Invited Paper

Challenges for micro-scale flapping-wing micro air vehicles

Robert J. Wood, Benjamin Finio, Michael Karpelson, Nestor O. Pérez-Arancibia, Pratheev Sreetharan, and John P. Whitney

Harvard School of Engineering and Applied Sciences, 33 Oxford St, Cambridge, MA 02138, USA

ABSTRACT

The challenges for successful flight of insect-scale micro air vehicles encompass basic questions of fabrication, design, propulsion, actuation, control, and power - topics that have in general been answered for larger aircraft. When developing a flying robot on the scale of flies and bees, all hardware must be developed from scratch as there are no "off-the-shelf" sensors, actuators, or microcontrollers that can satisfy the extreme mass and power limitations imposed by such vehicles. Similar challenges exist for fabrication and assembly of the structural and aeromechanical components of insect-scale micro air vehicles that neither macro-scale techniques nor MEMS can adequately solve. With these challenges in mind, this paper presents progress in the essential technologies for micro-scale flapping-wing robots.

Keywords: flapping-wings, micro air vehicles, microrobotics

1. INTRODUCTION

When observing insects in flight, their seemingly effortless motions mask the complexity of the underlying system. Take, for example, a bee lifting off from a flower. How are the wings generating and manipulating structures within the air? What are the mechanisms driving the wings? What is the musculature driving the mechanisms driving the wings? What are the metabolic processes that are powering the muscles? What are the sensor modalities that it is using to avoid obstacles and predators?

There are countless such questions and as engineers developing robotic insects, we can translate these biological questions into grand challenges for such microrobots. How can we build a robotic insect given the scale requirements and mass and power limitations? What are viable actuation mechanisms that will power flight? What can we understand about the functional morphology of the insect flight apparatus and how can we translate that knowledge into design rules that will result in effective propulsion systems? What are appropriate control strategies given the severe limitations on power, computation, and potentially on control authority? How can we power these robots? How can we address the computation needs, again given power and mass limitations? What algorithms can we develop to enable the robots to effectively coordinate? What are the programming methods applicable to colonies of hundreds or thousands of these devices?

Regardless of the question, one important common theme is the lack of an off-the-shelf solution for any of these topics. This presents numerous well-posed, but difficult engineering challenges. This paper describes some of these challenges - specifically for fabrication, sensing, and control - in the context of the creation of a robotic bee, the 'RoboBee'. The RoboBee concept, as shown in Fig. 1, will be used to guide the requirements for each of these topics.

1.1 Specifications

Approximate specifications for a RoboBee are listed in tab 1. The specifications highlight the challenges in constructing these robots, as is discussed in the following section.

Further author information: (Send correspondence to R.J.W..)
R.J.W.: E-mail: rjwood@seas.harvard.edu, Telephone: 1 617 496 1341

Micro- and Nanotechnology Sensors, Systems, and Applications IV, edited by Thomas George, M. Saif Islam, Achyut Dutta, Proc. of SPIE Vol. 8373, 83731J

doi: 10.1117/12.918154

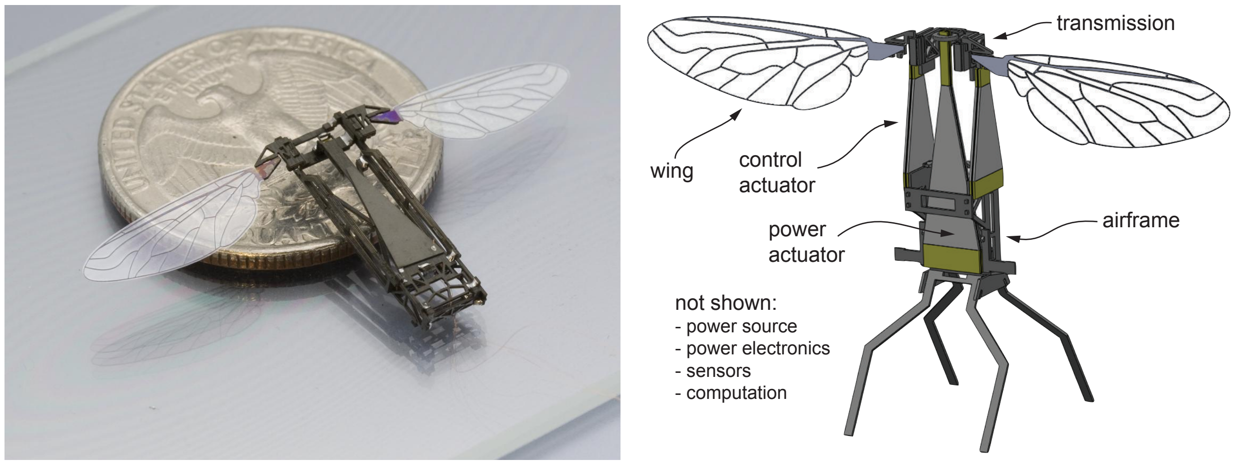

Figure 1. Recent prototype of a flapping-wing, insect-inspired micro air vehicle: the RoboBee.

Table 1. Specifications for a typical RoboBee.

Feature	Value	Notes
Total mass	53-125mg	Various versions
Thrust-to-weight	up to 3.5:1	Only aeromechanical components[1]
Actuator power density	$>200\text{W}\cdot\text{kg}^{-1}$	2×-4× insect flight muscles[2]
Total electrical power	∼50mW	For hover
Operating frequency	90-150Hz	Consistent with insect mass-frequency trends[3]
Reynolds number	∼3000	Wing tip Re
Control moments	$\sim 1\mu$Nm peak	Roll, pitch, and yaw[4]

2. FABRICATION

One of the biggest challenges for robots at this scale is fabrication. For devices with feature sizes on the order of micrometers, MEMS (Microelectromechanical Systems) provides one set of tools - traditionally derived from integrated circuit processing techniques. Indeed, many microrobots have been created using surface and bulk micromachining methods. Examples include MEMS crawling robots[5,6] and jumping robots.[7]

However, there are numerous drawbacks to these techniques. For example, the surface and bulk micromachining methods used in many MEMS processes are inherently aspect ratio limited. This means that high aspect ratio features are difficult to attain or require hinged structures.[8] A second limitation is materials restrictions typically associated with these methods. We would like to extend beyond the standard set of materials and include high performance composites, a variety of electroactive materials, and even discrete components. But most importantly, what we want is a process that will give us the ability to prototype these robots quickly, in-house, with minimal cost. The reason for this need is simple: given the complexity of these flying robots, complete dynamic models do not exist and thus a great deal can be learned through experimentation. Thus a fabrication method with a time constant measured in hours is desired (compared to time constants associated with MEMS which can typically be measured in months).

On the other end of the spectrum is more traditional macro-scale, 'nuts-and-bolts' methods based on bulk machining, rotary bearings, and electromagnetic motors. The physics of scaling tells us that as the characteristic dimension of a device is decreased, the surface-area-to-volume-ratio will increase. Therefore, even high efficiency bearings at larger scales will become inefficient as the feature size becomes much less than one millimeter due to the increased effect of area-dependent forces such as friction and van der Waals. Furthermore, macro-scale bulk machining and printing methods cannot achieve adequate resolutions.

Thus, a custom solution is required. The process begins with non-contact bulk machining of thin sheets of each constituent material using a diode-pumped solid-state (DPSS) UV laser. This provides the first key advantage: since most materials readily absorb UV, high quality and rapid machining is possible for virtually any class of material including polymers, ceramics, metals, and composites. The laser machining step also forms alignment features in each layer for the second step in the process. The second step is lamination using persistent pin alignment in a manner very similar to multi-layer printed circuit boards. Lamination is achieved by using free-standing acrylic sheet adhesives that are laser machined in the same manner as the structural materials. Upon curing, the structure is removed from the alignment jig and released from the supporting material using the DPSS laser. The third step in the process is assembly by folding. Since flexures are a simple component to manufacture using the machining and lamination steps, these steps provide the ability to create any 2D fold pattern. In previous iterations of this process, assembly folding was predominantly manual,[9] therefore requiring considerable skill and creating a bottleneck for rapid prototyping. The current process, called 'pop-up book MEMS', instead couples all the assembly folds to a single degree of freedom, analogous to children's pop-up books.[10] The ability to machine each of the individual layers and stack them in arbitrary order results in the ability to produce 'mechanical vias'. Analogous to electrical vias, mechanical vias connect any layer in the stack to any other layer distributed through the thickness and area of the quasi two dimensional device. This again enables the use of folding as an assembly tool, but now using parallel mechanisms built within the thickness of the device. The coupled motions of the parallel mechanisms defines the assembly trajectories for all the components of the device. Once this assembly is complete, the assembly degree of freedom is locked. In the case of the device in Fig. 1, locking is achieved through a dip soldering process. Once locked, the device is removed from the assembly scaffold with more laser release cuts. A final round of laser cuts release the functional degrees of freedom of the MAV.[11]

There are a couple key features of this process. First, there is no manual assembly involved. Second, the process is inherently derived from printed circuit boards. Therefore, embedding electronics within these devices is a trivial extension of the process. Third, by the inclusion of pre-stressed materials in the laminate, self-assembling structures are possible.[10] This process has been demonstrated on a number of example geometries and devices such as the MAV in Fig. 1. Fabrication and assembly time have been reduced from days to hours. However, given the complexity of the interconnections within the device and assembly scaffold, design is now a key bottleneck. CAD tools for the process do not yet exist and manual drawing can take weeks.

2.1 Design

As shown in Fig. 1, there are five key aeromechanics components of the flapping-wing MAV: wings, a transmission, power actuation, control actuation, and a rigid airframe. The transmission maps the motion of the power actuator to wing flapping which is illustrated in Fig. 2. The power and control actuators are clamped-free bending bimorph piezoelectric beams,[12] created using the same laser machining and lamination techniques described above. Similar to the function of Dipteran flight muscles,[2] the MAV in Fig. 1 has a morphological separation of power and control actuation. That is, the power actuator oscillates the transmission at the coupled resonant frequency of the actuator-transmission-wing system. The control actuators, by contrast, are smaller and lower power and create subtle asymmetries in the transmission resulting in bilaterally asymmetric wing motions and thus body moments.[13]

2.2 Propulsion

Propulsion is achieved by high velocity two degree of freedom wing motions. One key challenge in the development of such robots is an understanding of the functional morphology of the flight apparatus for purposes of design. While a systematic study of the insect flight apparatus may provide new insights into the structure-function relationships for flapping-wing insects, such a study is potentially expansive. Instead, the focus is on simplified models of the fluid dynamics of flapping wing flight, validated using experiments with at-scale models created using the techniques described in sec. 2. For example, recent work has validated the use of quasi-steady models originally derived for dynamically-scaled models of *Drosophila* flight[14] for these flapping-wing MAVs.[15] Ongoing work is exploring a variety of wing properties as part of an empirically-driven optimization of the propulsion system. Example wing properties of interest include aspect ratio, area distribution (i.e. in-board vs out-board), leading edge shape, and wing hinge compliance.

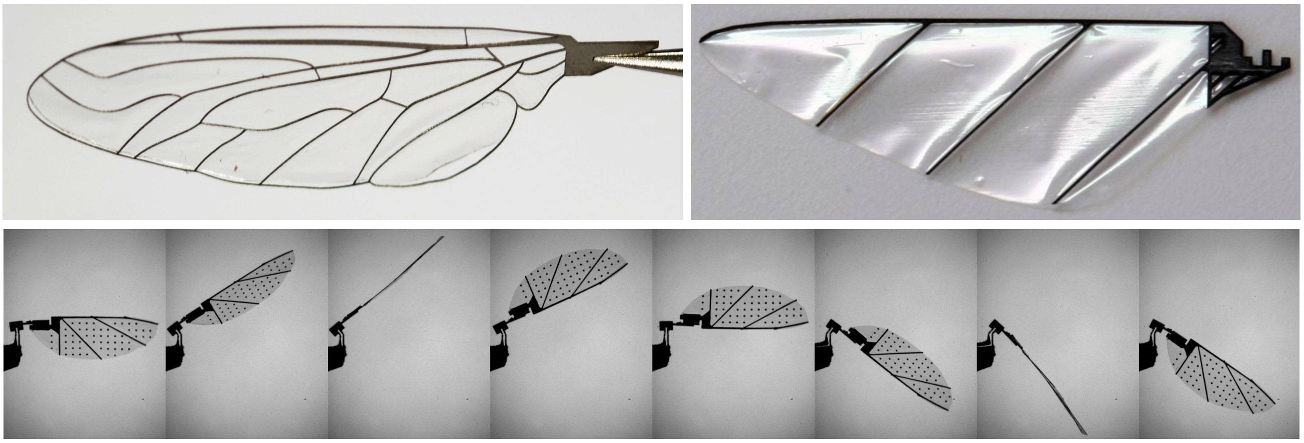

Figure 2. Two wing designs (top): a biomimetic wing vein structure made from laser-machined titanium foil (left) and a simplified vein pattern created from a carbon fiber reinforced composite (right). A typical wing motion is shown from an anterior perspective (bottom). Here the wing performs a two degree of freedom motion at 100Hz.

3. SENSING

Before considering control, it is important to explore the space of appropriate sensors. The challenges for effective sensors are three-fold. First, they must provide information about the state of the robot without the use of computation-expensive signal processing techniques (e.g. the zeroth, first, or second derivative of the body state). Second, they must comply with the strict payload budgets (i.e. mass and power). For example, from tab. 1, the payload capacity for a typical RoboBee will be approximately 100mg. Finally, the sensors must be simple to integrate within the body of the robot, with minimal manual assembly and, ideally, compatible with the process discussed in sec. 2.

3.1 Optical flow

Optical flow is a measurement of the velocity of objects in an observer's visual field due to the relative motion of the objects or the observer. It is clear that such vision sensing is important for a variety of maneuvers in insects including obstacle and predator avoidance, target tracking, and landing.[16] Recently, the first flight-worthy vision sensors have been integrated on an insect-scale MAV and used in closed-loop control of altitude.[17]

3.2 Horizon detection

Insects utilize 'simple eyes', called ocelli, for horizon detection and thus attitude stabilization. The simple eyes typically consist of three small photoreceptive sensors that can be thought of as single pixels arranged to view different areas of the visual field. These sensors therefore measure light intensity in different directions and thus can measure the orientation of the insect with respect to the sun or horizon.[18] A bio-inspired ocelli is shown in Fig. 3. At 15mg and consuming 50-100μW, this sensor is well within the payload and power capabilities of a RoboBee.

3.3 Inertial measurement

In addition to photoreceptive sensors, insects use a variety of inertial sensors. One of the more intriguing examples is found in Dipteran insects. Diptera - two-winged insects - evolved from four-winged insects. The hind wings lost their aerodynamic significance and became essentially oscillating proof masses able to detect Coriolis forces from body angular velocities. These sensors, called halteres, are thought to play a significant role in the astonishing maneuverability of many species of flies.[19] Artificial halteres have been constructed and shown to have favorable characteristics when compared with off-the-shelf inertial measurement units for small MAVs.[20]

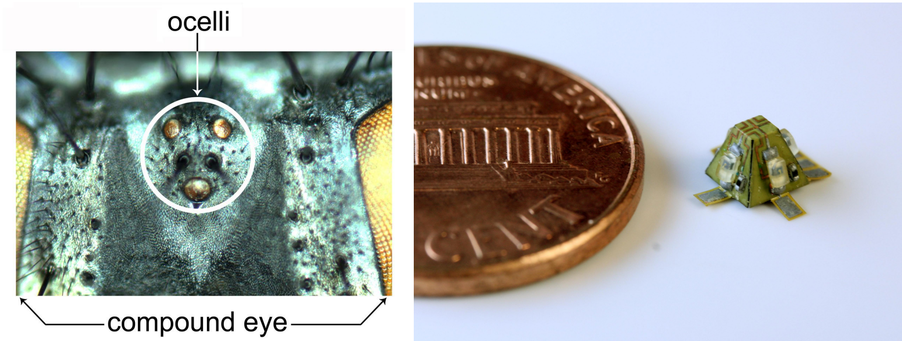

Figure 3. Location of the ocelli on the head of a *Caliphora* (left) and a prototype of a horizon detection sensor inspired by insect ocelli (right).

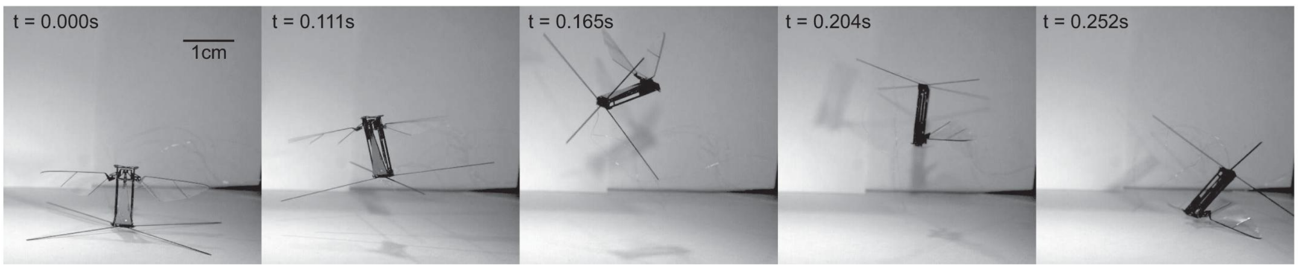

Figure 4. When unconstrained, these flapping-wing MAVs are inherently unstable, highlighting the need for active control.

4. CONTROL

To motivate control, consider what happens when the MAV from Fig. 1 is driven open-loop and unconstrained. The devices are designed such that the nominal wing trajectories are symmetric and the mean lift vector passes through the center of mass. However, in practice fabrication errors result in undesired body torques that trigger instabilities in body attitude. This is shown in the crash sequence in Fig. 4.

Topics for the control of flapping-wing MAVs fit into three categories: design of the wing drive mechanisms (i.e. transmission designs that result in controllable body torques), design of control algorithms for a given wing drive architecture, and passive mechanisms that can achieve perturbation rejection without active control.

The design of active mechanisms parallels the morphological separation of power and control muscles in Dipteran insects. In the MAV in Fig. 1, the power actuators are designed for power transfer (at or near resonance) to maximize the wing velocity while the control actuators are designed to provide quasi-static modifications to the transmission to create wing motion asymmetries. This is illustrated in the kinematic diagram in Fig. 5. There, the power actuator input is δ_1 and the control actuator inputs are δ_2 and δ_3. The action of the control actuators moves the ground points for the two nominally symmetric halves of the transmission. This creates an asymmetric transmission such that input from the power actuator is coupled differently to the left and right wings, thereby creating a difference between the two wing velocities and thus different aerodynamic forces. The design shown in Fig. 5 is not unique; there are many related designs that operate on the same principle of separation of power and control actuation.[21]

Controllers for these MAVs can do a number of things: follow a wing motion reference, follow a force and/or torque reference, or ultimately an altitude or attitude reference. In any of these cases, there are variety of options including controllers which are adaptive in nature based upon an estimate of the plant model,[22] controllers which are repetitive in nature that may be appropriate to reject periodic perturbations from an oscillating system, or some combination of the two.[23] Regardless of the controller, one key challenge lies in the practical application of these techniques to actual prototypes. Since even seemingly minor fabrication errors may cause significant differences in the dynamics of each prototype, controller synthesis for these MAVs is highly experimental. First, the device is connected either to a multi-axis force/torque sensor or to guides which restrict the motion to a small

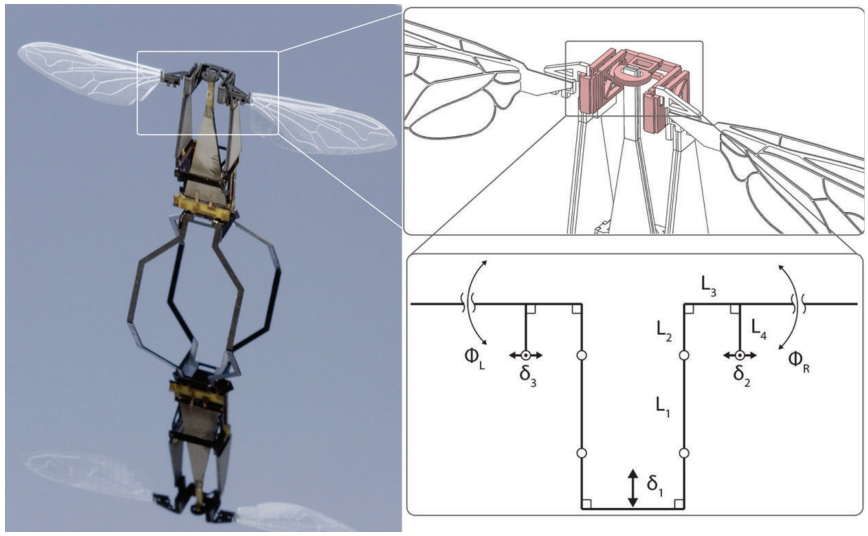

Figure 5. The algorithmic side of control is not considered separately from design. Here, the actuator inputs to the thorax of the MAV (upper right) are shown in a kinematic diagram (lower right).

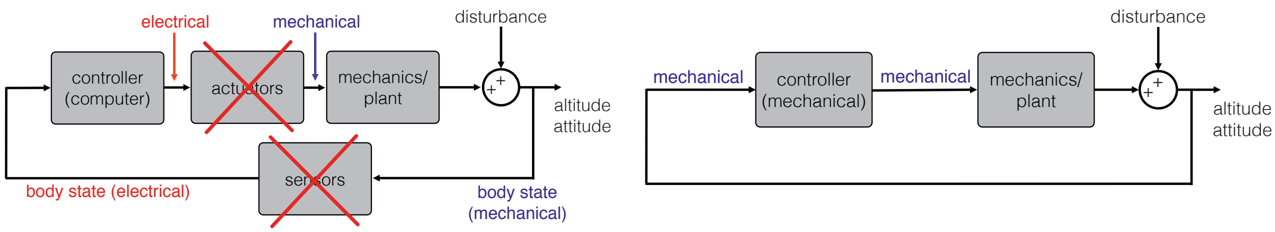

Figure 6. Diagram of a typical feedback control system highlighting the components used in transducing information throughout the system (left). An analogous system, but without sensors and actuators is entirely mechanical and passive (right). This is an abstraction of *mechanical intelligence*.

number of degrees of freedom. Second, the power and control actuators are systematically fed pseudo-random inputs while observing the response of the system. A subspace algorithm[24] then identifies the dynamics and a controller can be synthesized based upon the identified plant model. This method has successfully demonstrated wing force control,[22] altitude control,[1] and pitch control.[25]

Consider the traditional feedback control diagram on the left in Fig. 6. The (mechanical) body state is transduced into electrical information by some sensor(s). The sensor information is processed by a control computer resulting in an electrical signal that is fed to the actuator(s). The actuator(s) then transduce this electrical signal to forces or torques that are applied to the plant. For human-scale systems, the mass and power penalty associated with adding sensors, actuators, or computational elements into the system is relatively small. For the insect-scale devices considered here, that is not true - every milliwatt and every milligram counts. So this suggests the following question: can we create systems which perform some level of control but are purely mechanical in nature? Control, in this case, is not referring to high-level control tasks such as navigation. Instead, control here refers to more simple things such as perturbation rejection. Systems that can perform even simple control functions without computation are examples of *mechanical intelligence*. Mechanical intelligence is very common in everyday devices. For example, automobile differentials automatically balance torques on the left and right wheels without any sensing or actuation. In this example, the velocity of the wheels is unimportant, it is the torques that are controlled by the mechanical system that ensures proper function during operation. Similar concepts can be applied to flapping-wing MAVs to alleviate the sensing, actuation, and computation requirements. For example, introducing an additional passive degree of freedom in the flexure-based transmission can balance the reaction torques from asymmetric drag forces. This mechanism, called Passive Aeromechanical

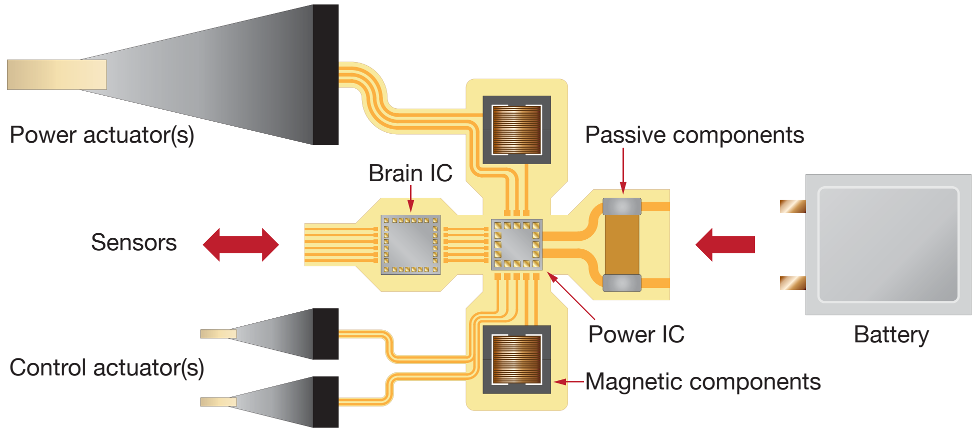

Figure 7. Illustration of the integration of power and control electronics with power and control actuators.

Regulation of Imbalanced Torques (PARITy), has been demonstrated by sequentially removing area from one wing in a two-wing MAV. In reaction to the reduced inertial and drag forces experienced by that wing, the PARITy mechanism flaps that wing at a higher stroke amplitude (and thus wing velocity) until the reaction torques are equal.[26]

5. FUTURE DIRECTIONS

There are numerous additional open challenges that need to be met in order to achieve the vision of fully autonomous insect-scale MAVs. Two of the most important considerations are power and system architecture. The proposed system architecture, which integrates all sensing, actuation, power, and computation, is shown in Fig. 7. With respect to the power source, there are multiple options (although nothing is available off-the-shelf). For example, commercially available lithium polymer batteries have reasonable energy density (approximately 450kJ/kg[27]) and according to the state of the art for all of the components (electrical and mechanical) of the MAV in Fig. 1, these batteries should be able to power tens of seconds of flight.[27] However, these batteries are not available in the appropriate form factor and thus integration becomes a question of repackaging. Higher capacity energy sources based on solid oxide micro fuel cells are also in development for the RoboBee.[28]

The actuators require relatively high voltages (on the order of 200-300V). Therefore, assuming a source voltage of 3-4V, a boost converter circuit is required. Previous work has demonstrated a tapped-inductor autotransformer topology that suits this purpose.[29] Finally, Fig. 7 shows a central 'brain' integrated circuit to process all sensor information and generate control signals for the actuators. Efforts are underway to develop a custom brain integrated circuit based on accelerator modules: blocks of specialized high-performance, low-power computational elements.[30]

ACKNOWLEDGMENTS

This work was partially supported by the National Science Foundation (award number CCF-0926148), the Army Research Laboratory (award number W911NF08-2-0004), and the Wyss Institute for Biologically Inspired Engineering. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1. N. Perez-Arancibia, K. Ma, K. Galloway, J. Greenberg, and R. Wood, "First controlled vertical flight of a biologically inspired microrobot," *Bioinspiration & Biomimetics* **6**, p. 036009, 2011.
2. M. Dickinson and M. Tu, "The function of dipteran flight muscle," in *Comp. Biochem. Physiol.*, **116A**, pp. 223–238, 1997.

3. R. Dudley, *The Biomechanics of Insect Flight*, Princeton University Press, Princeton, NJ, 2000.
4. B. Finio, K. Galloway, and R. Wood, "An ultra-high precision, high bandwidth torque sensor for microrobotics applications," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, (San Francisco, CA), Sept. 2011.
5. S. Hollar, A. Flynn, C. Bellew, and K. Pister, "Solar powered $10mg$ silicon robot," in *MEMS*, (Kyoto, Japan), Jan. 2003.
6. T. Ebefors, J. Mattsson, E. Kälvesten, and G. Stemme, "A walking silicon micro-robot," in *The 10th Int. Conf. on Solid-State Sensors and Actuators (Transducers '99)*, pp. 1202–1205, (Sendai, Japan), June 1999.
7. W. Churaman, A. P. Gerratt, and S. Bergbreiter, "First leaps toward jumping microrobots," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, (San Francisco, CA), Sept. 2011.
8. K. Pister, M. Judy, S. Burgett, and R. Fearing, "Microfabricated hinges," *J. of Sensors and Actuators A: Physical* **33**, pp. 249–256, 1992.
9. R. Wood, S. Avadhanula, R. Sahai, E. Steltz, and R. Fearing, "Microrobot design using fiber reinforced composites," *J. of Mech. Design* **130**, May 2008.
10. J. Whitney, P. Sreetharan, K. Ma, and R. Wood, "Pop-up book mems," *J. Micromech. Microeng.* **21**(11), p. 115021, 2011.
11. P. Sreetharan, J. Whitney, M. Strauss, and R. Wood, "Monolithic fabrication of millimeter-scale machines," *to appear: J. Micromech. Microeng.* , 2012.
12. R. Wood, E. Steltz, and R. Fearing, "Optimal energy density piezoelectric bending actuators," *J. of Sensors and Actuators A: Physical* **119**(2), pp. 476–488, 2005.
13. B. Finio, J. Shang, and R. Wood, "Body Torque Modulation for a Microrobotic Fly," in *IEEE Int. Conf. on Robotics and Automation*, pp. 3449–3456, (Kobe, Japan), 2009.
14. M. Dickinson, F.-O. Lehmann, and S. Sane, "Wing rotation and the aerodynamic basis of insect flight," *Science* **284**, pp. 1954–1960, June 1999.
15. J. Whitney and R. Wood, "Aeromechanics of passive rotation in flapping flight," *J. Fluid Mechanics* **660**, pp. 197–220, 2010.
16. A. Sherman and M. Dickinson, "A comparison of visual and haltere-mediated equilibrium reflexes in the fruit fly *Drosophila melanogaster*," *J. of Experimental Biology* **206**, pp. 295–302, 2003.
17. P.-E. Duhamel, N. Perez-Arancibia, G. Barrows, and R. Wood, "Altitude feedback control of a flapping-wing microrobot using an on- board biologically inspired optical flow sensor," in *IEEE Int. Conf. on Robotics and Automation*, (Saint Paul, Minnesota), May 2012.
18. H. Schuppe and R. Hengstenberg, "Optical properties of the ocelli of *Calliphora erythrocephala* and their role in the dorsal light response," *J. of Comparative Physiology A* **173**, pp. 143–149, 1993.
19. M. Dickinson, "Haltere-mediated equilibrium reflexes of the fruit fly *Drosophila melanogaster*," *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* **354**(1385), pp. 903–916, 1999.
20. W. Wu, R. Wood, and R. Fearing, "Halteres for the micromechanical flying insect," in *IEEE Int. Conf. on Robotics and Automation*, (Washington, DC), May 2002.
21. B. Finio, B. Eum, C. Oland, and R. Wood, "Asymmetric flapping for a robotic y using a hybrid power-control actuator," in *IEEE Int. Conf. on Robotics and Automation*, (St. Louis, MO), 2009.
22. N. Perez-Arancibia, J. Whitney, and R. Wood, "Lift force control of a flapping-wing microrobot," in *American Controls Conf.*, (San Francisco, CA), June 2011.
23. P. Chirarattananon, N. Perez-Arancibia, and R. Wood, "Repetitive and minimum-variance adaptive control for flapping-wing microrobots," in *American Controls Conf.*, (Montreal, Canada), June 2012.
24. P. V. Overschee and B. DeMoor, *Subspace Identification for Linear Systems*, Kluwer, Boston, MA, 1996.
25. N. Perez-Arancibia, P. Chirarattananon, B. Finio, and R. Wood, "Pitch-angle feedback control of a biologically inspired flapping-wing microrobot," in *IEEE Int. Conf. on Robotics and Biomimetics*, (Phuket Island, Thailand), Dec. 2011.
26. P. Sreetharan and R. Wood, "Passive torque regulation in an underactuated flapping wing robotic insect," *Autonomous Robots* **31**(2), pp. 225–234, 2011.

27. M. Karpelson, J. Whitney, G.-Y. Wei, and R. Wood, "Energetics of flapping-wing robotic insects: towards autonomous hovering flight," in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, (Taipei, Taiwan), Oct. 2010.
28. M. Tsuchiya, B. Lai, and S. Ramanathan, "Scalable nanostructured membranes for solid-oxide fuel cells," *Nature Nanotechnology* **6**, p. 282, 2011.
29. M. Karpelson, G.-Y. Wei, and R. Wood, "Milligram-scale high-voltage power electronics for piezoelectric microrobots," in *IEEE Int. Conf. on Robotics and Automation*, (Kobe, Japan), May 2009.
30. M. Lyons, M. Hempstead, G.-Y. Wei, and D. Brooks, "The accelerator store framework for high-performance, low-power accelerator-based systems," *IEEE Computer Architecture Letters* **9**(2), pp. 53–56, 2010.