Bio-inspiration for Deployed Autonomous Systems
The Good, the Bad, and the Unknowns

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Overview

Introductions

Biologically-inspired Mapping and Navigation & Sensing

The Mystery of Navigational Grid Cells in the Brain

Translating Research to Industry Autonomous Vehicles
Today’s talk will only cover a small fraction of our research and activities

Please reach out to chat:

- autonomous vehicles
- neuroscience-inspired tech
- robotics
- computer vision
- active navigation
- mapping and localization
- machine and deep learning
  inc. reinforcement learning
- artificial intelligence
- startups
- STEM (Science Technology Engineering Maths) education
- movie & fiction-based edutainment
- collaboration

Professor Michael Milford | Australian Research Council Future Fellow | Microsoft Research Faculty Fellow | Chief Investigator, Australian Centre for Robotic Vision
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LoST? Appearance-Invariant Place Recognition for Opposite Viewpoints using Visual Semantics
Robotics and AI at QUT

Eyes Underground
A vision for mine safety
Extensive Outreach Engagement Consulting in AVs
Where to go for more information... (high level)

IEEE Spectrum June 2017

The Conversation and other media outlets

Username: MilfordRobotics

Engineers Australia Create Magazine Nov 2018

Niko Sünderhauf, Oliver Brock, Walter Scheirer, Raia Hadsell, Dieter Fox, Jürgen Leitner, Ben Upcroft, Pieter Abbeel, Wolfram Burgard, Michael Milford and Peter Corke, “The limits and potentials of deep learning for robotics”, in International Journal of Robotics Research, 37 (4-5), 2018
Open Source Code and Datasets

- OpenSeqSLAM 2.0: http://seqslam.com/
- OpenSeqSLAM: https://openslam.org/opensegslam.html
- OpenRatSLAM: https://code.google.com/p/ratslam/wiki/RatSLAMROS
- OpenFABMAP (also in OpenCV): https://github.com/arrenglover/openfabmap
- Learning to Navigate at Scale: rl-navigation.github.io/deployable
- Local Semantic Tensors: https://github.com/oravus/lostX
- Multi-Process Fusion: https://github.com/StephenHausler/Multi-Process-Fusion
- Look No Deeper: Recognizing Places from Opposing Viewpoints: https://github.com/oravus/seq2single
“Understanding spatial and perceptual intelligence as a gateway to understanding, creating and applying general intelligence”
Research Philosophy
RatSLAM*: rat-inspired mapping and navigation

Key contributors
Michael Milford
Gordon Wyeth
Janet Wiles
David Prasser
David Ball
Brett Browning

... plus many others over the past 20 years

*SLAM = Simultaneous Localisation And Mapping
Spatial Mapping: Robotics versus Nature
Rats as inspiration

Well-characterized Sensing & Perception

Human vision

Normally-pigmented rats have blurry dichromatic vision with a little color

Albino rats may see a very blurry, light-dazzled world

http://www.ratbehavior.org/RatVision.htm
A LED is triggered when the firing rate of the place cell is above 10 Hz.

Well-characterized Neural Navigation Systems
Place and Head-Direction Cells

Cells that are perfect for encoding a robot’s location (1971) and orientation (1984)

(Muller, R. et al., 1987)

(Yoganarasimha, Yu and Knierim, 2006)
Modelling the Neural System?

**Neuroscientist System Overview**

- **Place Cells**
  - Hippocampus
  - Postsubiculum
  - Entorhinal Cortex
  - Subiculum
  - Posterior Parietal Cortex
  - Visual Cortex
  - Auditory & Olfactory Cortices
  - Medial Vestibular Nuclei
  - Dorsal Tegmentum
  - Ventral Tegmentum
  - Medial Mammillary Nuclei
  - Lateral Mammillary Nuclei
  - Posterior Dorsal Nucleus of Thalamus
  - Anterior Dorsal Nucleus of Thalamus
  - Reticular Nuclei of Thalamus
  - Laterodorsal Nucleus of Thalamus
  - Posterior Dorsomedial Nucleus of Thalamus
  - Dorsomedial Nucleus of Thalamus

- **Head Direction Cells**
  - Retrosplenial Granular Cortex
  - Head Direction Cells

- **Action Selection**
  - Lateral Dorsal Thalamus

- **Self-Motion Cues**
  - Striatum via Motor Cortex

- **Place Recognition**
  - Striatum

- **Self-Motion Cues**
  - Striatum via Motor Cortex

- **Landmark Cues**

*(based on J. Taube, 1998)*

**Roboticist Abstraction**

- **RatSLAM Mark 1**
  - Place Cells
  - Head Direction Cells
  - Action
  - Self-Motion Cues
Modelling with Continuous Attractor Networks (CAN)
Key Mapping and Navigation Demonstrations

1) Mapping a Suburb
2) Persistent Mapping and Navigation
Mapping a Suburb

- Used vision for local view and odometry.
- Vision from built-in camera of a Mac iBook mounted on experimenter’s car.
- Mapped 66 km over just under 2 hours.

Visual Odometry and Place Recognition

- Forward speed estimated from change in scanline intensity profile between current profile and rotated previous profile.
- Template matching based on profiles with rotation accounted.

Mapping an Entire Suburb

CatSLAM* (Maddern et al) and many others…

*CatSLAM is not biologically inspired
RatSLAM: Over a decade from neuroscience to deployment

Source: www.gtec.at
MJ Milford, Robot navigation from nature, *Springer Tracts in Advanced Robotics* 41
Recent & Ongoing Bio-inspired Research
NeuroSLAM: A Brain inspired 6-DOF SLAM System for 3D Environments

Fangwen Yu

This work was supported by the National Key Research and Development Program of China (No. 2016YFB0502200), the Fundamental Research Founds for National University, China University of Geosciences (Wuhan) (No. 1610491T08) and the Hubei Soft Science Research Program (No. LZX2014010).

Fig. 1 NeuroSLAM architecture. The system consists of conjunctive pose cells combining the 3D grid cells and multilayered head direction cells, the multilayered experience map and vision modules. The conjunctive pose cell network performs path integration based on the local view cues and self-motion information. Local view cells encode distinct scenes in 3D environment. The self-motion information including translational velocity, altitude velocity and rotational velocity is estimated based on a lightweight 3D visual odometry system. The output from three components of the conjunctive pose cells, local view cells and 3D visual odometry drives the creation of a multilayered experience map, a hybrid spatial representation with topological, metric 3D graphical map of the 3D environment.
Fangwen Yu, Jianga Shang, Youjian Hu and Michael Milford, “NeuroSLAM: a brain-inspired SLAM system for 3D environments”, Biological Cybernetics, 2019
Winner of a Innovation Grand Prize at the 2019 International Collegiate Competition for Brain-inspired Computing run by Tsinghua University

Fangwen Yu, Jianga Shang, Youjian Hu and Michael Milford, “NeuroSLAM: a brain-inspired SLAM system for 3D environments”, Biological Cybernetics, 2019
Bio-inspired Sensing

**Event Cameras**

Towards Visual SLAM with Event-based Cameras

Michael Milford¹, Harmen Kire², Stefan Leutenegger¹ and Andrew Davison²

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²Department of Computing, Imperial College London

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In “The Problem of Mobile Sensors: Setting future goals and indicators of progress for SLAM” Workshop at Robotics and Science Systems 2015

**Low light cameras**

James Mount

**Stereo Polarized Cameras**

Chuong Nguyen

**UV-sensitive cameras**

Tom Stone
How Bio-inspired Research Can Spur Breakthroughs
The Core Challenge

Place A

_same place, low similarity_

Place A'

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Place A

_difference place, high similarity_

Place B

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A-A'

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A-B
One of our core research foci

Some papers from 2018-2019

- S Hausler, A Jacobson, M Milford, “Filter Early, Match Late: Improving Network-Based Visual Place Recognition,” IEEE International Conference on Robotics and Automation, 2019
- S Garg, N Suenderhauf, M Milford, “Lost? appearance-invariant place recognition for opposite viewpoints using visual semantics”, in Robotics Science and Systems, 2018

Correctly confirmed match: true positive

Correctly rejected match hypothesis: true negative

How SeqSLAM Came About

• Experimentation with spike train sequence generation
• Very low resolution images proven by prior RatSLAM bio-inspired work
• Attempting to generate self-sustaining spike trains in software, corresponding to image sequences
• Final SeqSLAM was an algorithmic, non-spiking simplification
BTEL: A Binary Tree Encoding Approach for Visual Localization

Huu Le\textsuperscript{1}, Tuan Hoang\textsuperscript{2}, and Michael Milford\textsuperscript{3}

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The Nuances of Compression & Storage

• Early days of robotics: critical factors for deployment & feasibility
• Recent years: move towards focus on maximal recall / accuracy / precision / other performance
• All other things being equal, better compression & storage enables:
  – Cheaper, less bulky / power hungry compute hardware
  – On-board rather than off-board operations
  – Better absolute performance with no growth in compute
Absolute versus Scalability

- Much focus on absolute scalability
- But still at least linear growth
- Can we achieve sub-linear *storage* growth?
- Can we achieve this while maintaining competitive performance?
- Can we achieve sub-linear growth while maintaining compact *absolute* storage requirements?

- Multi-scale grid cell mapping. ~5+ scales, $\sqrt{2}$ scaling

2014 Nobel Prize for Physiology or Medicine: Edvard Moser, May-Britt Moser and John O'Keefe

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A Mystery We’ve Been Investigating Thoroughly

- Why have multiple scales?
- What scale ratio?
- How to set the scales?
- Interaction with all sensing modalities?
- What memory and computational advantages?


- A Jacobson, Z Chen, M. Milford, Biological Cybernetics, 2018
- Adam Jacobson, Walter Scheirer and Michael Milford, "De ja vu: Scalable Place Recognition Using Mutually Supportive Feature Frequencies", in IEEE International Conference on Intelligent Robots and Systems, 2017
Exploiting a Cyclic World

Feature 1
Frequency $F_1$

Feature 2
Frequency $F_2$
Exploiting a Cyclic World

Place ID: 1 2 3 4 5 6 7 8

Feature 1: 0 1 0 1 0 1 0 1
Feature 2: 0 1 2 0 1 2 0 1 2

6 places, 5 units of storage

Feature 1: [0 1]
Feature 2: [0 1 2]

Memory collision

Real World Sub-Linear Dataset Compression

BTEL: A Binary Tree Encoding Approach for Visual Localization

Huu Le¹, Tuan Hoang², and Michael Milford³

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¹Chalmers University of Technology, ²Singapore University of Technology and Design, ³QUT
Future Work

- Co-investigating both absolute storage compression and sub-linear scaling
- Scaling up to global-size datasets
Applications:
Industry and Government Projects
Example Application Areas

- Positioning Systems for Autonomous Mining Vehicles
- Robust hazard detection on construction and mining sites
- Robust multimodal toolpoint positioning
- How Automated Vehicles Will Interact With Road Infrastructure Now and in the Future
- Automating Analysis of Vegetation with Computer Vision: Cover Estimates and Classification
- An Infinitely Scalable Learning and Recognition Network
Automation-enabling positioning for underground mining
No drive in the park...

Clear images  Low light

Water  Dust  Glare

The Early Days...

“Octobox”

Cameras

Adam


Partially censored for confidentiality reasons
Going from biological inspiration to deployment

- Mixture of bio-inspired + conventional.
- Why?:
  - Sensor differences (both limited and opportunistic)
  - AI limitations
  - Embodiment differences
  - Different risk appetites
  - Provability
What Bio-inspiration Made it In

• Image processing techniques partially derived from bio-inspired research

• Short bespoke sequence-matching techniques

• Topological mapping techniques partially derived from bio-inspired research

• Image matching techniques derived from fundamental primate-inspired vision research several years ago
We are hiring!
Current and upcoming roles including PhDs, Postdocs, Research Engineers, and Academic Roles

We work here

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Collaboration Opportunities

- Access to unique or limited access datasets / sensors / compute
- Non-critical-path but important big picture research problems
- Co-authored publications
- Grants
- Consulting
- Part-time academic roles
- Student & researcher exchanges
- Intern programs
- Co-organization of workshops / conferences etc...

Some groups we have published with or held joint grants with

- Imperial College London
- University of Oxford
- University of Notre Dame
- Jet Propulsion Laboratory
- California Institute of Technology
- DeepMind
- Stanford University
- Harvard University
- University of Cambridge
- University of Manchester
- University of Liverpool
- University of Leeds
- University of Edinburgh
- University of Exeter
- University of Essex
- University of Wales
- University of Sydney
- University of Queensland
- University of New South Wales
- University of Technology Sydney
- University of Western Australia
- University of South Australia
- University of Adelaide
- University of Melbourne
- Monash University
- University of Twente
- University of Antwerp
- University of Bielefeld
- Boston University
- Caterpillar
- Tata Consultancy Services