Sensory Information Systems Program

6 March 2012

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Air Force Research Laboratory

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### Report Documentation Page

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PORTFOLIO OVERVIEW

Program manager: Willard Larkin

BRIEF DESCRIPTION OF PORTFOLIO:

• Auditory modeling for acoustic analysis
• Biological polarization optics & vision
• Sensori-motor control of bio-flight & navigation

SUB-AREAS IN PORTFOLIO:

Sensory Information Systems (3003/L)
Program Trends and Strategy:  
TOPIC AREA OVERVIEW

Advanced Auditory Modeling:  
**Scientific Question:** How does the auditory brain parse acoustic landscapes, bind sensory inputs, adapt its filters, hear through noise and distortion? Could autonomous listening devices emulate neurology to match or exceed human auditory analysis, e.g., to detect and identify speech targets in noise and reverberation?

Polarization Vision & Optics:  
**Scientific Question:** How do natural photoreceptors detect and how do animal brains interpret polarization information? How is it used for nocturnal navigation or recognition of obscured targets? Can these unique bio-optical systems be emulated?

Sensorimotor Control of Flight & Navigation:  
**Scientific Question:** How does neural control make natural, low-Reynolds No. flight autonomous, efficient, and robust? Discover principles of multisensory fusion, distributed sensors and actuators. Develop control laws for emulation in MAVs.

**Strategy:** Forge useful connections between math and biology
Grantees’ Self-Organized Research Workshops (2011)

Neural Oscillations and Speech Perception.
24 May. Hosted by NYU.

23-25 May. Hosted by AFRL/RW.

Bio-Optics and Photoreception.
Fund by the Rank Prize Foundation

Encoding for Auditory Representations.

Informational Masking & Binaural Hearing.
17-19 Nov. Hosted by Boston U.

Brain Rhythms and Cortical Computation.
18 Nov. Hosted by NYU.

Convened by grantees; No AFOSR workshop funding
Primary Coordination

NSF
B. Tuller

ARO
E. Schmeisser

AFRL/RI
A. Noga

AFRL/RH
D. Luginbuhl
N. Iyer

AFRL/MN
R. Wehling

ONR
T. McKenna
M. Steinberg

WRAMC
D. Brungart

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Dr. Jennifer Talley, Biology

Dr. Talley (Ph.D. 2010) was recruited from AFOSR-sponsored project at Case Western U. to insect flight lab at AFRL/Eglin

2012

Judith A. Resnik Medal
Dr. Pramod Varshney, Syracuse U.

Dr. Eric Thompson, Acoustics

Dr. Thompson (Ph.D. 2009) was recruited from AFOSR-sponsored projects at Boston Univ. to psychoacoustics lab at AFRL/RH
RECENT HIGHLIGHTS

OPSIN MAP

New Genomic Analysis reveals maximum-likelihood phylogenetic model for Photoreceptor Opsins

AFOSR Polarization Biology Sub-program featured in J. Royal Society Special Issue

DR. KEY DISMUKES

Keynote Speaker for AFRL – Wright State Internat. Symposium on Aviation Psychology
**Recent Transitions**

**TO: Navy**: Bio-inspired method to classify acoustic sources, e.g., vehicles, humans, marine animals etc., using cortical auditory model. Dr. Sam Pascarelle, Advanced Acoustic Concepts, Inc.


**TO: Bloedel Hearing Institute**: New, patented method to improve auditory coding in cochlear implants. Developed by Dr. Les Atlas, U. Wash. Dr. Jay Rebenstein will develop commercial applications.

**TO: AFIT**: Techniques in electrophysiology and neuroanatomy for mechanical engineering projects to emulate flapping wing flight. Dr. Mark Willis, Case Western U., Dr. Anthony Palazotto, AFIT

**TO: DARPA**: System for adaptive, autonomous control of robotic movement, based upon hierarchical neural model of biological control. Roger Quinn &. Roy Ritzmann, Case West. U.; G. Pratt, DARPA.
Quadrotor implements autonomous 3D navigation using wide field-of-view optic flow

**Inspiration:**

- Insect Compound Eye Research  
  *Eglin AFB 6.1 (M. Wehling, et al.)*

- Insect Visual Target Detection Modeling  
  *Tanner Research (P. Shoemaker.)*  
  *U. Adelaide (D. O’Carroll)*

- Insect Flight Behavior Modeling  
  *U. MD. (J. S. Humbert)*

Microautonomous Systems and Technology  
http://www.avl.umd.edu/
1. Discovery:

Polarization photoreceptor imparts $\lambda$-invariant 90° phase delay

Honeycomb structure of photoreceptor’s optical retarder membrane

2. Optical Modeling:

“Nature’s Perfect Waveplate”

Key property: Intrinsic birefringence of microvilli elements, in balance with form birefringence, yields wavelength-invariant phase delay.

3. Emulation
Nano-Rod Deposition Recipe Emulates Biological Achromatic Phase Retarder

Deposition Angles Alternate in Ta$_2$O$_5$ Nano-rod Layers

Yi-Jun Jen, Nature Comm. 21 June 2011

Nano-rod array exhibits birefringence

Upright nanorods (red layers)

Tilted nanorods (yellow layers)

All 4 Stokes parameters remain nearly constant in a multi-layer structure
Auditory Modeling for Acoustic Analysis – Extramural Grants

- **L. Atlas** (U. Washington):
  New approach to modulation representation and filtering.

- **E. Bleszynski** (Monopole Research):
  Math model of bone- & tissue-conducted sound

- **M. Elhilali** (Johns Hopkins U.):
  Cortical model for acoustic scene segregation

- **O. Ghitza** (Boston U.):
  Theory of speech parsing via brain rhythms

- **W. Hartmann** (Mich. State U.):
  Sound localization

- **G. Kidd** (Boston U.):
  Informational masking & speech segregation

- **R. Kumaresan & P. Cariani** (U. Rhode Is. & Harvard):
  Spectro-temporal codes for auditory signal representation

- **D. Wang** (Ohio State U.):
  Computational auditory scene analysis
New Technique Isolates Informational & Energetic Masking

**Background:**

- What listeners can hear in real, multisource acoustic environments is more constrained by informational masking, than by direct, energetic interference of one sound by another.

- AFOSR seeks techniques to study & suppress informational masking.

- Sparse pointillistic coding leaves speech remarkably intelligible, eliminates energy overlaps, isolates effects of informational “cross-talk.”

- Briefed to AFRL/RI in Dec. 2011.

A sparse, pointillistic rendition of the word “SHOES,” overlaid on the conventional spectrogram. Each time/frequency slice of speech has been replaced with a matching cosine fragment. Red color scales the intensity.
Scientific Challenge:

How does binaural hearing disclose the locus of sound in real 3D environments?

Transaural Synthesis Method:

• Eliminates inter-aural crosstalk, compares localization judgments with precisely known acoustic parameters in the ear canals.

• Tests auditory theory by manipulating Interaural phase and amplitude, comparing real sounds with “virtual” sounds.

• Tests in real rooms & environments, with varied reverberation – no headphones.

• Self-compensates for probe-tube positions, enables precise reproducability.
Acoustic Source Separation: Recovering Multiple Speech Signals from a Single Channel

Research Challenge:
Devise a factorization method to:

• Recover both magnitude and phase for each speech component superimposed in a single channel

• Avoid trial-and-error basis selection.

Why Phase Matters:

New Complex Matrix Factorization method solves superposition and phase problems, eliminates ad hoc basis selection, & improves speech recognition scores

Brian King
U. Washington
Ph.D. Candidate
& RH Summer Student

SPEECH RECOVERY INDEX
0 5 10 15 20 25 30 35 40%
ORIG. NMF CMF

King & Atlas, IEEE Trans on Audio, Speech and Language Processing (Nov. 2011)
Scientific Question:  
When each ear receives a distinct message, can the auditory brain extract key information from both?

Surprising Result:  
Manipulation of word predictability in dichotic listening strongly supports a model of attention-switching, rejects hypothesis of divided attention.

N. Iyer, B. Simpson, Principal Investigators, 711th HPW/AFRL/RHCB Battlespace Acoustics
Mathematical challenge:
Estimate and separate the linear time-invariant and frequency-invariant components of an acoustic source.

Approach:
Theory of Complex Modulation Filtering, devised by Prof. Les Atlas (originally for analysis of speech signals.)

Unexpected Application:
A simple, one-microphone set-up detects hole quality while drilling in airframe composite material.
**Fundamental Question:**

What underlying principles drive biology’s design of actuation and sensing architectures?

**Motivating Observations from Insect Research:**

- Sensors are “noisy,” redundant, distributed in non-orthogonal coordinates.
- Inputs fuse across modalities prior to activating flight muscles.
- No conventional distinctions between estimate/control or inner/outer loop.
- Sensors differ radically in bandwidth & temporal response, e.g., vision lags mechanoreception.
Sensori-motor Control of Natural Flight and Navigation

= AFOSR BIO-NAVIGATION FUNDING INITIATIVE

T. Daniel (U. Washington):
Wing mechanosensor functions.

J. Evers (AFRL/RW):
Natural 3D flight dynamics

M. Frye (UCLA):
Higher-order motion detection

S. Humbert (U. Maryland):
Modeling sensorimotor control

H. Krapp (Imp. College London):
Neural basis of visual steering

P. Krishnaprasad (U. MD):
Modeling formation flight control

S. Reppert (U. Mass):
Clock-compensated navigation

R. Ritzmann (Case Western):
Adaptive locomotion control

R. Olberg (Union College):
Dragonfly flight to target capture

S. Sane (Tata Institute):
Insect multisensory integration

P. Shoemaker (Tanner Res.):
Visual detection of small targets

S. Sterbing (U. MD):
Wing sensors in bat flight control

G. Taylor (Oxford):
Raptor pursuit strategies in 3D

E. Warrant (Lund U.):
Nocturnal navigation

M. Wehling (AFRL/RW):
Neural analysis of optic flow.

M. Willis (Case Western):
Visual / olfactory target tracking
AFRL-DSTL Working Group
Biologically-Motivated Micro-Air-Vehicles

“STATE OF THE ART REVIEW”
Georgia Tech
15-18 June, 2010

Organizers: M. Wehling, AFRL. P. Biggins, Dstl
30 Participants from UK, US, Industry, Academia, & Gov.

Presentations:
https://livelink.ebs.afrl.af.mil/livelink/l/isapi.dll?func=ll&objId=24091294&objAction=browse&viewType=1

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Span of Natural Flier Research: A Few Program Participants

Vertebrates

- Hawks & Falcons

Invertebrates

- Megalopta genalis (Nocturnal Bee)
- Bombus terrestris
- Echolocating Bats
- Dragonfly
- Hawkmoth

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1. Precise control of antennae position is critical for aerial flight maneuvers.

2. Control system is closed-loop, with sensory latency of 15 msec.

3. Antennae integrate mechanosensory & photoreceptor inputs.

4. Antennae position in flight is governed by Bohm’s bristles only at pedicel.
Wings are Sensory Receptors
- - - A New Research Effort

Hypothesis:
Wings not only drive flight, but also detect inertial moments.
- - - strain receptors modulate wing shape and position.

T. Daniel (biology) and K. Morgensen (Aeronautics) U. Washington.
The Mode Sensing Hypothesis for Biological Flight Control

Proposed by 3 AFOSR scientists:

Theory:
Biological sensors and actuators compose a suite of “matched filters,” tuned to salient patterns (“modes”) of self-motion – organized to combine multiple inputs into actuation signals encoded in modal coordinates.

Challenge from AFOSR:
• Test the theory in neurobiology and flight behavior
• Devise mathematical emulation suitable for MAVs

Each Visual System Cell is Tuned to a Preferred Axis of Rotation

Calliphora vicina
Lobular Plate Tangential Cells
(Compound Eye System)

- Sensory Integration begins by selectively merging these inputs.
- The resulting “matched filters” for self-motion are robust and innate.

H. Krapp, Imperial College, London

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Other Motion Sensor Tuning Differs from Compound Eye Eye Tuning

Plots derived from single-unit recordings during controlled rotational stimulation

Theory:
- Short-latency mechanosensors first detect body rotation, then feed forward to induce compensatory head roll via neck motor system …
- Long-latency visual system acts on residual optic flow feedback from incomplete mechanical compensation.
- Behavioral data fit preliminary model for multimodal sensory integration.

Data from U. Cambridge, (M. Parsons) & Imperial College, London (H. Krapp)

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Insect

Bird

Bat

Natural Fliers’ Wing Joints

(●) with potential to be controlled during flight

Bat wing has Intrinsic, non-joint muscles

Research Questions:

• Discover joint coordination timing

• Determine functional redundancy

• Do joint muscles control force or position?

• Discover what the intrinsic muscles do.
Large bat (1.2kg) in low speed flight has precise control via wing skeletal muscles and wing intramembranous (intrinsic) muscles

**Research Techniques:**
- Electromyography during flight
- Thermal videography for metabolic load
- Selective, reversible muscle paralysis
- 3D X-ray mapping of skeletal motion

**Intrinsic Muscles Active only During Wing Upstroke:**

… A Discovery from AFOSR MURI
SUMMARY: Transformational Impacts & Opportunities

**Hearing protection:**
- Massive improvements in high-noise attenuation.

**Advanced auditory modeling:**
- Mathematics for coherent modulation analysis
- Neural-Inspired analyses to parse acoustic scenes

**Optical processing:**
- Polarization vision and signaling adapted from biology
- Achromatic 1/4 wave optical retarders
- Emulating compound eye in new optical devices

**Autonomous flight control:**
- Adaptive airfoils based upon bio-sensory mechanisms
- Steering based upon neural autonomous systems
- Discover sensorimotor basis of formation flight
Questions?

Thank you for your attention.

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New Lab for Insect Vision
Spectral & Polarization
Electroretinography
AFRL/RWG  PI: Martin Wehling

Robber Fly
No Ocelli
Halteres
No VS cells
5-18 HS cells
Large bat (1.2kg) in low speed flight maintains precise control via wing skeletal muscles and wing intramembranous muscles

Techniques:
Electromyography during flight
Thermal videography (to measure metabolic load)
Selective, reversible muscle paralysis
3D X-ray mapping of skeletal motion
1.5 gm EMG Telemetry for in-flight muscle activity

Muscles active during upstroke: