MURI Status 9–14–01

Using Silicon Electronics to Study the Control of Insect Flight

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Michael Tu, University of Washington
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The team and effort to develop implantable electronics is ramping up quickly. The Daniel/Tu and Diorio labs are pushing forward with preliminary implantation experiments. The Dickinson and Willis labs are making good progress with aerodynamics and visualization, but their rampup is delayed because both labs are moving (Dickinson to Caltech and Willis to Case Western Reserve). As a consequence of the rampup and lab moves, our projected first-year spending is $433,253, below the budgeted amount of $718,262. We will accelerate our research and spending in the coming months, and will be on track in the second year of the project. We show a projected budget below.

Web page: We intend to use a public web page both for project status, and to promote our research. We have a preliminary version of the web page at http://www.cs.washington.edu/homes/rprieto/MURI/ We will update this page over the course of the next two weeks, and roll out a final version on 10/1/01.

Budget:

P.I.	Total spent thru 11/30/01	Total billed thru 12/31/01	NOTES
Diorio	$102,948	$77,948	
Daniel/Tu	$188,290	$175,667	
Dickinson	$117,285	$77,285	Spending may dip due to Mike's transition to Caltech
Willis	$25,000	$0	This is a reasonable estimate for costs to start a new lab
Total	$433,523	$330,900	
Budget		$718,262	
Shortfall		$387,362	

Daniel Lab Status

Progress on Manduca Research (http://faculty.washington.edu/danielt/)

1. We have developed an initial attached chip and battery system to show (a) moths can carry a mass of approximate 500 mg with batteries, (b) we can record from steering muscles or the motor neurons in an animal flying with on-board microelectronics, and (c) local amplification and tiny wire distances lead to an extremely favorable result so that we no longer need AC coupling nor noise filtering. These are important results because they guide us in the final development for software and hardware requirements of an on-board data-processing chip.
2. We have preliminary recordings from the visual processing pathway of *Manduca sexta*. For flight, visual processing is a key part of the sensory world required for effective control. We have shown that we can record from an exceedingly accessible part of the brain that processes visual information (the Lobula plate) in the form of spiking neurons that measure horizontal or vertical motions of the visual world. Thus we have a site where we can probe the processing done "on the fly"
3. We have completed initial studies that show the link between neuromuscular control and actual musculo-skeletal movements. Here we have developed finite-element models of the wing and thorax and how these are mechanically coupled to the flight motor system (Combes, Trimble and Flick).
4. We have developed a test bed for driving and measuring behavior in free flight (see http://faculty.washington.edu/danielt/tracker.html). This exploits a powerful, visually mediated, behavior in which freely flying hawkmoths track moving flowers. This permits us to drive the animal (in free flight) without any physical connections to the animal.
5. We have completed initial computer models that integrate neuronal signaling of muscles to actual flight dynamics and wing motions, exploring the significant role of phase relationships for the activation of various steering muscles. We have independently worked with evidence that these muscles are driven by a sensory feedback loop that responds to both wing position (Frye) and to visual stimuli (Theobold).
6. We have completed software for analyzing behavior in a 3 D image. Which is a fundamental issue in analyzing flight.

We presented research associated with the MURI at the 2001 meetings of the *Society of Integrative Biology*, comprising the following abstracts:

- Frye, M.A. and Daniel, T.L.. Mechanical encoding properties of the wing hinge stretch receptor in the hawkmoth *Manduca sexta*. SICB 2001, Atlanta
- Combes, S.A., Trimble, A.C., and Daniel, T.L. Spatial profiles of wing stiffness in hawkmoths and dragonflies. SICB 2001, Atlanta
- Moreno, C.A., Tu, M.S., and Daniel, T.L. Visual-motion feedback in the tracking behavior of hovering Manduca sexta. SICB 2001, Atlanta.

Two of our papers were awarded first place at this meeting, a first for the society in which one lab placed in more than one area (we actually won in three!)

This coming year, in the 2002 meetings of the S*ociety of Integrative Biology*, the combined Diorio/Daniel labs will be presenting 9 papers, 7 of which are directly related to Manduca flight research. The abstracts were submitted September 7, 2000 and will appear in the winter issue of the *American Zoologist*.

Our next major push will be to complete the 3D filming apparatus (nearly done). Most of our current effort has focused on lab reorganization to house an 8 ft × 8 ft rig in which Manduca can fly freely.

As we ramp up filming of both free and tethered preparations, we will look ever closer at both visual pathways and the elusive integrating region in the cervical connective. This, in coordination with the Willis lab, will prove to be an exciting new preparation where upstream sensory data and downstream motor data meet.

Staffing: Two postdoctoral students are starting on the project in January. One is Sanjay Sane, who is completing his degree with Mike Dickinson and will form a fantastic link between the groups. Sanjay brings expertise in robotics and fluid dynamics. The second is Alan Trimble, who has extensive video and imaging skills (and will be ONR's first postdoctoral student to have 3 Emmy's under his belt!). We will continue to support at least two graduate students and several undergraduate students on the MURI.

Dickinson Lab Status

Our research has focused on three main areas:

1) **Development of analysis software for extracting 3D kinematics of flapping flight.**
We have developed a comprehensive digitization platform driven by a graphical user interface (GUI) in MATLAB for extracting body and wing kinematics from freely flying insects. When completed, the analysis platform will be suitable for use with *Manduca* experiments in Seattle and Cleveland. The software produces arrays of kinematic data that may be 'played out' through the dynamically-scaled robotic insect in Berkeley for measurement of forces and flows created during flight.

2) **Construction of 'Bride of Robofly' aerodynamic test apparatus.**
To accommodate the studies of flight control in *Manduca*, we have begun construction of a new and more sophisticated dynamically scaled flapping insect. The apparatus will permit tests at the higher Reynolds numbers characteristic of *Manduca*, and will allow the study of forward and reverse flapping flight. To date, we have completed construction of the translation tank and tank scaffold, flapping servo motor array and gear drives, and force sensors. We have also purchased 500 gallons of low viscosity mineral oil for use at Reynolds number over 1000. The final remaining tasks are to complete construction of the translation stage system software.

3) **Preliminary analysis of high Re aerodynamics.**
While waiting for parts to complete the new facility, we have used our existing robot to examine the aerodynamics of flapping flight in *Manduca* to test if the underlying mechanisms are fundamentally different than those that have been described for the fruit fly, *Drosophila*. As shown in Fig. 1, changing the Reynolds number by a factor of 10 (accomplished by lowering the viscosity of the surrounding oil), has almost no effect on the time course or magnitude of forces generated by flapping kinematics modeled on *Manduca*. For this reason, we are confident that our existing body of knowledge, gathered from studies on smaller fruit flies, will be applicable to the new research on the much larger hawk moths.

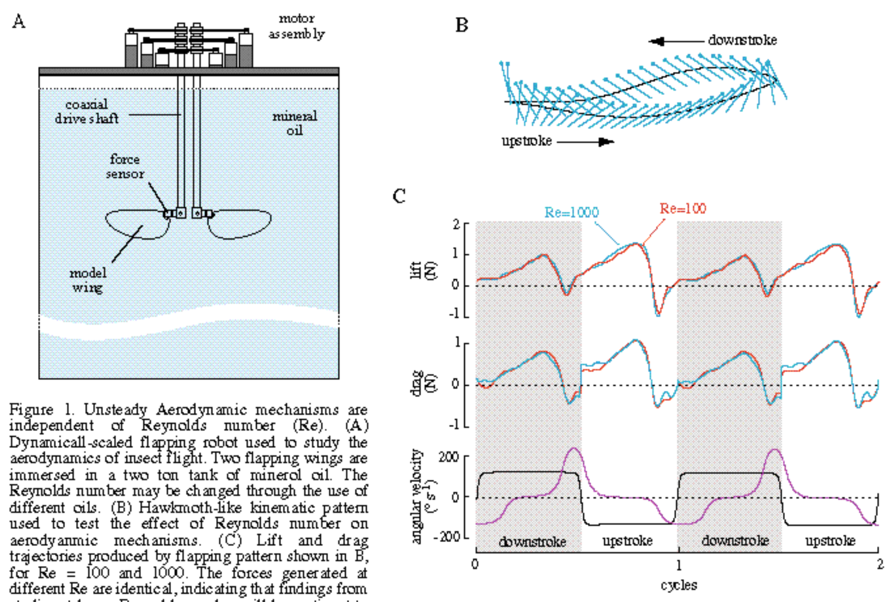


Figure 1. Unsteady Aerodynamic mechanisms are independent of Reynolds number (Re). (A) Dynamicall-scaled flapping robot used to study the aerodynamics of insect flight. Two flapping wings are immersed in a two ton tank of minerol oil. The Reynolds number may be changed through the use of different oils. (B) Hawkmoth-like kinematic pattern used to test the effect of Reynolds number on aerodyanmic mechanisms. (C) Lift and drag trajectories produced by flapping pattern shown in B, for Re = 100 and 1000. The forces generated at different Re are identical, indicating that findings from studies at lower Reynolds number will be pertinent to hawkmoth flight.

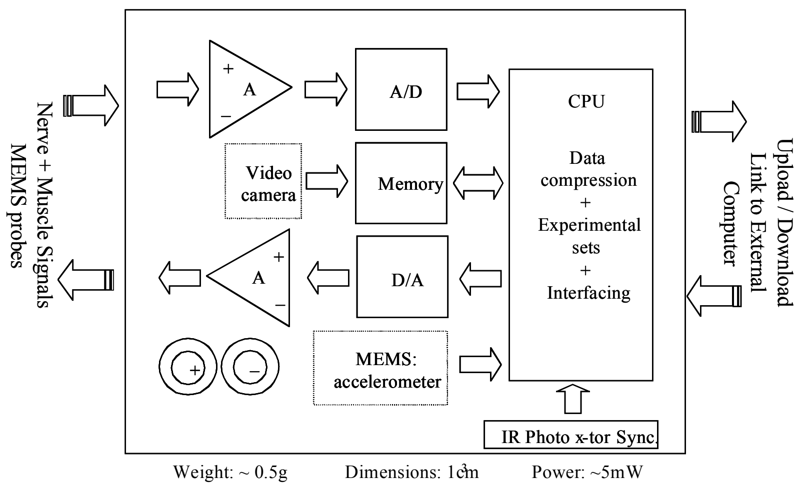
Staffing: In flux, as we are in the process of moving from Berkeley to Caltech.

Diorio Lab Status

We have undertaken several parallel tasks towards building the implantable electronics. All of our initial research uses commercial (COTS) electronic circuits; we will develop custom electronics only after we learn about interfacing to the moth. Our research to date falls into four main categories: (1) Developing a programmable system-on-a-chip to perform in-flight recordings using existing (Cypress Semiconductor Corporation) electronics; (2) developing the battery and packaging technology to support the implantable electronics; (3) developing infrared arrays and modulation to both illuminate the moth and communicate with the electronics, and (4) investigating signal fidelity and interface issues.

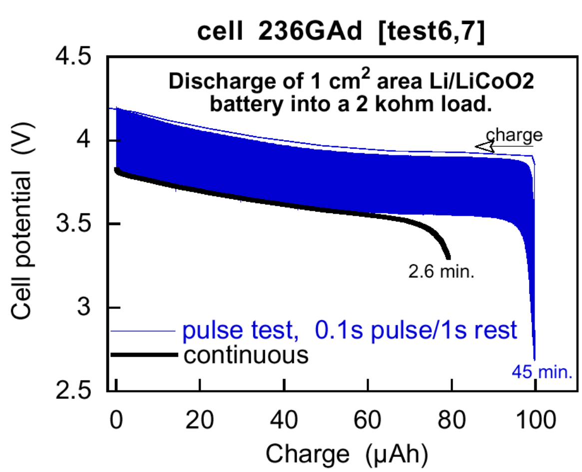
1) Programmable system-on-a-chip

We have identified COTS electronic circuitry that satisfies the size, weight, and power consumption requirements for simple recording experiments. The primary components are a programmable system on a chip (psoc) and serial nonvolatile memory. The system can digitize and store a maximum of 4 recording channels; we are currently prototyping the hardware and firmware. Our near-term plans are to build functioning prototypes by 4Q01, and test on constrained (i.e. tethered) moths in 4Q01.



2) Battery and packaging technology

Our baseline power source is thin-film rechargeable batteries currently in final development at ORNL (Oak Ridge National Labs— www.ssd.ornl.gov). This battery technology is funded by DOE. Li or Li-free batteries with LiCoO2 cathodes have the most attractive current density.



Our baseline packaging technology is a multi-chip module (MCM), with KCP (a DOE funded prototyping lab) the leading vendor. Our short-term plan is, by 1Q02, to fabricate packaged MCM circuits with thin-film rechargeable batteries that can collect in-flight neuromuscular data.

3) Infrared illumination and modulation

We have developed infrared LED arrays to illuminate the moth during free-flight experiments in darkness (Manduca is nocturnal), and are developing a phototransistor receiver to synchronize the in-flight recorder with high-speed video footage of the moth's flight.

Using infrared LEDs for camera lighting offers several advantages over high-power lamps. The most important is that the LED wavelength is not visible to the moth. Our 4×6 LED arrays are about 2 inches high by 3 inches wide by half an inch thick, making them easy to place in experimental rigs. Power is supplied from any 12V DC source. Because LED arrays produce less heat than filament lamps, they do not need cooling.

Infrared LEDs have fast switching capability, with optical rise/fall time as fast as 40ns (HSDL-4220). This presents the possibility of sending simple commands to the in-flight recorder by modulating the power supplied to the LED arrays, and placing an infrared photosensor on the moth PCB. We tested this concept experimentally, at a 1 kilobit/second transfer rate. This rate is sufficient for sending simple commands to the PCB, such as start and shutdown.

4) Signal interfacing

The implanted wires produce voltage signals with roughly 20mV peak amplitudes. Unfortunately, the source impedance is high, so the drive current is small. Consequently, any interface circuitry must have very high input impedance, low input-bias current, differential inputs, and wide common-mode voltage range. For the initial (COTS) circuits, we will likely need an external instrumentation amplifier. We are currently using a Burr-Brown INA118. We have made numerous test recordings using this amp, to condition flight muscle signals for an ADC.

Staffing: We have one research associate, one graduate student, and one undergraduate working on the chip-development effort. The research associate has 13 years industry experience at DEC and Microsoft; the graduate student has 7 years industry experience at TI.

Willis Lab Status

We are in the process of moving our lab to Case Western Reserve. The moving van arrives September 28; we arrive Case Western on October 1st. We are working with the Case Western Biology Department to rebudget our portion of the MURI, and to advertise for a postdoctoral student and a technician. We will activate our MURI subcontract on Oct. 1st (start date at Case). We have discussed this briefly with Joel Davis (via e-mail).

On a progress note, my technician Laurel and Mike Dickinson's postdoctoral student Steven Frye have been successful in adapting the three-D fly-flight video digitizer to work with our (and anybody else's) recordings of Manduca in free flight. This recent breakthrough will definitely make things much easier for all of the moth flight folks.

Staffing: In flux, as we are in the process of moving to Case Western.