17th U.S. National Congress on Theoretical and Applied Mechanics
Michigan State University, 15-20 June 2014

Abstract: F-04-1204

Design, Fabrication, and Control of Sub-Gram Flapping-Wing Artificial Flyers

Néstor O. PÉREZ-ARANCIBIA, Department of Aerospace & Mechanical Engineering, USC, perezara@usc.edu

Flapping-wing flight is ubiquitous in nature, and therefore, *artificial flyers* (AFs) that employ this way of locomotion are intrinsically biologically inspired. The notion of finding inspiration in nature in order to create novel engineering systems, flapping-wing AFs in particular, follows from the observation that nature has already found feasible solutions to a great variety of problems. The process of evolution by natural selection has produced flapping-wing flyers with great diversity in terms of size, shape and preferred flight modes. Individual members of a given species might display a gamut of flight gaits, well adapted to different conditions, which might induce to believe that flying animals evolved to function in an optimal way according to some figure of merit in order to increase their flying performance in terms of efficiency, maneuverability or other relevant system characteristic. However, the evolved designs of flying animals are a compromise between several biological functions. For example, the wings of some butterflies act in sexual and territorial display, in cryptic or warning defense and in thermoregulation [1, 2, 3]. Similarly, some elements in the complex flying behavior of honeybees might reflect an evolutionary adaptation to their complex social structure, or to the extraordinary navigational challenges they face as part of their daily routine [4], and not necessarily reflect advantages from an aerodynamic perspective. With this precaution in mind, it is possible to envision a systematic method for designing flapping-wing AFs, in which the first step is to translate the aerodynamic properties and parameters of a feasible benchmark system (a natural flyer) into a robotic design. Thus, parameters such as the flapping frequency, stroke amplitude, wing aspect ratio, steady-state effective angle of attack, angle of the stroke plane, total weight, and other relevant characteristics of the biological system are taken as given design specifications, so that, dimensionless numbers commonly used in the analysis and design of aerodynamic systems (*Reynolds number* (Re), *Strouhal number* (St), *lift coefficient* (C_L), *drag coefficient* (C_D), etc.) remain inside ranges that make flight of biologically-inspired flapping-wing AFs feasible.

A frequent reason invoked to support the use of flapping-wing flight is great maneuverability and agility [5, 6]. However, there exist other strong reasons to employ flapping-wing flight at small scale and moderate Reynolds numbers ($10^2 \leqslant Re \leqslant 10^4$) [7]. The most compelling one is the integration of lift and thrust together with stability and control mechanisms. Thus, all forces on the surrounding fluid derive from the motions of the same actuators, as for example reported in [8], which has great implications in managing the final total vehicle weight. Also, it has been argued that for small Reynolds numbers, flapping-wing flight and steady flight have similar aerodynamic power requirements [7]. Furthermore, it has been suggested that for appropriate flight modes, flapping-wing flight can save aerodynamic power compared to steady flight [9].

Due to stringent constraints on weight and volume, the creation of insect-scale flapping-wing AFs is, arguably, one of the most difficult cases of biologically-inspired engineering, because the subsystems composing the robot are required to be extremely complex while remaining light and small. During the last few years, significant progress in the development of *sub-gram artificial flapping-wing flyers* (SAF^2s) has been published [10, 11, 5, 12, 13, 14, 8] and recent versions of piezoelectric-actuated SAF^2s represent significant advances in terms of robotic design, micro-fabrication, micro-sensing, and control [6]. However, power and energy constraints limit future progress toward the autonomy of piezoelectric-actuated SAF^2s. The problem emerges because in order to make a completely autonomous SAF^2, the microrobot has to carry its own source of energy and if piezoelectric actuators are used, the obvious energy source is batteries. However, even under extraordinary optimistic conditions, *state-of-the-art batteries* (SBs) would allow for only a couple of minutes of autonomous flight, because their *energy density* (ED) is very low compared to other sources of energy ($\sim 2.7 \times 10^5$ J $\cdot$ Kg^{-1} at the sub-gram scale). Furthermore, no existing battery technology can provide the power required by a piezoelectric-actuated SAF^2 of the kind in [6]. In contrast, the ED in the sources that natural insects use (proteins, carbohydrates and fat) is significantly larger than that of the SBs. In particular, the ED in animal fat is up to two orders magnitude ($\sim 3.7\times 10^7$ J $\cdot$ Kg^{-1}) larger than the ED corresponding to the best batteries available today. Similarly, the ED in hydrocarbon fuels is also up to two orders of magnitude larger than the ED in SBs, which suggests that the grand vision of creating an autonomous colony of SAF^{2}s will be realized only when novel actuators capable of transforming chemical energy into mechanical energy are developed, even though this kind of energy transformation is more inefficient than transforming electrical energy into mechanical energy.

Another limitation of the SAF^{2}s described in [6] is that they employ, as a default, the normal hovering flight mode as defined in [15], which requires a much greater power than other flight modes [4, 16]. This phenomenon is explained by the fact that normal hovering uses a horizontal stroke plane, so that, thrust is generated vertically and used to directly counteract the weight of the flyer. In contrast, other flight modes, such as, *flight forward flapping* (FFF) and gliding take advantage of forward velocity to generate positive vertical forces. In the case of FFF flight, the thrust generated by the flapping wings is employed to propel the flyer forward and lift is produced because flyers' wings move horizontally with an average positive effective angle of attack. In fact, using the quasi-steady blade element method [15, 17, 18] and control-and-systems analytical tools, it can be shown that it is possible to design a SAF^2 that uses FFF as its default flight mode with an *aerodynamic power efficiency* (APE) of ~ 4 W $\cdot$ Kg^{-1}, while in contrast, the estimated APE for the state-of-the-art piezoelectric-actuated SAF^2 in [6], that uses normal hovering as its default flight mode, is ~ 28 W $\cdot$ Kg^{-1}.

The development of new actuation methods and aerodynamic designs requires the invention of new control algorithms and real-time implementation techniques for low-level actuator excitation and high-level flight control. In specific, the control challenges emerge because the materialization of new SAF^2 designs implies the creation of new feedback control strategies in order to stabilize highly unstable systems and follow desired flight trajectories. Both objectives can be achieved by controlling altitude, and the pitch and roll angles. At the actuator level, new feedforward and feedback high-performance control methods are required to take advantage of the high ED in chemical sources of energy, such as, hydrocarbon fuels. New microrobotic designs (aerodynamic configurations + actuation techniques) can be materialized employing the meso/micro-fabrication techniques and materials described in [5]. Further research will be required for the development of new electronics for the computation of algorithms for control and communication.

References

[1] C. R. Betts and R. J. Wootton. Wing Shape and Flight Behaviour in Butterflies (Lepidoptera: Papilionoidea and Hesperioidea): A Preliminary Analysis. *J. Exp. Biol.*, 138(1):271–288, September 1988.

[2] R. Dudley. Biomechanics of Flight in Neotropical Butterflies: Aerodynamics and Mechanical Power Requirements. *J. Exp. Biol.*, 159(1):335–357, September 1991.

[3] R. Dudley. *The Biomechanics of Insect Flight*. Princeton University Press, Princeton, NJ, 2000.

[4] D. E. Alexander. *Nature's Flyers*. The Johns Hopkins University Press, Baltimore, MD, 2002.

[5] N. O. Pérez-Arancibia, K. Y. Ma, K. C. Galloway, J. D. Greenberg, and R. J. Wood. First Controlled Vertical Flight of a Biologically Inspired Microrobot. *Bioinspir. Biomim.*, 6(3):036009 (11pp.), September 2011.

[6] R. J. Wood, B. Finio, M. Karpelson, K. Ma, N. O. Pérez-Arancibia, P. S. Sreetharan, H. Tanaka, and J. P. Whitney. Progress on pico air vehicles. *Int. J. Robot. Res.*, 31(11):1292–1302, September 2012.

[7] G. R. Spedding and P. B. S. Lissaman. Technical aspects of microscale flight systems. *J. Avian Biol.*, 29(4):458–468, December 1998.

[8] N. O. Pérez-Arancibia, P.-E. J. Duhamel, K. Y. Ma, and R. J. Wood. Model-Free Control of a Flapping-Wing Microrobot. In *Proc. 16th Int. Conf. Adv. Robot. (ICAR 2013)*, Montevideo, Uruguay, November 2013.

[9] U. Pesavento and Z. J. Wang. Flapping Wing Flight Can Save Aerodynamic Power Compared to Steady Flight. *Phys. Rev. Lett.*, 103(11):118102 (4pp.), September 2009.

[10] R. J. Wood. The First Takeoff of a Biologically Inspired At-Scale Robotic Insect. *IEEE Trans. Robot.*, 24(2):341–347, April 2008.

[11] N. O. Pérez-Arancibia, J. P. Whitney, and R. J. Wood. Lift Force Control of a Flapping-Wing Microrobot. In *Proc. 2011 Amer. Cont. Conf.*, pages 4761–4768, San Francisco, CA, July 2011.

[12] N. O. Pérez-Arancibia, P. Chirarattananon, B. M. Finio, and R. J. Wood. Pitch-Angle Feedback Control of a Biologically Inspired Flapping-Wing Microrobot. In *Proc. 2011 IEEE Int. Conf. Robot. Biomim.*, pages 1495–1502, Phuket Island, Thailand, December 2011.

[13] N. O. Pérez-Arancibia, J. P. Whitney, and R. J. Wood. Lift Force Control of Flapping-Wing Microrobots Using Adaptive Feedforward Schemes. *IEEE/ASME Trans. Mechatron.*, 18(1):155–168, February 2013.

[14] P.-E. J. Duhamel, N. O. Pérez-Arancibia, G. L. Barrows, and R. J. Wood. Biologically Inspired Optical-Flow Sensing for Altitude Control of Flapping-Wing Microrobots. *IEEE/ASME Trans. Mechatron.*, 18(2):556 – 568, April 2013.

[15] C. P. Ellington. The Aerodynamics of Hovering Insect Flight. I. The Quasi-Steady Analysis. *Phil. Trans. R. Soc. Lond. B*, 305(1122):1–15, February 1984.

[16] G. R. Spedding. The Aerodynamics of Flight. In R. McN. Alexander, editor, *Mechanics of Animal Locomotion*. Springer-Verlag, Berlin & Heidelberg, Germany, 1992.

[17] M. F. M. Osborne. Aerodynamics of Flapping Flight with Application to Insects. *J. Exp. Biol.*, 28(2):221–245, June 1951.

[18] T. Weis-Fogh. Biology and Physics of Locust Flight II. Flight Performance of the Desert Locust (Schistocerca Gregaria). *Phil. Trans. R. Soc. Lond. B*, 239(667):459–510, July 1956.