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Air Force Center of Excellence on Nature Inspired Flight Technologies and Ideas

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UNIVERSITY OF WASHINGTON

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Final Report

AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

MIIFD

Tom Daniel, Sanjay Sane, Holger Krapp

Final Report: AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

I. SUMMARY

In July 17-19, 2019 we convened a workshop in Bangalore India that brought together leading researchers from across the world to review recent understanding of how the central nervous system of insects integrates inputs from diverse sensory modalities, and processes the dynamic mix of exafferent stimuli from the surroundings *vs*. the reafferent stimuli that result from their own movements. We are particularly interested in developing a new class of experiments and models to reveal the principles by which natural systems acquire and process information from disparate modalities in ways that depend on both external and internal states.

The workshop sought to address several key questions:

(1) What are the neural principles that govern multisensory integration?

(2) How can we apply advanced computing technologies, experimental resources, and expertise from neuroscience, physics and engineering to reveal new and deeper understanding of movement control in flying animals?

(3) How can we extend our understanding of such systems to inspire technological innovations of direct benefit to the fields of robotics and autonomy?

The outcomes of the workshop are (1) proposals for a potential MURI topics surrounding this general set of issues and (2) a dedicated portion of a volume of the Royal Society Biology Letters with contributions from the participants.

1. MURI topics
We are pleased to report that the workshop generated three MURI topic concepts:

(1) Target tracking and interception in natural systems
(2) Mode sensing for dynamic control of flight systems
(3) The "Grand Unified Fly" – central circuit analyses using emerging technologies.

Of the three MURI topics, the first is most likely to come forward in the form of a white paper likely produced by Professor Paloma Gonzalez Bellido. While all of the topics were of considerable interest, the general plan of natural mechanisms for efficient target tracking and interception draw on all three of the general questions surrounding the workshop. In particular, this task draws strongly on multisensory integration with vision (both target and widefield), proprioception and inertial sensing coming to play. The endeavor would likely draw on a variety of advanced emerging technologies including computational methods, machine vision, and even some machine learning (e.g. path planning, object classification). These methods would likely be used to handle massive data arising from state-of-the-art highspeed image acquisition.

Additionally, one can foresee direct bio-inspired applications for a range of Air Force interests including target interception as well as target tracking.

The other two MURI topics are also interesting. Professor Sean Humbert would be a logical lead for a focused effort in addressing the mode sensing hypothesis. Like the target tracking a MURI white paper would likely draw on multisensory integration and emerging technological advances in computing and device development. Professor Humbert, while interested in helping develop this area further feels it is a bit premature for him to lead an effort in that domain.

The third MURI topic draws on the amazing confluence of three major scientific revolutions: advances in genetic technologies and molecular tools, emerging new imaging methods and, like the other topics, advances in computational techniques (machine vision, machine learning). The stunning genetic reagents are now online via accomplishments of the HHMI Janelia Farm. These genetic lines will allow research programs to explain behavior from the level of neurons and connectomes to whole organisms (Drosophila). We suspect that the advent of CRISPR technologies will allow similar research programs to develop for a much wider range of model systems.

2. Special Issue of Biology Letters (Royal Society)

As part of the output of our workshop, we collectively felt that the broader community of engineers and scientists would benefit from the concepts that were discussed and the ideas for future endeavors. As such, we began discussions with the editors of Biology Letters and have arranged to allocate a part of one issue solely focused on the research ideas of the workshop. A tentative date for submission of all manuscripts from the PIs is slated for the autumn 2020. We expect about 10 papers. The issue would begin with an overview by the conference organizers (Sane, Krapp and Daniel) along with Dr. Ric Wehling.

II: Background and focus of the workshop

Traditionally, many researches tend to assume that insect behavior is determined by external stimuli which trigger a chain of activities ranging from sensory signal transduction to the generation of motor commands. This may include the parallel acquisition and processing of information within a given sensory system followed by cross-modal signal integration to generate robust multimodal feedback signals in pre-motor and motor circuits which ultimately cause muscle contraction. However, in sharp contrast to this notion, animal nervous systems are capable of internally generating motor activity, in the absence of external stimuli, and they are also capable of modulating their behavior even when the external stimuli remain unchanged.

Animals are faced with the challenge of discriminating between the sensory consequences of their own motor action, as opposed to sensory stimuli resulting from events taking place in the external world. Indeed, this ability is key to nearly all locomotor behaviors such as territorial chases, prey-tracking or positional control, and of key importance also for artificial autonomous vehicles. Insects, in particular, are fascinating from this perspective because they not only

accomplish these tasks while on their wings,but do so at extraordinary speeds which suggests that they are able to extract, filter and process their sensory feedback in a way that we do not fully understand.

Recent research efforts in these areas have begun to yield interesting insights into how insects can generate locomotor behaviors in a way that disambiguates self-generated visual and mechanosensory cues from externally generated stimuli. These studies offer unique insights into how nervous systems establish the planning and execution of complex motor tasks in the face of conflicting sensory information. This capability remains poorly explored. Therefore, the main focus of our proposal addresses the question as to how animals play out ('generate') coherent motor programs in the face of varying external and internal states/state changes. Indeed this workshop offers a unique platform to addresses the specific need for synthesizing the diverse studies.

Over the past decade we have witnessed a dramatic growth in technologies and theories associated with robotic systems and autonomy. The vast majority of efforts in these areas have focused on controls and sensing as well as structural materials – in both synthetic and natural systems. Nature has frequently inspired the development of synthetic systems and synthetic systems, in turn, provided novel tools which significantly refined methodological approaches for studying natural systems. Now, technological advances in machine learning, machine vision, and molecular methods for neural imaging as well as multisite electrophysiological recording devices present new inroads that enable us to unravel the neural substrates underlying the control of complex behavior. In some instances, wireless recording technologies will allow us to monitor neuronal activity during free flight, a situation in which multisensory integration is fully operational.

At the same time, device and software development has allowed us to reveal mechanisms for how neural systems operate with incredibly high levels of efficiency. An example of intermingling of neuroscience, technology, and computing lies in the importance of sparse computing and sensing. In this regard, sparse sensor placement has been receiving considerable attention over the past decade as a mechanism for generating classifiers with high computational efficiency. When sensor information is algorithmically combined with neural processing, the efficiency improves by an additional order of magnitude. Thus biology combined with technology and software engineering heralds a new synthesis.

The flight systems of animals operate under incredibly stringent size, weight and power requirements. The circuits that have evolved to support complex maneuvering and navigation under such requirements provide inspiration for the next generation of control architectures implemented on fully integrated autonomous systems. Indeed, autonomy requires both the elegantly structured reflexive feedback architecture of natural flight control systems along with path planning and guidance as a result of neural processing in central brain areas. As we develop a deeper understanding of how natural systems sparsely and efficiently sample information, we will advance the development of new technologies that are capable of operating under constraints similar to those faced by natural systems.

Final Report: AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

III. Relevance to the AFOSR:

The flight systems of animals operate under incredibly stringent size, weight and power requirements. The circuits that have evolved to support complex maneuvering and navigation under such requirements provide inspiration for the next generation of control architectures implemented on fully integrated autonomous systems. Indeed, autonomy requires both the elegantly structured reflexive feedback architecture of natural flight control systems along with path planning and guidance as a result of neural processing in central brain areas. As we develop a deeper understanding of how natural systems sparsely and efficiently sample information, we will advance the development of new technologies that are capable of operating under constraints similar to those faced by natural systems.

We were also aware of the importance of coordinating research efforts between countries that enjoy the support of AFOSR/AFRL investments through the Windows on Science program. Thus the European Office of Aerospace Research and Development (EOARD) and the Asian Office of Aerospace Research and Development (AOARD) interests are well served by this effort.

Finally, we encouraged the participation of students and postdocs in this program, enriching the pipeline of trainees from all three participating countries. To accomplish this, we will included poster sessions for students from India and any others that will attend from the participating laboratories.

IV. Venue, structure, and timing of the workshop

The workshop occured June 17 – 19, 2019 at the National Centre for Biological Sciences in Bangalore India (NCBS https://www.ncbs.res.in/). Our schedule consisted of 40 minute keynote presentations. Each day culminated in a synthesis discussion to highlight (a) technical limitations that need to be addressed and (b) potential areas for future research and potential topics for funding – with the idea of suggesting potential MURI topics of relevance to the Air Force. One of the days will concluded with an exciting evening session of posters by students and postdoctoral trainees.

We chose to hold the conference at the National Centre for Biological Sciences in Bangalore (NCBS Bengaluru) for several reasons. First, NCBS is the premier institute in India focusing on biological research, with an eye towards technical applications. Moreover, NCBS has the strongest program in the country on sensory systems in both common and unconventional model organisms. Additionally, while transportation costs are higher than those for workshops in the US, they are comparable to travel costs to the UK. Importantly, the costs for food and housing are a very small compared to those we would encounter anywhere in the US or UK.

We also hoped to promote a deeper connection with scientists among our three countries, particularly regarding advances in sensing and actuation for flight control. Indeed, research programs in India are on the cusp of expanding into directions that are expected to promote significant progress in this domain.

Final Report: AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

US Participants

Bing Brunton, University of Washington
Tom Daniel, University of Washington (co-organizer)
Michael Dickinson, California Institute of Technology
Paloma Gonzalez-Bellido, Minnesota
Sean Humbert, University of Colorado
Kit Longden, HHMI Janelia Farm
Jamie Theobald, Florida International University
Floris van Breugel, University of Nevada Reno

UK Participants

Holger Krapp, Imperial College (co-organizer)
Graham Taylor, Oxford University
Shane Windsor, Bristol University

India Participants

Axel Brockmann, National Centre for Biological Sciences
Anand Krishnan, India Institute of Science Education and Research, Pune
Shannon Olsson, National Centre for Biological Sciences
Sanjay Sane, National Centre for Biological Sciences (co-organizer)

Schedule

	Monday, June 17
8:30	**Coffee Canteen**
09:30	**Sanjay Sane, Holger Krapp, Tom Daniel:** Welcome and goals for the workshop **…**
09:40	**Holger Krapp Imperial College** Multimodal control architectures for gaze and flight control – integrating inner- and outer-loop behaviour
10:20	Break
11:00	**Ric Wehling, AFRL** How do flying insects reacquire 'targets'
11:40	**Graham Taylor, Oxford University** Modelling optic flow estimation, gaze strategy, and sensorimotor integration in birds and insects through deep learning
12:20	**LUNCH**
14:00	**Paloma Gonzalez-Bellido, University of Minnesota** The effects of image stabilization and gravity in the aerial attack of visually guided predatory insects
14:40	**Kit Longden, HHMI Janelia Farm** Ultraviolet color motion vision for object detection and elevation control in *Drosophila*
15:20	BREAK
16:00	**Jamie Theobald, Florida International University** Size, speed, and photon noise during flight
16:40	**Speaker panel summary 1**

17:20	**Posters day 1**
18:00	

	Tuesday, June 18
08:30	Gather and drink coffee
09:00	**Jennifer Talley, AFRL** Common Feature Representation Across Sensory Systems as a Basis for Multimodal Processing
09:40	**Steve Brunton , University of Washington** Optimal design of sensing and actuation in flight control
10:20	BREAK Drink more coffee
11:00	**Shannon Olson, National Centre for Biological Sciences** Multimodal Virtual Reality and the Anthropocene
11:40	**Axel Broackmann, National Centre for Biological Sciences**
12:20	LUNCH
14:00	**Michael Dickinson, California Institute of Technology** Straighten up and fly right: guidance and navigation in *Drosophila*
14:40	**Floris van Breugel, University of Nevada** Multi-sensory integration during search behavior
15:20	BREAK
16:00	**Bing Brunton, University of Washington** Sparse sensing and control for agile flight
16:40	**Speaker panel summary 2**
17:20	**Poster session 2**

18:00	

Final Report: AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

	Wednesday, June 19
08:30	Gather and drink coffee
09:00	**Sanjay Sane, National Centre for Biological Sciences** Flying in a multisensory world: the role of descending interneurons processing multimodal cues
09:40	**Tom Daniel, Tanvi Deora, Mahad Ahmed, Bing Brunton** Multisensor integration and active sensing in plant-pollinator interactions
10:20	**BREAK** Drink more coffee
11:00	**Shane Windsor, Bristol University** Bio-inspired distributed flow and force sensing systems for Unmanned Air Vehicle flight control
11:40	**Sean Humbert, University of Colorado** Biological Sensorimotor Convergence: Opportunities to Enhance Future Engineered Systems
12:20	LUNCH
14:00	**Speaker panel summary 3**
14:40	
15:20	
16:00	
16:40	
17:20	**Workshop Banquet Dinner.**
18:00	

Final Report: AFOSR Workshop on Multisensory Integration in Insect Flight Dynamics

	Monday June 17	**Tuesday June 18**	**Wednesday June 19**
08:30	Coffee in the Canteen	Coffee in the Canteen	Coffee in the Canteen
09:20	Sanjay, Holger, and Tom	Jennifer Talley	Sanjay Sane
09:40	Holger Krapp	Steve Brunton	Tom Daniel
10:20	BREAK Drink more coffee	BREAK Drink more coffee	BREAK Drink more coffee
11:00	Ric Wehling	Shannon Olson	Shane Windsor
11:40	Graham Taylor	Axel Broackmann	Sean Humbert
12:20	LUNCH	LUNCH	LUNCH
14:00	Paloma Gonzalez-Bellido	Michael Dickinson	Speaker Panel 3
14:40	Kit Longden	Floris van Breugel	
15:20	BREAK	BREAK	BREAK
16:00	Jamie Theobald	Bing Brunton	
16:40	Speaker Panel 1	Speaker Panel 2	
17:20	Student Postdoc Posters 1	Student Postdoc Posters 2	
18:00			

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Thomas Daniel

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The AFOSR Program Officer currently assigned to the award

Patrick Bradshaw

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Abstract

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Total			

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