [2]. Advances in the work, however, led to the development of novel bimorph piezoelectric actuators along with carbon fiber/polyester links and flexures. The MFI electromechanical plant consists of bimorph PZT actuators, a fourbar transmission mechanism, a differential mechanism to allow wing rotation and the wing itself. Figure 4 shows the current version of the 4 DOF, 2 wing MFI that weighs approximately 100 mg, without battery or electronics [18].

4.2 University of Missouri-Rolla MAV

A common housefly has been modeled functionally for a MAV project being researched at the University of Missouri-Rolla (UMR). Due to complexities of sensor and mobility design, the UMR MAV and many other MAVs are not mature enough to compare with the complete housefly at a function-form (morphological) level. For this reason, the flight mobility was extracted from the housefly functional model and compared to a simpler MAV, which provides an engineering solution for only the flight aspect of the housefly [15].

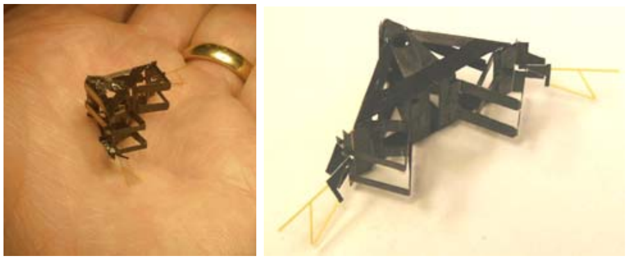

Figure 4. Micromechanical Flying Insect

4.3 University of Delaware Sparrow Flapping Wing MAV

Also the Sparrow Flapping Wing Micro Air Vehicle (FWMAV), developed at the University of Delaware, mimics the flight aspect of a common housefly (Figure 5) [21, 22]. This model simplicity is the result of the exclusion of all sensors and navigational control. It consists solely of a power source, power train, wings and chassis, allowing it to fly freely in circular paths. The wings of the FWMAV are directly analogous to nature, with their optimization of weight, local and overall stiffness and fluid dynamics properties.

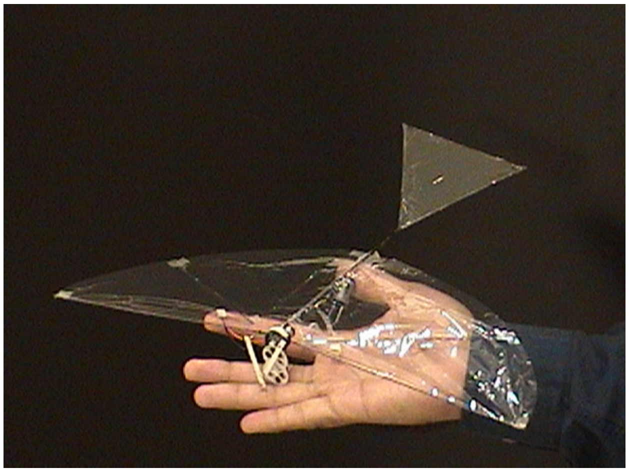

Figure 5. University of Delaware Sparrow Flapping Wing MAV

4.4 Solid Sate Aircraft

A research group, with funding from the NASA Institute for Advanced Concepts, completed a feasibility study and worked out an initial design, and even some functional proof-of-principle models, for an unmanned, solar-powered, and made of strong, lightweight materials, ultra-slim flying vehicle inspired on birds flight. This plane wings should be able to adjust some of their characteristics, such as cross section, length, area, sweep, and inclination. This vehicle will glide most of the time while collecting power from the sun and flapping only to maintain altitude [7].

This machine size could range from a few meters across to perhaps a hundred meters, depending on its mission. Thanks to its flexible body, it could be stowed, transported, and then deployed in remote places on Earth or even on other planets whose inhospitable atmospheres would make unviable planes that need oxygen to burn their fuel. Rather than a metal framework covered by riveted plates and hydraulically actuated parts, that give the wing its aerodynamic shape, like most planes, this vehicle's structure will consist of layering together different materials to form a compact, nonhollow body and a thin and slightly curved airfoil that would approximate that of a pteranodon wing [7]. The body and wings would consist of a material called an ionic polymer-metal composite, or IPMC, which deforms when exposed to an electric field (Figure 6 – left). The deformation is proportional to the electric field's strength and, once the field is removed, the sheet returns to its original shape. If the voltages are applied just right, the material can be made to flap like a wing. On top of the composite wings would be paper-thin sheets of photovoltaic material and lithium-ion batteries, layered on by thin-film deposition. Together, these layers would power the plane. Because it will not have a single moving part, they call it the solid-state aircraft [7].

Figure 6. An artist's rendering of the solid-state aircraft (left) and two little wings, each 5 centimetres long, fabricated out of ionic polymer-metal composite (right)

The first tests started with two 5 cm long IPMC strips. After control electrodes were attached to each of these wings and a variable voltage was applied to the electrodes (Figure 6 – right). It was possible to see this primitive mechanism beating its wings fairly well, even at high flapping rates [7]. This research group then built a larger model, with 46 cm long wings, but this prototype responded erratically to the electric field.

4.5 Microflight Mechanism on Silicon Wafer

Other authors, namely Miki and Shimoyama, argue that, the Reynolds number is very low for the air flow around micro robots, the ratio of lift to drag becomes smaller and gliding is not a suitable method for the flight of micro robots [19]. Therefore, they propose a flight system which gains thrust by rotating the magnetized wings in an alternating magnetic field. Furthermore, they state that a rotating wing is easier to fabricate and analyse aerodynamically when compared to a flapping wing. It is also known that the beating of wings corresponds to a nervous stimulus in most insects, just like on-off control. In some insects, like bees and mosquitoes, the beating frequency is higher than that of the nervous stimuli, being this frequency determined by the resonant frequency of the entire system, which consists of muscles, elastic hinges and the thorax. Later, based on this fact, Shimoyama *et al*. present a flying micromechanism implemented on a Silicon wafer [20].

5. Control of Flight

Conventional flight control uses a little measurement and a lot of computation. It is believed that the fly does exactly the opposite: a lot of measurement from many sensors and little computation. The fly attains remarkable performance, yet it is computationally quite simple, relying on extensive, distributed measurement of parameters of interest. Studies suggest that the fly's flight control commands originate from a few hundred neurons in its brain (out of the brain's total of about 338000 neurons). Then, flies are not executing millions of calculations to solve forbidding differential equations in midair. But they still must obey the same laws of physics as any man made plane so, whatever they are doing, it must be functionally equivalent to solving those equations in real time. Zbikowski calls this the sensor-rich feedback control paradigm [2]. From an engineering viewpoint, this opens up new possibilities in control, as well as in sensors and instrumentation.

The current focus of the MFI project is to realize the proper wing stroke (flapping and rotation) sufficient to achieve the necessary amount of lift. A simple control strategy has been chosen for the MFI (due to actuator limitations) in which the wings will be controlled (open loop) with the ability to switch between several different wing strokes determined, a priori, to generate known amounts of forces and torques. To realize open loop control it is necessary to determine an experimental model of the mechanical plant. To realize proper stroke, the wing position itself would ideally be sensed and then controlled, but if the fourbar and differential are considered to have a high serial stiffness, any part of the fourbar or actuator can be used to infer the position of the wing [18]. With this purpose the authors developed a fiberoptic reflection position sensor and associated circuitry that yields a high resolution (approximately 5 μm of linear motion), appropriate scale, and real time method for sensing the state of the MFI [18].

Concerning the high level MFI flight control, Schenato *et al.* combine the outputs from the *ocelli* and the *halteres* to obtain global stabilizing control laws to align the axis of the body frame with the axis of the fixed frame. Based on the intuition that the input torque should rotate the insect body frame such that the angle would decrease, they propose an output feedback law to stabilize the insect orientation [10]. From their experiments, they conclude that a simple proportional feedback law of the *ocelli* and *halteres* outputs can steer the orientation such that the insect's axis will always point toward the light source regardless of the initial condition. Furthermore, they also conclude that if the damping gain is sufficiently large and the dynamics of the insect is slow enough, the field generated by the ocelli feedback steers, in practice, all the trajectories toward the stable orientation. According to these authors, this control law is very promising for three main reasons: it is simple, it is robust, and it is globally stabilizing.

6. Future Research Directions

Despite the several prototypes developed up to now, no research group has built a flying autonomous ornithopter. A number of factors are keeping this from happen, including weight reduction and a good power source, but the key issue is flight control. It is not good enough to have "something flying". The great draw of insect flight is its extreme agility, and this amazing capability can be achieved only by appropriate flight control. Unraveling the secret of insect maneuverability requires first understanding the underlying aerodynamics and mechanics of insect flapping [2].

7. Conclusion

This paper has presented a series of research issues that are under study in order to allow the development of true autonomous flapping wings flying robots. Although not an exhaustive study, we believe that were able to show that in order to achieve autonomy for a flapping vehicle, there is the need to promote further developments in the actuators to drive the wings, in the sensors to provide measurements of both internal and external parameters, and in the controller that processes the sensors measurements to determine what signals to send to the actuators. Furthermore, a great effort is also needed in the areas of modeling and simulation of insect and birds flight in order to better understand how these creatures fly.

References

[1] M.F. Silva, & J.A.T. Machado, A Historical Perspective of Legged Robots, *J. of Vibration and Control, 13*(9-10), 2007, 1447 – 1486.

[2] R. Zbikowski, Fly Like a Fly, *IEEE Spectrum, 42*(11), 2005, 46–51.

[3] M. Motamed & J. Yan, A Review of Biological, Biomimetic and Miniature Force Sensing for Microflight, *Proc. of the IROS'2005*, Canada, 2005, 2630–2637.

[4] M. Cianchi, *Leonardo da Vinci's Machines* (Florence: Becocci Editore, 1988).

[5] Ornithopter Zone, Nathan Chronister, Ornithopter Media Collection, [cited 2007 Oct. 5]; Available from: http://www.ornithopter.org.

[6] J. Grasmeyer & M. Keennon, Development of the Black Widow Micro Air Vehicle, *Proc. of the 39th AIAA Aerospace Sciences Meeting and Exhibit*, NV, USA, 2001, AIAA Paper No. AIAA-2001-0127.

[7] A. Colozza, Fly Like a Bird, *IEEE Spectrum, 44*(5), 2007, 38–43.

[8] Z.J. Wang, Dissecting Insect Flight, *Annual Review of Fluid Dynamics*, *37*(1), 2005, 183–210.

[9] M. Hamamoto, Y. Ohta, K. Hara & T. Hisada, Feasibility Study of an Actuator for Flapping Flight Using Fluid-Structure Interaction Analysis, *Proc. of the ICRA'2006*, USA, 2006, 2176–2181.

[10] L. Schenato, W.C. Wu & S. Sastry, Attitude Control for a Micromechanical Flying Insect via Sensor Output Feedback, *IEEE Trans. on Rob. and Aut., 20*(1), 2004, 93-106.

[11] X. Deng, L. Schenato, W.C. Wu & S.S. Sastry, Flapping Flight for Biomimetic Robotic Insects: Part I – System Modeling, *IEEE Trans. on Rob.*, *22*(4), 2006, 776–788.

[12] L. Schenato, X. Deng, W.C. Wu & S.S. Sastry, Virtual Insect Flight Simulator (VIFS): A Software Testbed for Insect Flight, *Proc. of the ICRA'2001*, South Korea, 2001, 3885–3892.

[13] Morphing Aircraft Project at Cornell Unversity [cited 2007 Oct. 11]; Available from: http://morphing.mae.cornell.edu/mission.htm.

[14] T.Y. Hou, V.G. Stredie & T.Y. Wu, Mathematical Modeling and Simulation of Aquatic and Aerial Animal Locomotion, *J. of Comp. Physics*, *225*(2), 2007, 1603–1631.

[15] A. Tinsley, P.A. Midha, R.L. Nagel, D.A. McAdams, R.B. Stone & L.H. Shu, Exploring the use of Functional Models as a Foundation for Biomimetic Conceptual Design, *Proc. of the ASME 2007 Int. Design Engineering Technical Conf. & Computers and Information in Eng. Conf.*, USA, 2007, DETC2007–35604, in CD-ROM.

[16] W.C. Wu, L. Schenato, R.J. Wood & R.S. Fearing, Biomimetic Sensor Suite for Flight Control of a Micromechanical Flying Insect: Design and Experimental Results, *Proc. of the ICRA'2003*, Taiwan, 2003, 1146-1151.

[17] M.H. Dickinson, F.-O. Lehmann & S.P. Sane. Wing rotation and the aerodynamic basis of insect flight, *Science, 284*(6), 1999, 1954–1960.

[18] E. Steltz, R.J. Wood, S. Avadhanula & R.S. Fearing, Characterization of the Micromechanical Flying Insect by Optical Position Sensing, *Proc. of the ICRA'2005*, Spain, 2005, 1264–1269.

[19] N. Miki, & I. Shimoyama, Analysis of the Flight Performance of Small Magnetic Rotating Wings for Use in Microrobots, *Proc. of the ICRA'1998*, Belgium, 1998, 3065–3070.

[20] I. Shimoyama, Y: Kubo, T. Kaneda & H. Miura, Simple Microflight Mechanism on Silicon Wafer, *Proc. of the IEEE Workshop on MEMS*, Japan, 1994, 148–152.

[21] S.H. McIntosh, S.K. Agrawal, & Z. Khan, Design of a Mechanism for Biaxial Rotation of a Wing for a Hovering Vehicle, *IEEE/ASME Trans. on Mechatronics*, *11*(2), 2006, 145–153.

[22] Z.A. Khan & S.K. Agrawal, Design of Flapping Mechanisms Based on Transverse Bending Phenomena in Insects, *Proc. of the ICRA'2006*, USA, 2006, 2323–2328.