Reverse-Engineering the Fly An Engineer's Approach to the Fly Visual System

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This research was supported by grants from the National Institutes of Health (NCRR) and from the US Air Force Office of Scientific Research.

Computational Neuroethology

- •The use of computational methods to study the neuronal basis of behavior
- How are networks of neurons used to perform complex sensorimotor tasks?
 - Reverse-engineering the fly brain, so eventually I can build one!
- •My lab approaches this by (life \rightarrow nonlife):
 - •Behavioral experiments on bees and moths
 - Electrophysiology on flies
 - Robots which incorporate the sensory systems of living insects
 - Computational simulations of neuronally-based models
 - Robotic emulations of models in the real world
 - Neuromorphic VLSI implementations of bio-inspired algorithms
- Both scientific and engineering goals
 - Science: develop neuronal models sufficient for behavior control
 - Engineering: develop novel algorithms and implementations



Why Insects are Good for Neuroethology

•Insects have relatively small brains (~ 10⁶ neurons)

- Compare to perhaps 10¹¹ in humans
- •Still, insects have sophisticated visual systems:
 - Compound eye with 10² 10⁵ visual sampling points
 - Multiple spectral bands ("green", "blue", "UV")
 - Polarization sensitivity
 - Highly sophisticated visual motion processing
 - No true stereo (eyes too close), but binocular overlap

Highly successful in the "real world"
Navigation, predator evasion, finding food, reproduction
As much as 550 million years of successful field-testing
Proto-human perhaps 6 million years ago

Very low level of "intelligence", "consciousness"
Few ethical issues (try this with mouse, rat, cat, monkey)
Yet, much shared in common with low-level processing in primates
Hypothesis: very similar set of processing stages, but less feedback



Calliphora vicina Stay tuned for a closer look



Power consumption of a fly

- A fly can live on one grain of sugar a day
 - Turbinado sugar from Starbucks, of course
- Four grains of white sugar = 10 Joules (<u>www.practicalphysics.org</u>)
- Say that 10 grains of white sugar = 1 grain of Turbinado
 - One grain of Turbinado = 25 Joules
- Imagine fly is "turned off" (sleeping) for 12 hours per day
- Watts = Joules / seconds, so power = 25 / 12*60*60 = 578 microWatts
- What percentage is dedicated to flapping motor system?
 - 80%, conservatively
- Visual system power consumption < 116 microWatts
 - The whole brain, not just the visual system!
- Are our artificial systems close to biological efficiency?

"The brain," of course



The neuronal substrate of visual motion A guide to the visual system of a fly



A guide to the visual system of a fly

Retinotopic visual processing in lamina, medulla
Substrate for motion detection (and all other vision)
Monopolar cells (must record from axon/dendrite)
Non-spiking cells (analogous to primate retina)

Lobula contains many visual structures
Various RF sizes, lower resolution than lamina/medulla
Hard to record from, relatively little known
Mostly non-spiking cells (short axons)

Lobula plate contains around 60 tangential cells (LPTCs)
Some cells spike (cross to other side of brain)
Relatively easy to record from
Wide receptive fields
Integrate many EMD outputs
Many appear to subserve optomotor response







Existence of Common Neuronal Structures

The "Dirty Little Secret" of Insect Science

- Different insects are used for various experiments for practical reasons
 - Honeybees can be easily trained, and are used for behavioral expts.
 Bumblebees are harder to train, but better for electrophysiology
 Blowflies (Calliphora) are very robust for electrophysiology / anatomy
 - Fruit flies (Drosophila) can be genetically manipulated rapidly
 - Wasps have complex behavior, but are stubborn and won't cooperate
- An underlying assumption is that these insects share common visual system structures
 - This is supported by much evidence (e.g. visual motion systems), but the similarities cannot be taken too far.
 - Honeybee: simple apposition eye (diurnal, slow-moving)
 - Fly: apposition eye with "neural superposition" for increased SNR (fast)
 - Moth: optical superposition eye for night vision (nocturnal, slow-moving)

Insect Visual Navigation

•My lab's research focuses on visual navigation in insects, particularly behaviors seemingly enabled by visual motion

- •Visual motion is an important cue for insects (and for humans), and a lot of brain circuitry is dedicated to processing it
- •We are usually interested in behaviors that have been quantified in experiments with bees or flies

•Today I will focus on just two projects: **The centering response and visual odometry Hybrid bio-robotics**

Part I: The centering response and visual odometry

A Model of the Centering Response

- Behavioral experiments indicate that honeybees can estimate image speed on their compound eyes regardless of texture
 - The centering response (fly down the center of a tunnel with different narrowband gratings on either side)
 - Speed control in a tapered tunnel (slow down at narrow points)
 - Grazing landings by holding angular image speed constant
 - Measure distance by integrating image speed (visual odometry)
- This is puzzling because "standard" motion detector models can't do this
- We have proposed a motion subunit that can be used to estimate speed
- Response roughly proportional to speed
- Non-directional unit is simpler than a standard motion detector!
- Implicates a particular cell (TmI)



C. M. Higgins, "Non-directional motion may underlie insect behavioural use of image speed," **Biological Cybernetics**, vol. 91, no. 5, pp. 326-332, November 2004.

Response of the non-directional motion model

- Peak response is temporal frequency tuned, but responses follow line of constant image speed until peak!
- Bees tend to fly at stereotyped image speeds on compound eye
- Standard (spatio-temporal frequency tuned) models, by comparison, do not follow lines of constant speed



Centering Response Simulation

• Jon Dyhr's research: (ID visual field, 2D world)



Centering Response Results

- We have shown that our model is sufficient for the simulated insect to center its "flight" regardless of texture
- By integrating these speed signals, could estimate distance flown (visual odometry)
- Could also control flight speed in other situations
 - Tapered tunnel
 - "Landing"
- Our model makes predictions about a specific neuron, which can be tested by electrophysiology
 - Specifically: Tm1 response proportional to image speed until peak
- Finally, this provides an algorithm for robotic collision avoidance!



Centering Response Robot

- Algorithm has also been implemented on a robotic platform
- Allows experimentation with real-world scenery
- Requires closing the control loop in real-time
- Requires admission of finite frame rate, imaging variations
- Implemented on a laptop, using webcams and an RC car
- •Simulations now include more realistic imagery
- However, not enough detail available about honeybee behavior to verify model
 - Only averages reported
 - Want details of paths
 - Want wider range of SFs
- •We are proceeding with behavioral experiments



Jon Dyhr, 2006



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Behavioral Studies Closed-loop flight experiments

Arena controller

Bumblebee

Wingbeat analyzer

Pair of photosensors

Part II: Hybrid Bio-Robotics

Hybrid BioRobotics

- The challenge: interfacing live insects with robots
- Hawkmoth *Manduca sexta* chosen for robustness, convenience (locally available)
 - Excellent preparation for long-term recordings



- Record simultaneously from muscles and neurons and close the sensorimotor loop
 - Engineering: enables robots with sophisticated sensory systems
 - Science: allows real-world expts. with properties of visual interneurons
 - Real-world visual stimuli, olfactory stimuli, actual motion of body
 - Specifically: closed-loop properties of LPTC, descending interneuron, muscle
- Tungsten electrode to do extracellular recordings, copper wire for muscle
- Main technological development: electrophysiology PCB
 - Supports multichannel extracellular recording, sends commands to robot
 - Wireless (bluetooth) interface to PC (serial link)
 - Matlab interface to transmit commands, get telemetry
 - Traces its lineage back to Jörg Conradt, met at Telluride!

Electrophysiology board



Electrophysiology board performance

- Same blowfly neuron recorded with ephys board and A-M 1700
 - Slightly different lowpass filter settings
- Compares very well, considering complete lack of shielding!



Automatic spike threshold detection

- Additional analog circuit tracks max and min of neuronal signal
- Microprocessor software adjusts spike detector threshold to account for changes in SNR





Recording from this muscle

Left Eye

Abdomen



So how does it work?

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Current Biorobot Experiments

- Robot in rotating arena, tracked from above with overhead camera
- Goal: record simultaneously from:
 - Optic lobe neuron
 - Descending interneuron responding to motion
 - 3rd axillary muscle (responds to motion)
- Use spikes from optic lobe to compensate for motion of arena in closed loop control
- Study delays, stimulus encoding to muscle, control system properties
 - How is stimulus encoded to descending neuron, muscle activation?
 - Difference between closing loop with optic lobe, descending, muscle?

Future work Towards the Ultimate BioRobot

• Aim: record with bilateral tetrodes, do real-time spike sorting

• This would allow simultaneous recording from multiple neurons, and provide a lot of information for navigation or experimentation

etrode

- Requires 8-channel ephys board with spike sorting on board
- Board being developed in Fall 2008 (industry funded senior project)
- Working towards custom "neuroprosthetic processor" with multiple extracellular electrode amplifiers, real-time spike sorting, custom instruction set for spike processing and stimulation

Common electrodes are not ideal for us

- Tetrode spacing much too large (we need perhaps 5 microns)
- Standard micromanipulator too heavy (meant to be), causes vibration
- Solution: a MEMS tetrode with closely-spaced electrodes
 - Also with ability to advance/retract electrode (to hold cells longer)
 - Can cement assembly in place and remove manipulator
 - A number of labs have made such devices, hoping to use one

Summary If you forget everything else, remember this stuff

•Considered as machines, insects are incredibly power-efficient

- Insect brains vastly outnumber "primate" brains, so who's of first importance??
 - At 1.6 billion to one, primates are in the tenth decimal place
- •Despite their small size, insects are convenient and logistically easy for electrophysiology
 - Any evil manipulation you can imagine is **OK!**
- Highly functional vision systems need not be at all like naive (non-Neuromorphic) engineers would design them
 - Non-directional motion first, then directional from that...
 - Don't need detailed image speed computation to do speed-based navigation...

•Interfacing insects w. robots will enable a new set of experiments, and provide robots access to an awesome sensory suite •No reason why hardware cannot be used with rat, cat, ..., elephant

Acknowledgements Jon "Virtual Honeys" Dyhr Tim "Moth Terrorist" Melano

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The End