Bio-inspiration for Deployed Autonomous Systems

The Good, the Bad, and the Unknowns

Professor Michael Milford | Australian Research Council Future Fellow | Microsoft Research Faculty Fellow | Chief Investigator, Australian Centre for Robotic Vision
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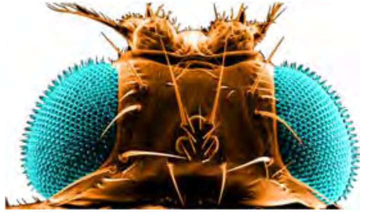
Australian Centre for Robotic Vision

QUT

Overview

Introductions

Biologically-inspired Mapping and Navigation & Sensing



The Mystery of Navigational Grid Cells in the Brain

Translating Research to Industry Autonomous Vehicles

michael.milford@qut.edu.au
Twitter: @maththrills
https://www.youtube.com/milfordrobotics
http://www.tinyurl.com/milfordm
https://goo.gl/rczsle

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

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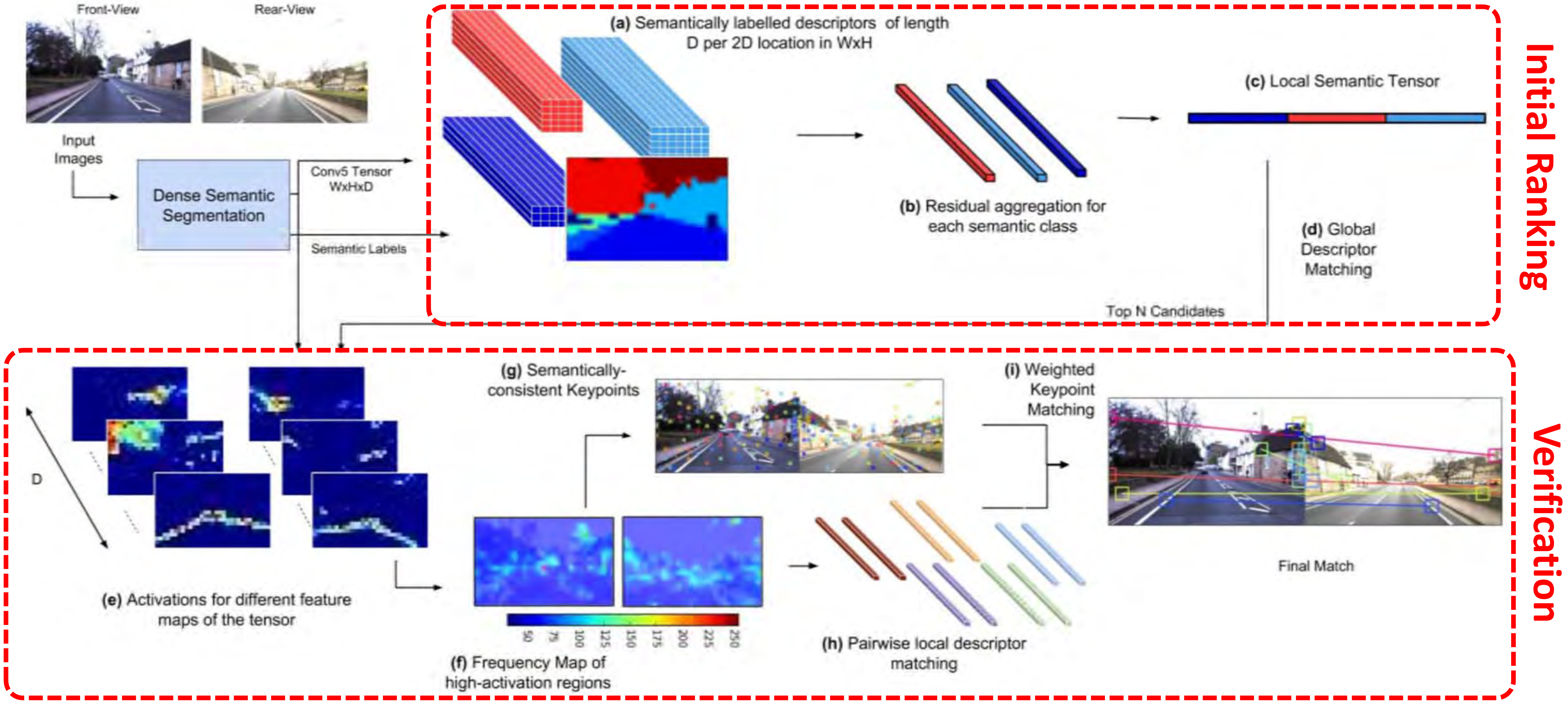
LoST? Appearance-Invariant Place Recognition for Opposite Viewpoints using Visual Semantics



Robotics and AI at QUT

QUT Queensland University of Technology

MONASH University

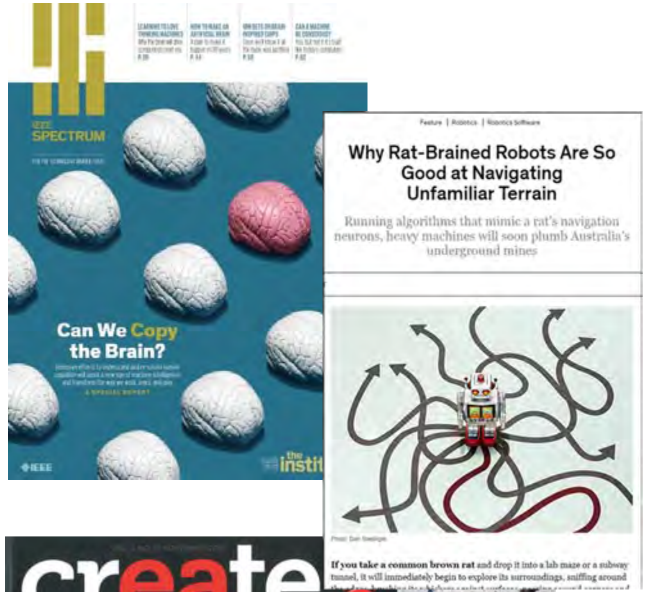
ANU THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY of ADELAIDE

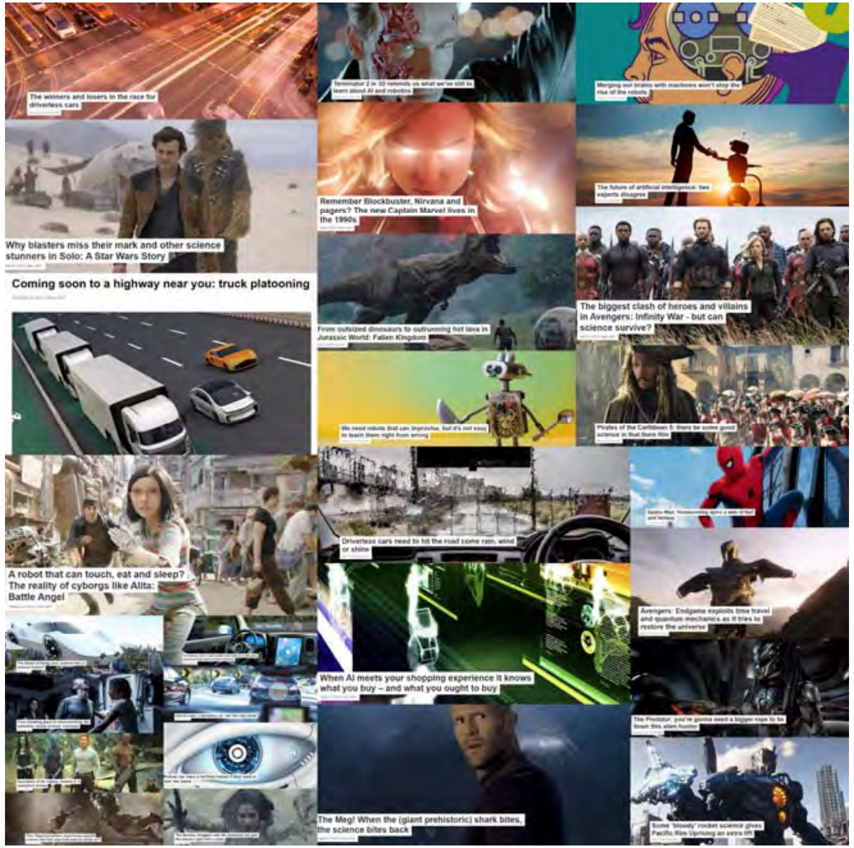
Extensive Outreach Engagement Consulting in AVs

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

Publications and Key Survey/Review Papers

Google Scholar: http://scholar.google.com/citations?user=TDSmCKgAAAAJ


Visual Place Recognition: A Survey

Stephanie Lowry, Niko Sünderhauf, Paul Newman, Fellow, IEEE, John J. Leonard, Fellow, IEEE, David Cox, Peter Corke, Fellow, IEEE, and Michael J. Milford, Member, IEEE


The limits and potentials of deep learning for robotics

Niko Sünderhauf, Oliver Brock, Walter Scheirer, Raia Hadsell, Dieter Fox, Jürgen Leitner, Ben Upcroft, Pieter Abbeel, Wolfram Burgard, Michael Milford and Peter Corke

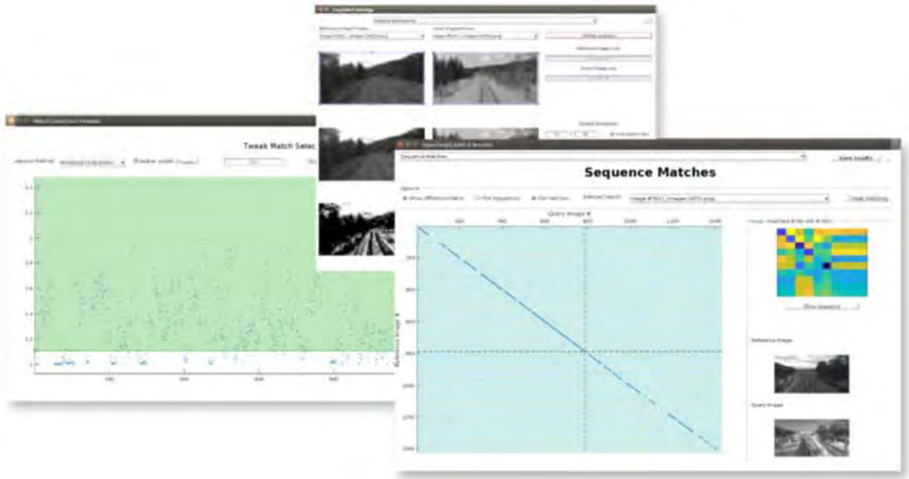
Stephanie Lowry, Niko Sünderhauf, Paul Newman, John J. Leonard, David Cox, Peter Corke,and Michael J. Milford, “**Visual Place Recognition: A Survey**”, in *IEEE Transactions on Robotics and Automation*, 32 (1), 2016

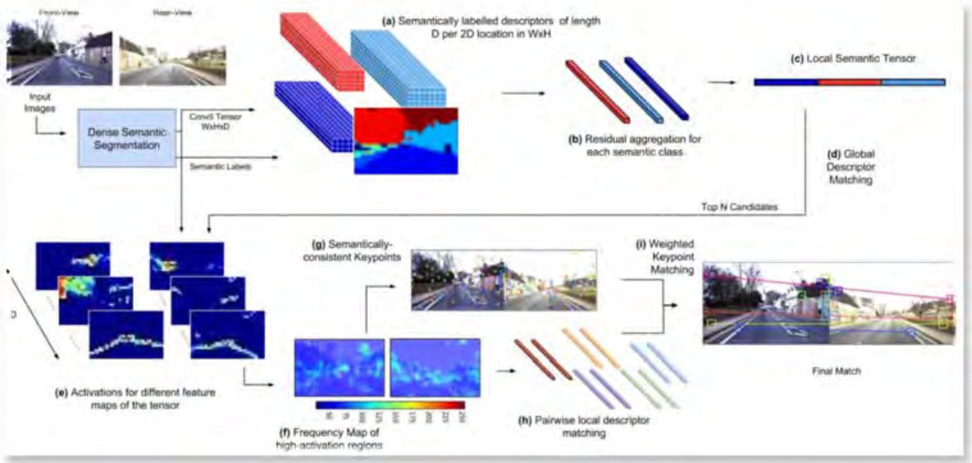
Niko Sünderhauf, Oliver Brock, Walter Scheirer, Raia Hadsell, Dieter Fox, Jürgen Leitner, Ben Upcroft, Pieter Abbeel, Wolfram Burgard, Michael Milford and Peter Corke, “**The limits and potentials of deep learning for robotics**”, in *International Journal of Robotics Research*, 37 (4-5), 2018

During the talk, publication references highlighted in red like this

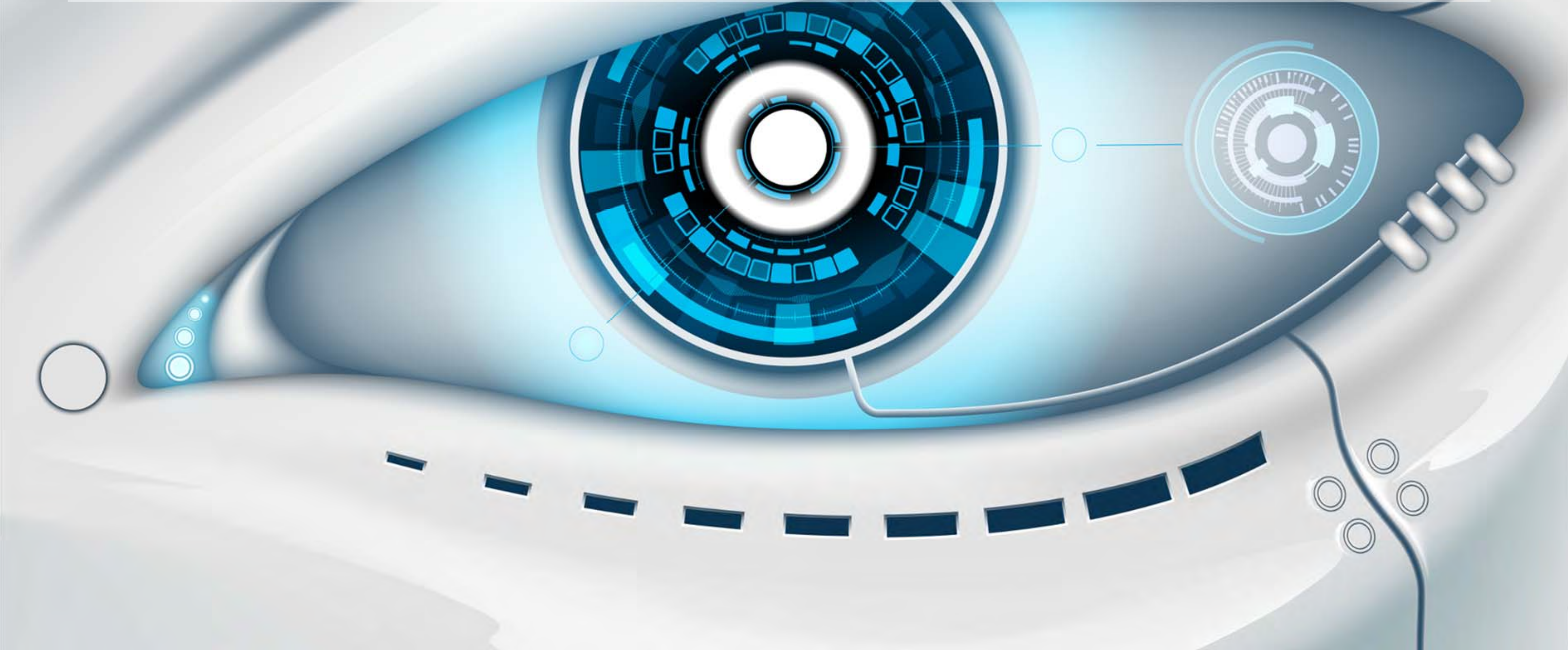
Open Source Code and Datasets

- **OpenSeqSLAM 2.0**: http://seqslam.com/
- **OpenSeqSLAM**: https://openslam.org/openseqslam.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

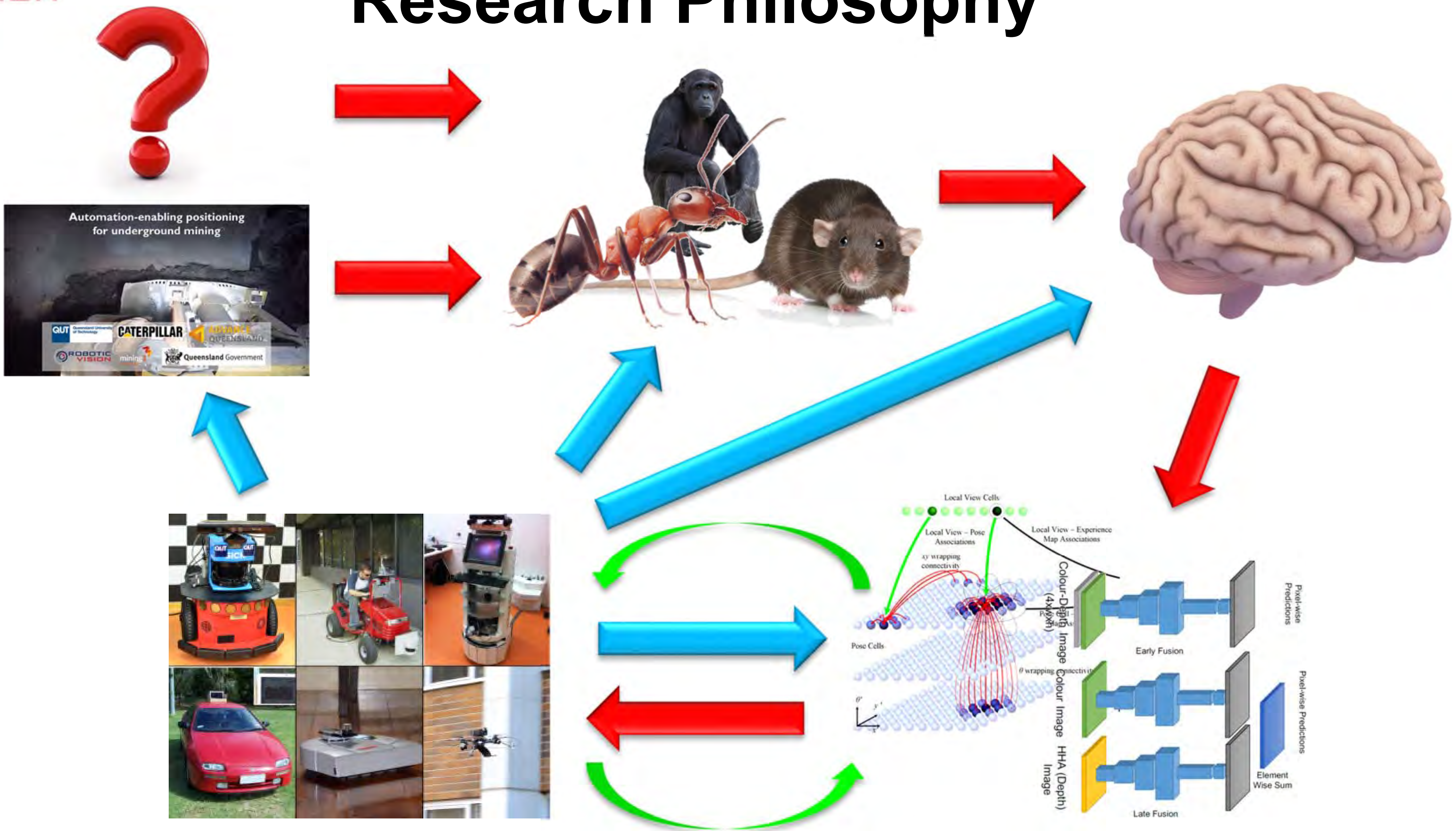




“Understanding spatial and perceptual intelligence as a gateway to understanding, creating and applying general intelligence”



Research Philosophy



RatSLAM*: rat-inspired mapping and navigation

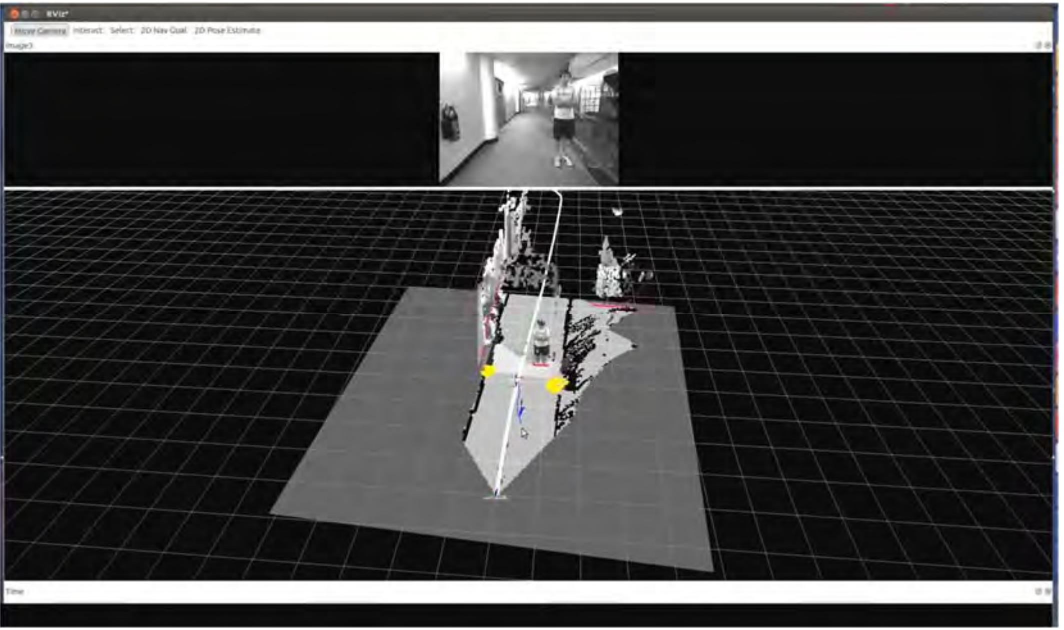
Key contributors

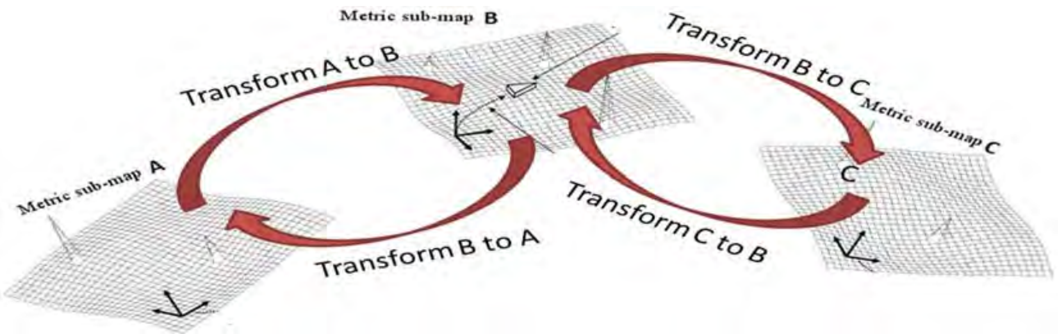
Michael Milford	Gordon Wyeth	Janet Wiles	David Prasser	David Ball	Brett Browning

… plus many others over the past 20 years

*SLAM = Simultaneous Localisation And Mapping

Spatial Mapping: Robotics versus Nature





Rats as inspiration

A. P. Buckle and R. H. Smith, Rodent pests and their control. CABI, 2015.
A Jacobson, Z Chen, M Milford , "Autonomous Multisensor Calibration and Closed-loop Fusion for SLAM", *Journal of Field Robotics* 32 (1), 85-122, 2015

Well-characterized Sensing & Perception

Human vision

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

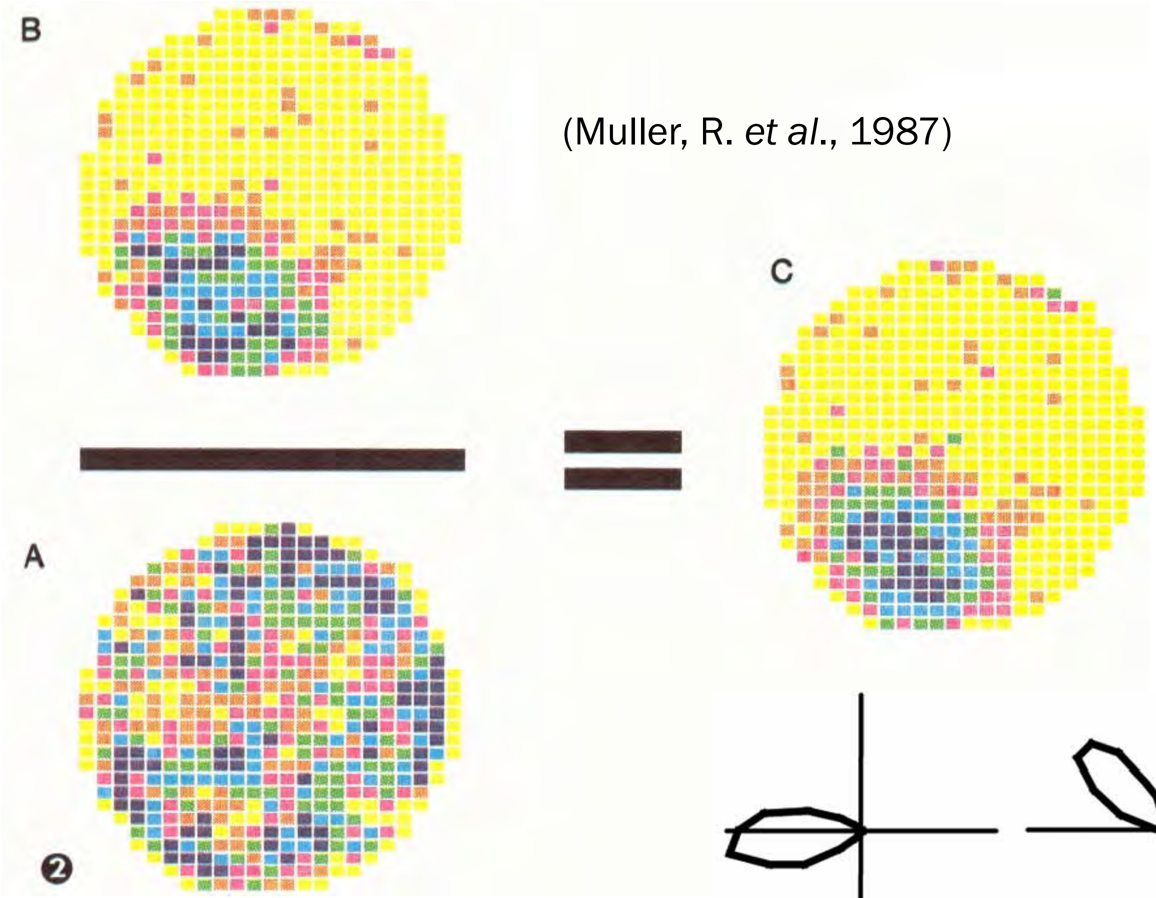
Albino rats may see a very blurry, light-dazzled world

http://www.ratbehavior.org/RatVision.htm

Source: www.gtec.at

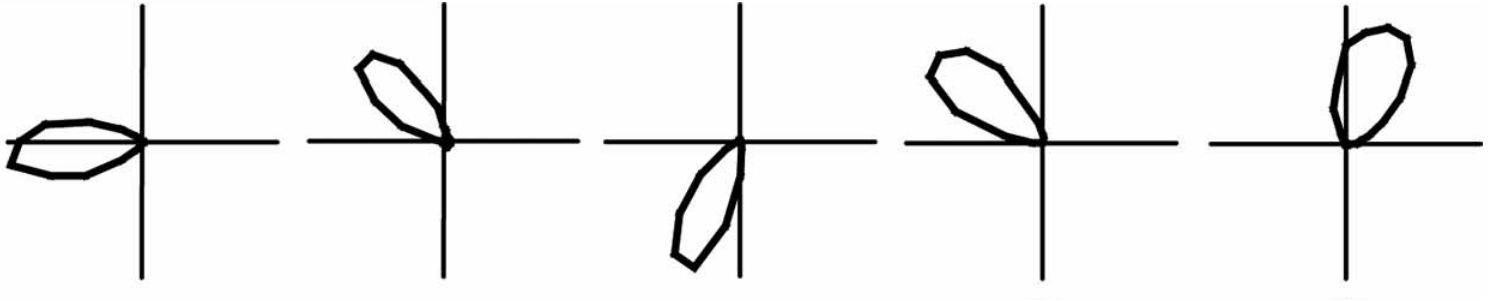
Well-characterized Neural Navigation Systems

Place and Head-Direction Cells



(Muller, R. *et al.*, 1987)

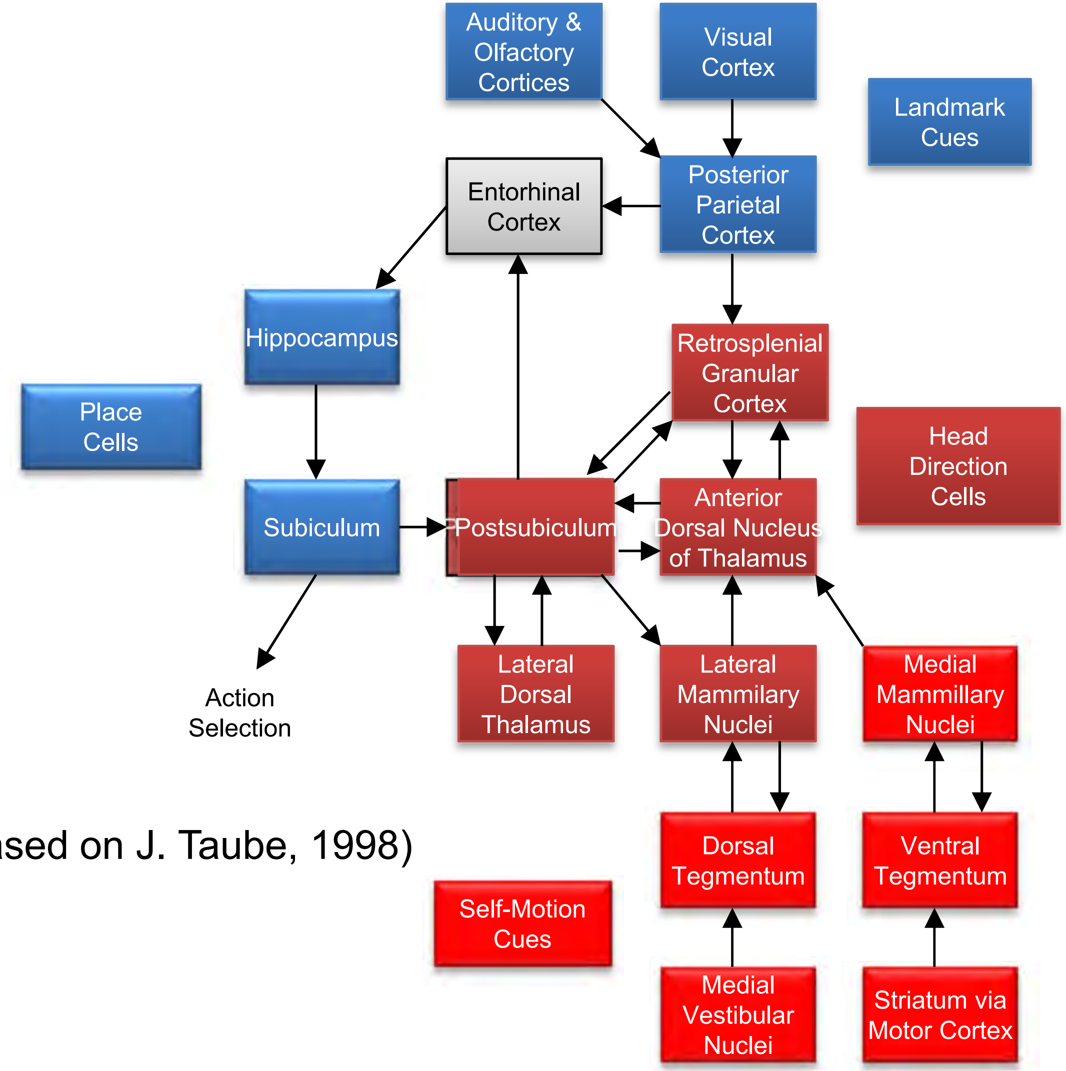
Cells that are perfect for encoding a robot's location (1971) and orientation (1984)



(Yoganarasimha, Yu and Knierim, 2006)

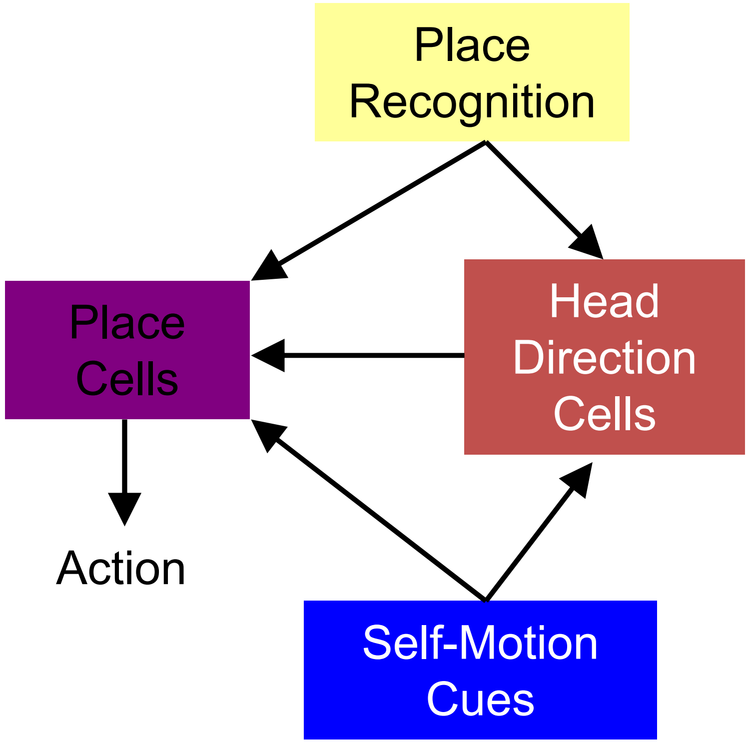
Modelling the Neural System?

Neuroscientist System Overview

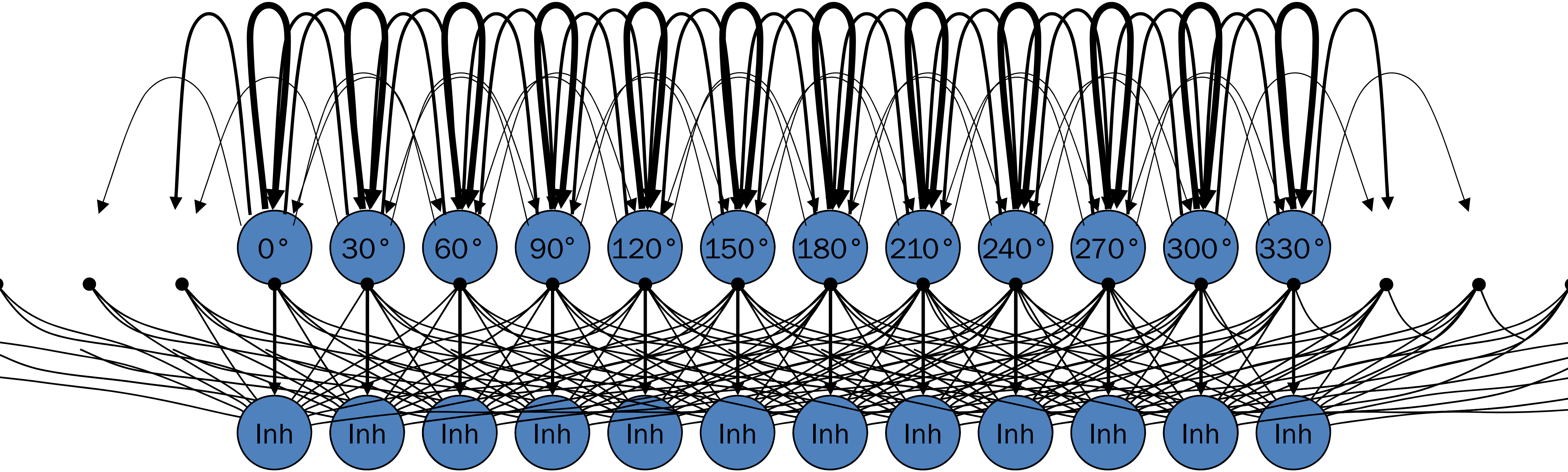


(based on J. Taube, 1998)

Roboticist Abstraction RatSLAM Mark 1



Modelling with Continuous Attractor Networks (CAN)

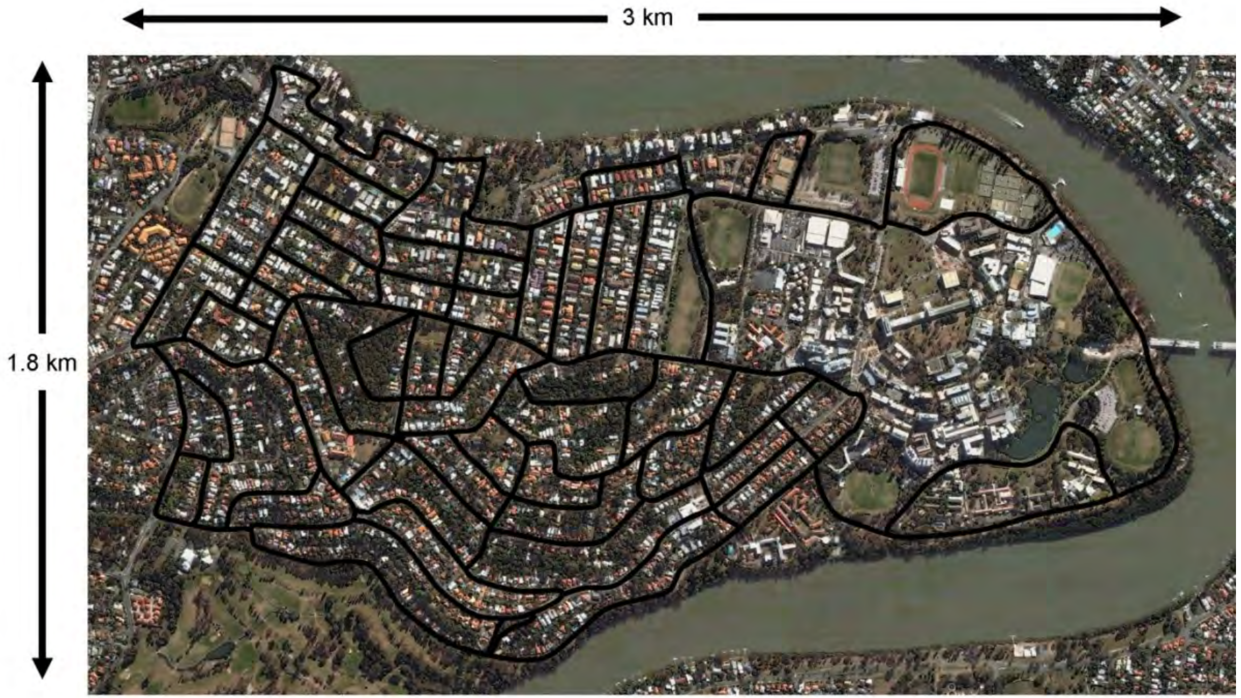


Key Mapping and Navigation Demonstrations

1) Mapping a Suburb
2) Persistent Mapping and Navigation

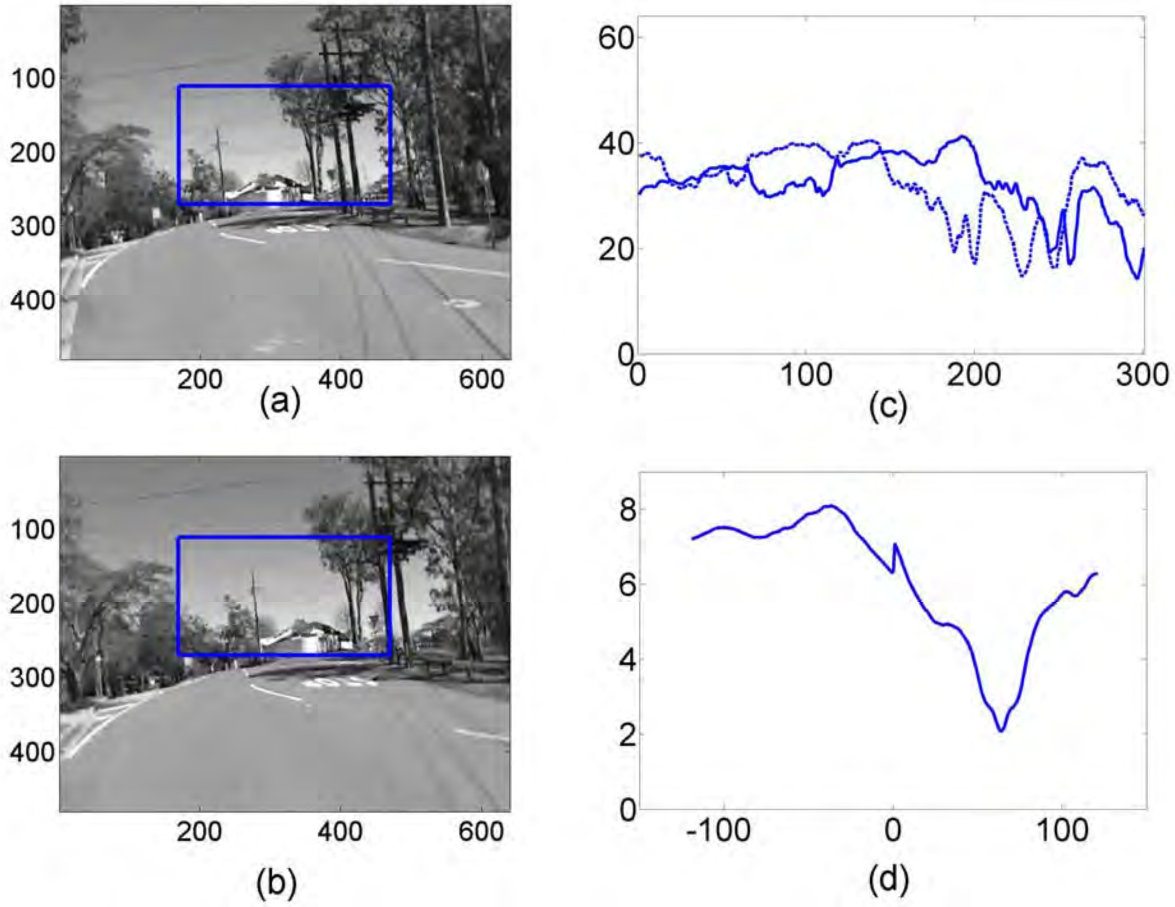
Mapping a Suburb

- 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.



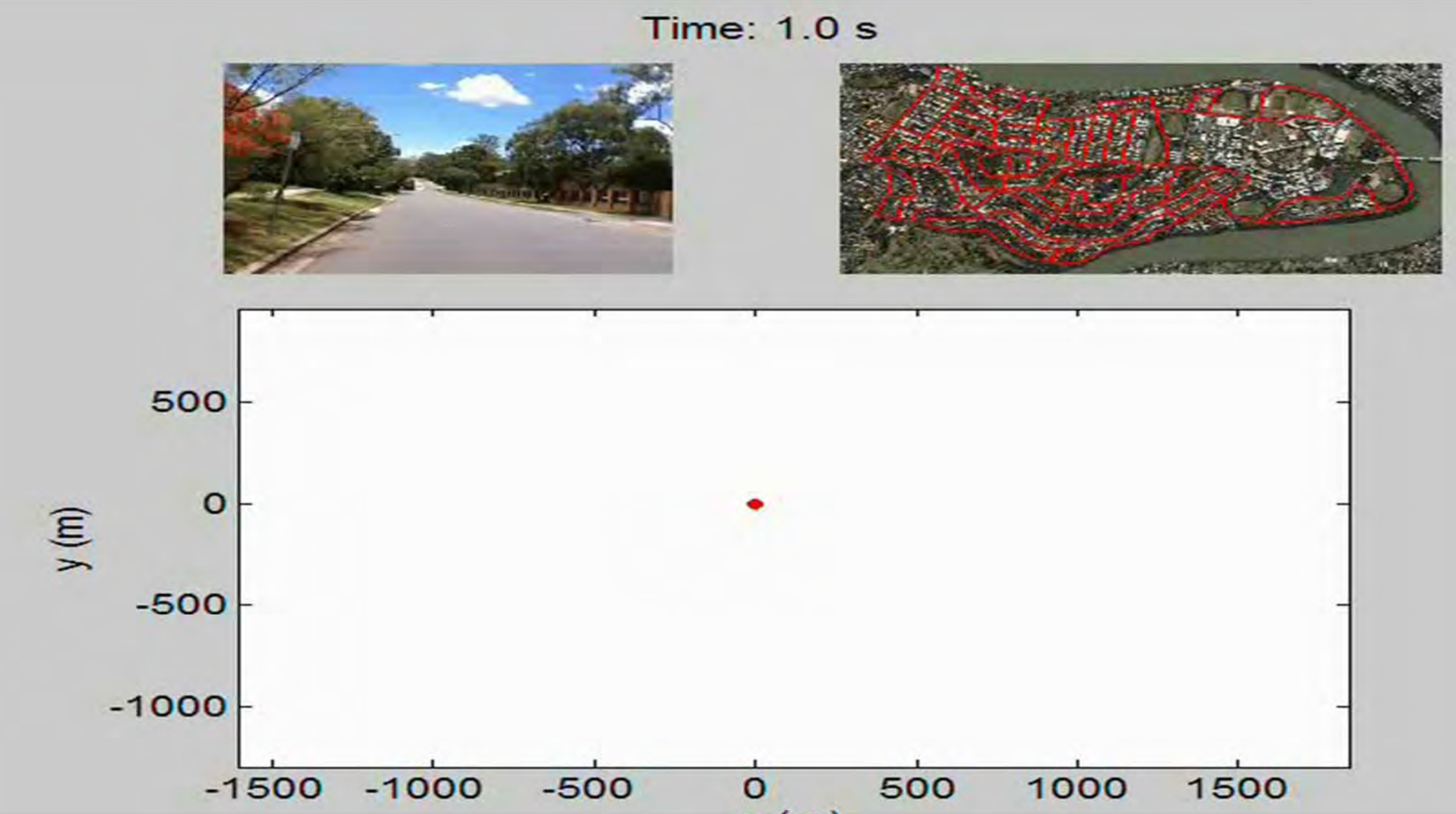
MJ Milford, GF Wyeth, "Mapping a suburb with a single camera using a biologically inspired SLAM system", *IEEE Transactions on Robotics 24(5), 2008.*

Visual Odometry and Place Recognition

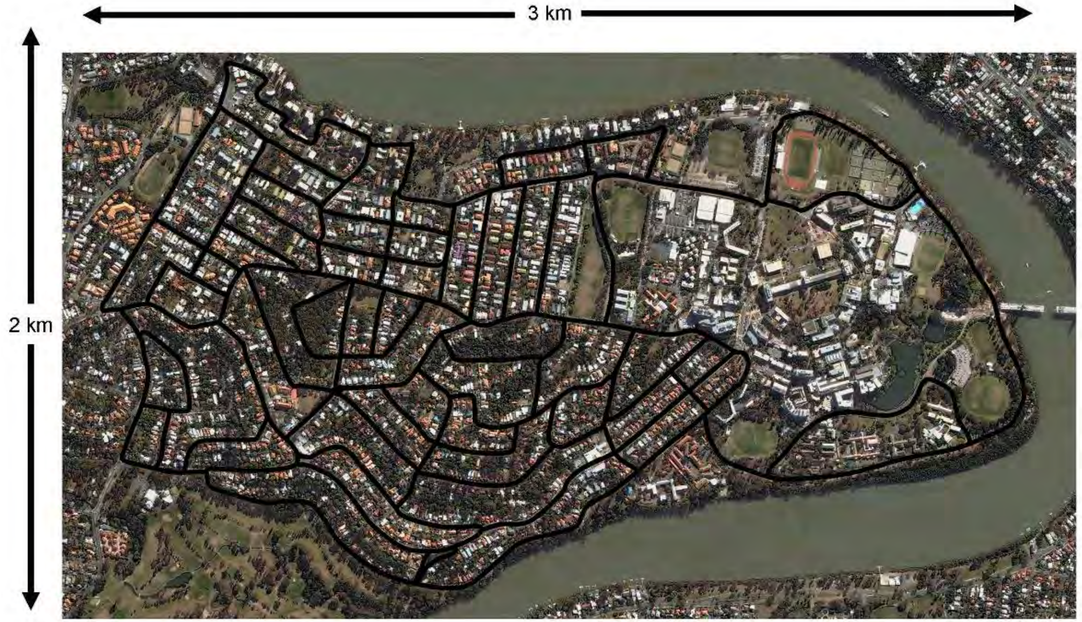


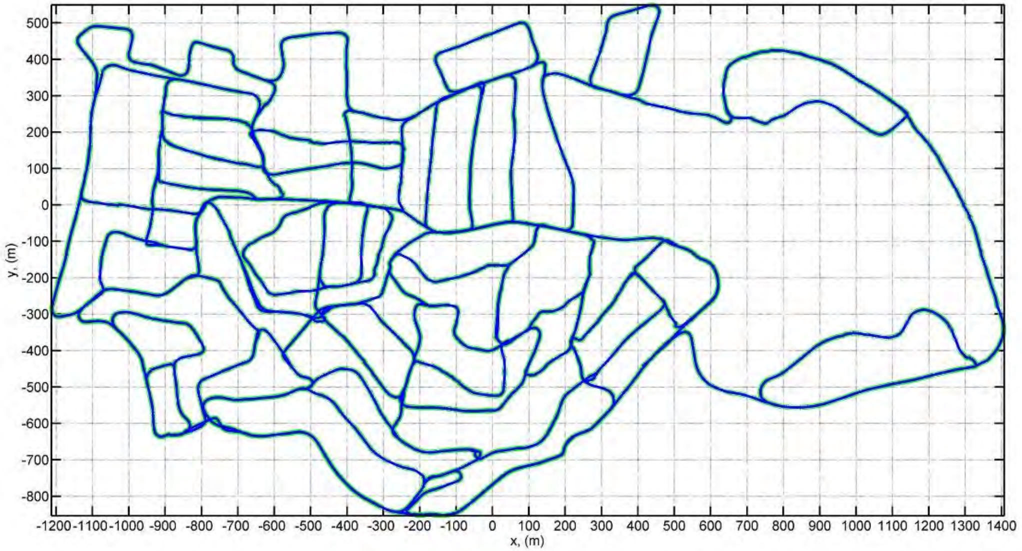
- Forward speed estimated from change in scanline intensity profile between current profile and rotated previous profile.
- Template matching based on profiles with rotation accounted.

Mapping an Entire Suburb



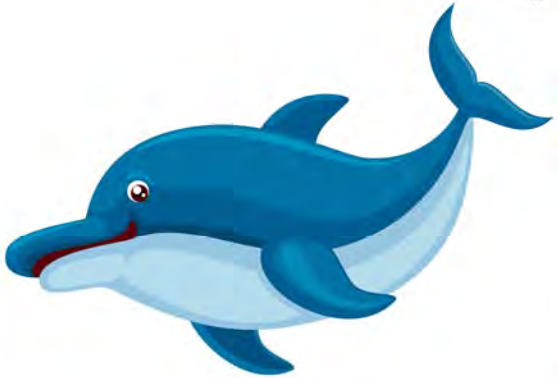
MJ Milford, GF Wyeth, “Mapping a suburb with a single camera using a biologically inspired SLAM system”, *IEEE Transactions on Robotics 24(5), 2008.*

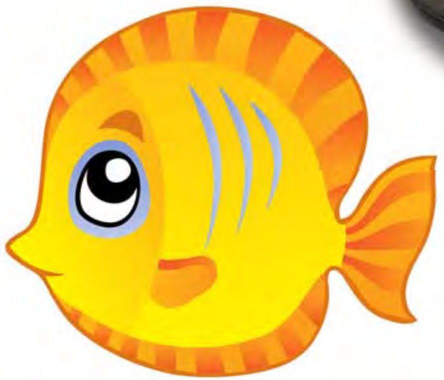




MJ Milford, GF Wyeth, “Mapping a suburb with a single camera using a biologically inspired SLAM system”, *IEEE Transactions on Robotics 24(5), 2008.*

CatSLAM* (Maddern et al) and many others…

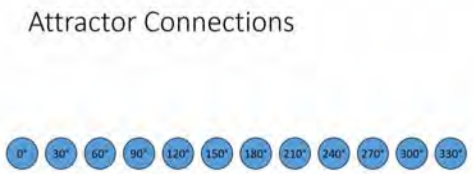


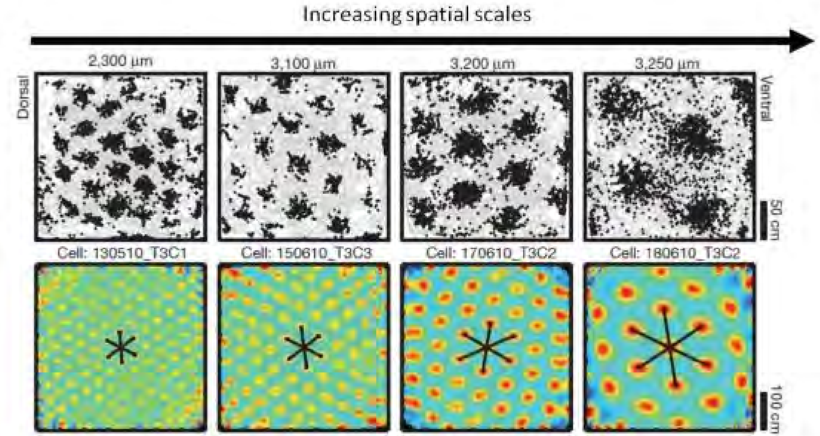


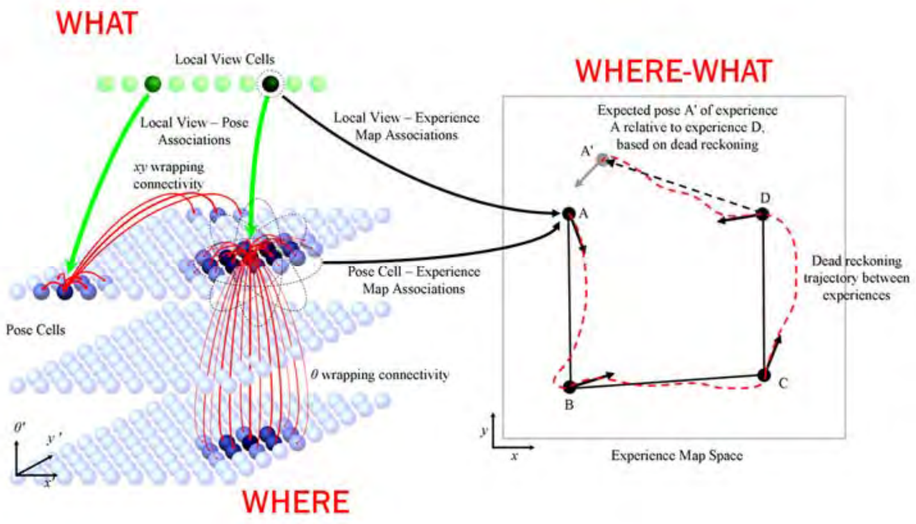
ViTa-SLAM

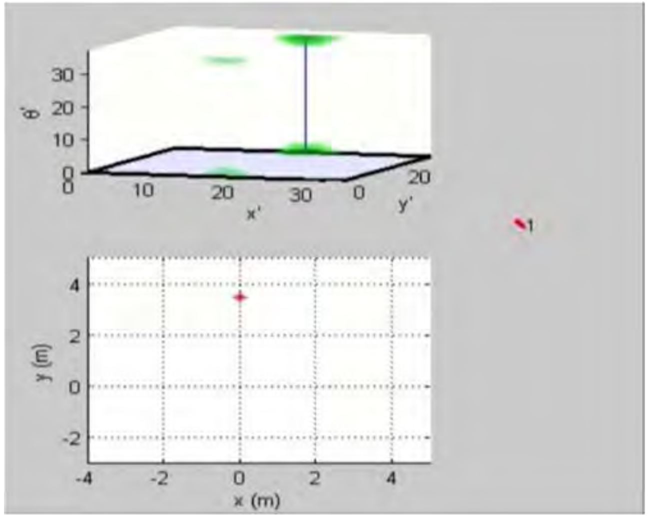
*CatSLAM is not biologically inspired

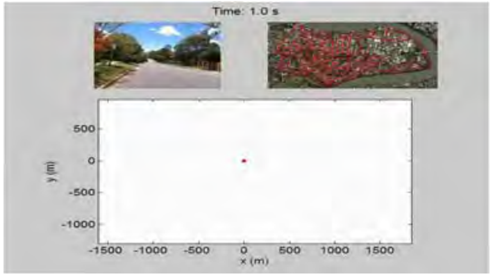
RatSLAM: Over a decade from neuroscience to deployment





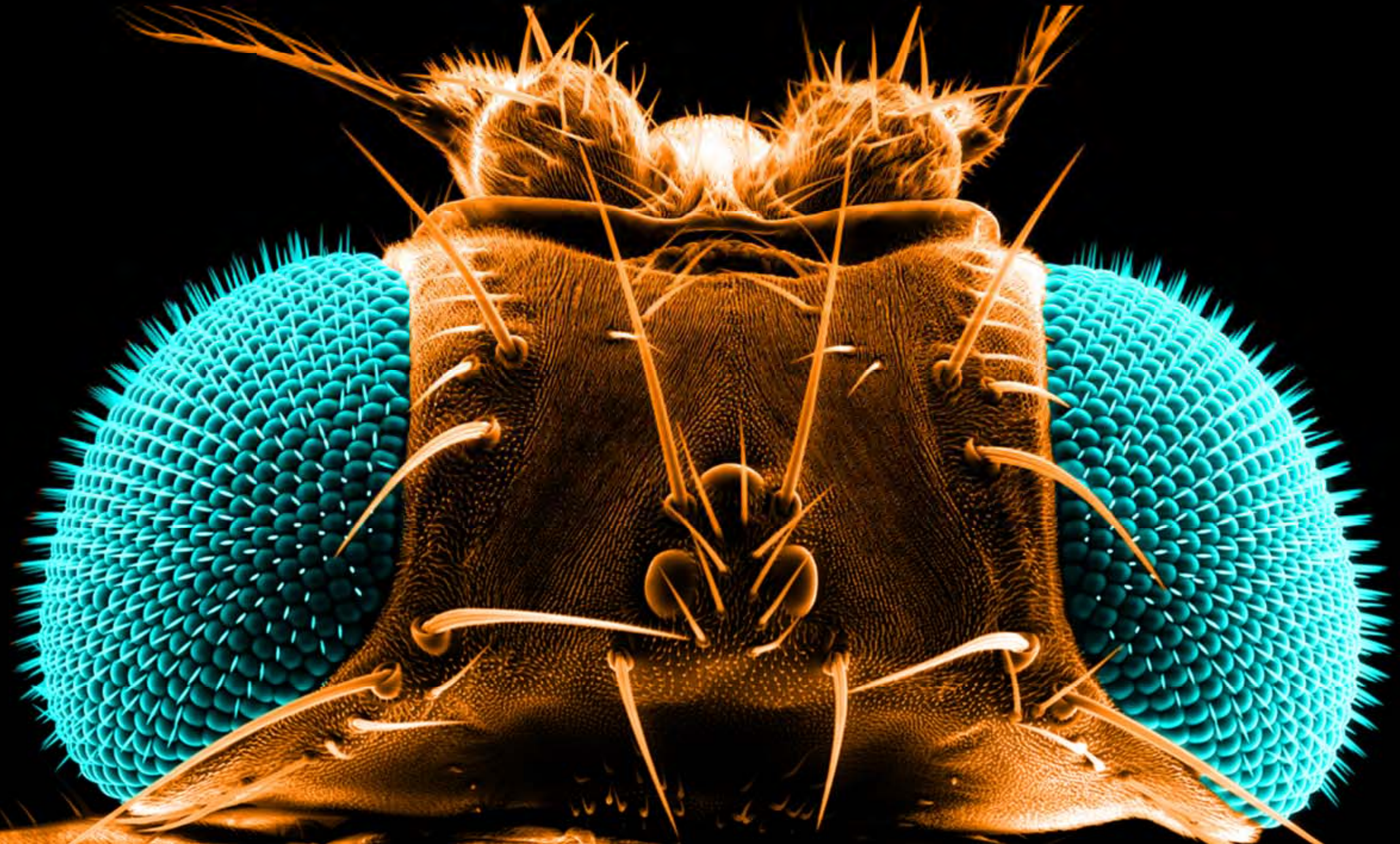






Source: www.gtec.at
MJ Milford, Robot navigation from nature, *Springer Tracts in Advanced Robotics* 41
[2] H. Stensola, T. Stensola, T. Solstad, K. Froland, M. Moser, and E. Moser, "The entorhinal grid map is discretized," Nature, vol. 492, pp. 72-78, 2012

Recent & Ongoing Bio-inspired Research



NeuroSLAM: A Brain inspired 6-DOF SLAM System for 3D Environments

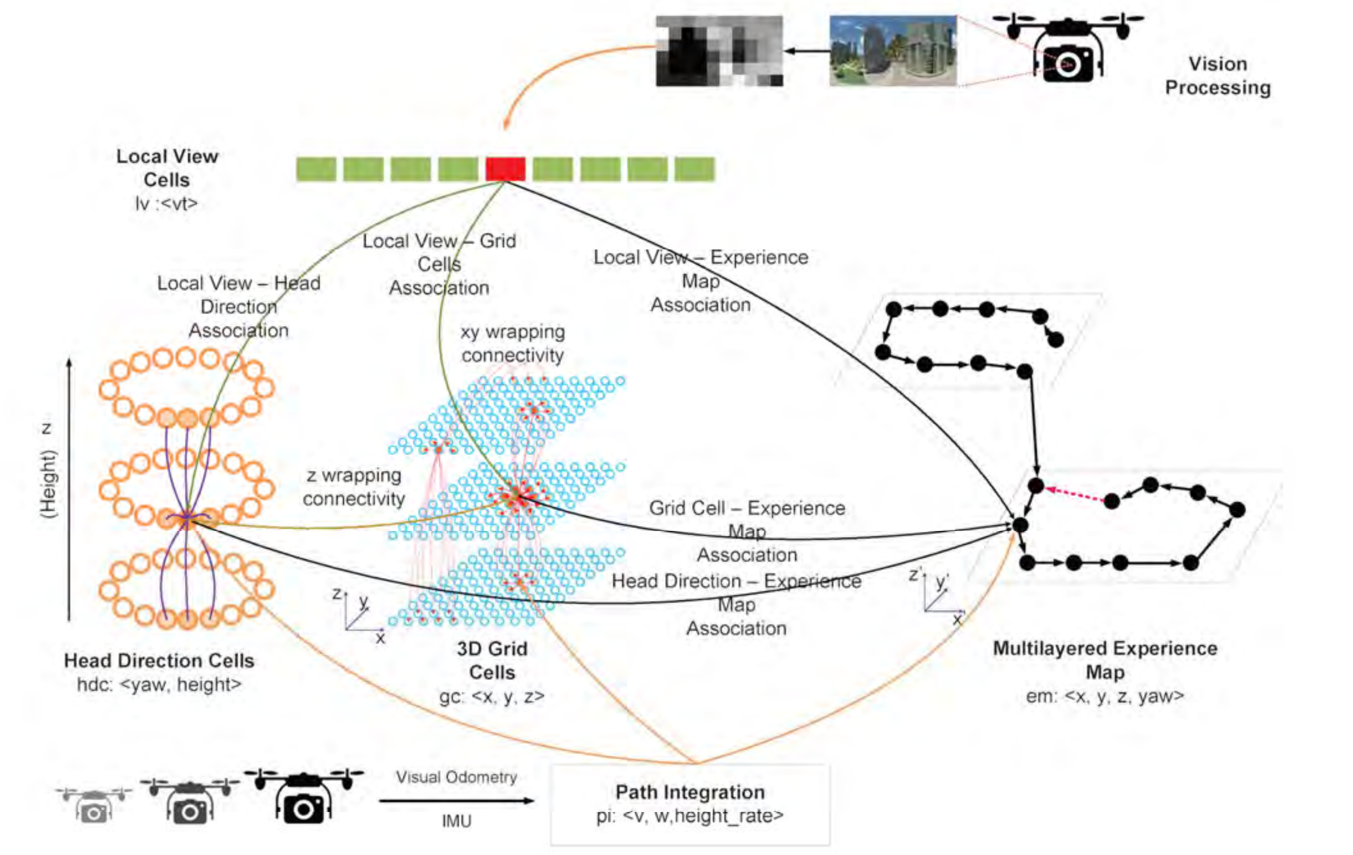
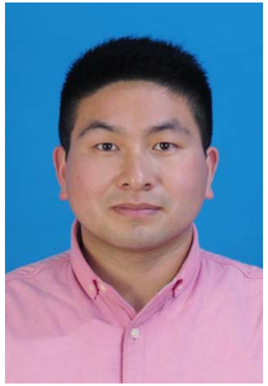
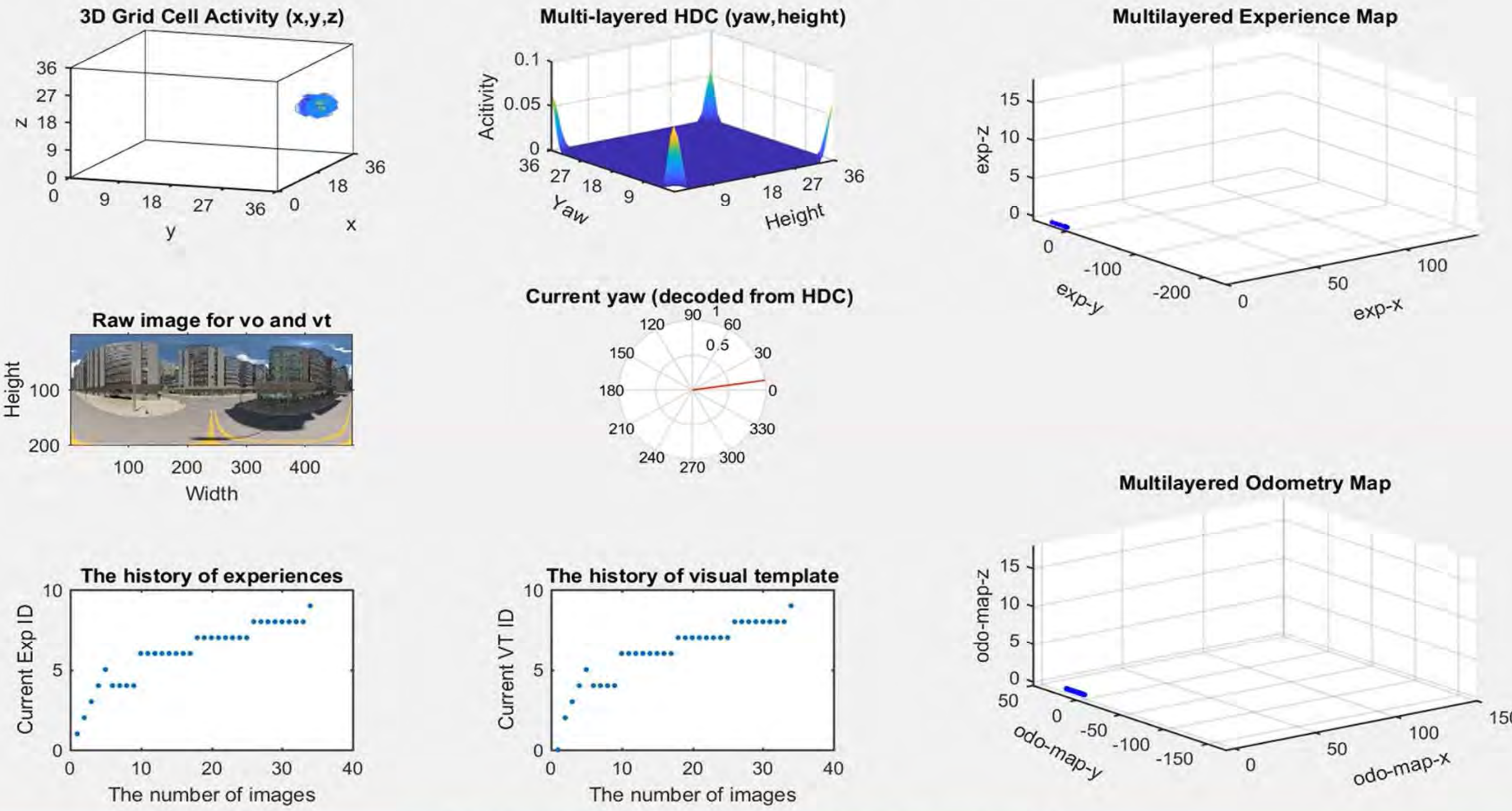


Fig. 1 NeuroSLAM architecture. The system consists of conjunctive pose cells combining the 3D grid cells and multilayered head direction cells, the multilayered experience map and vision modules. The conjunctive pose cell network performs path integration based on the local view cues and self-motion 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



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 Geo-sciences (Wuhan) (No. 1610491T08) and the Hubei Soft Science Research Program (No. LZX2014010).



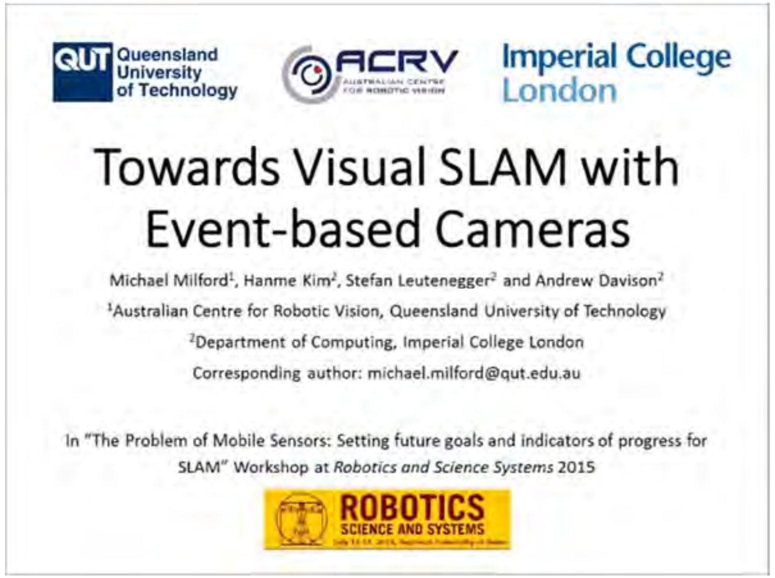
Fangwen Yu, Jianga Shang, Youjian Hu and Michael Milford, “NeuroSLAM: a brain-inspired SLAM system for 3D environments”, *Biological Cybernetics*, 2019

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

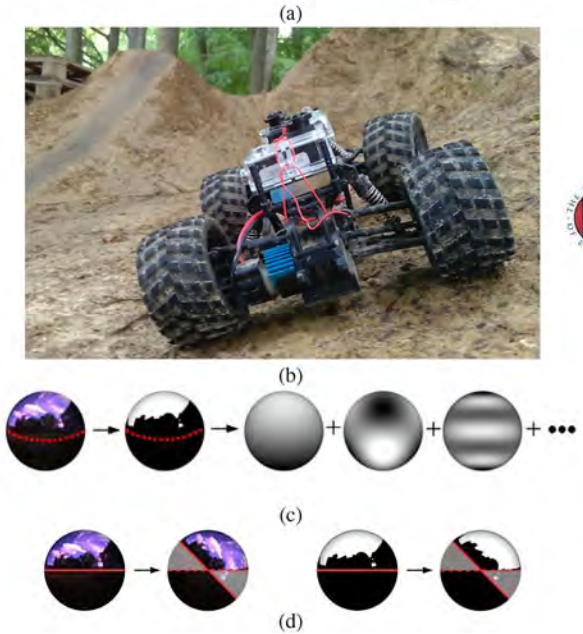

Queensland University of Technology ACRV Imperial College London

Towards Visual SLAM with Event-based Cameras

Michael Milford[1], Hanme Kim[2], Stefan Leutenegger[2] and Andrew Davison[2]
[1]Australian Centre for Robotic Vision, Queensland University of Technology
[2]Department of Computing, Imperial College London
Corresponding author: michael.milford@qut.edu.au

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

ROBOTICS SCIENCE AND SYSTEMS

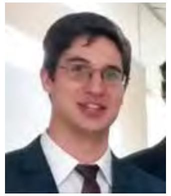


UV-sensitive cameras

THE UNIVERSITY of EDINBURGH informatics
Universität Bielefeld

Tom Stone

Low light cameras

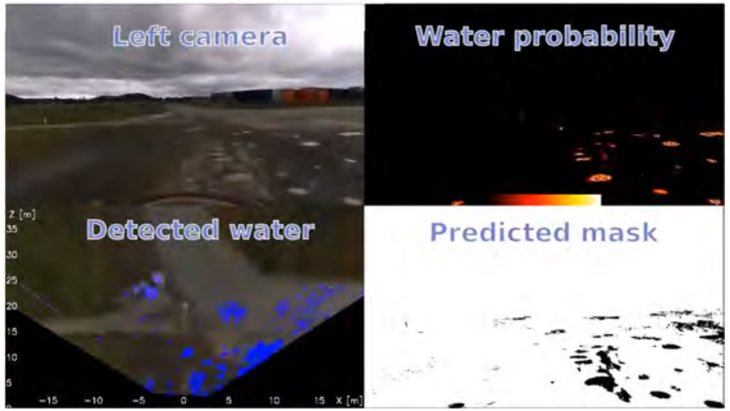


James Mount

Stereo Polarized Cameras

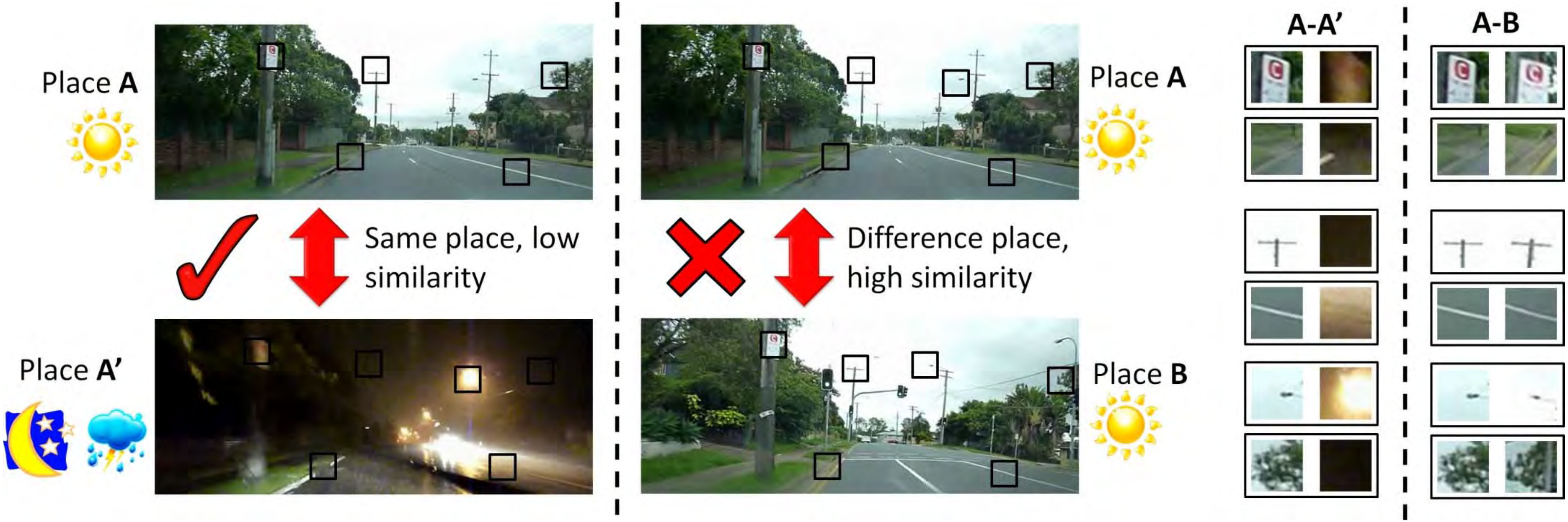
Australian National University

Chuong Nguyen



How Bio-inspired Research Can Spur Breakthroughs

The Core Challenge



M Milford, G Wyeth "SeqSLAM: Visual route-based navigation for sunny summer days and stormy winter nights", *IEEE International Conference on Robotics and Automation, 2012. Best Vision Paper Award.*

One of our core research foci

Visual Place Recognition: A Survey

Stephanie Lowry, Niko Sünderhauf, Paul Newman, *Fellow, IEEE*, John J. Leonard, *Fellow, IEEE*, David Cox, Peter Corke, *Fellow, IEEE*, and Michael J. Milford, *Member, IEEE*

Stephanie Lowry, Niko Sünderhauf, Paul Newman, John J. Leonard, David Cox, Peter Corke,and Michael J. Milford, “**Visual Place Recognition: A Survey**”, in *IEEE Transactions on Robotics and Automation*, 32 (1), 2016

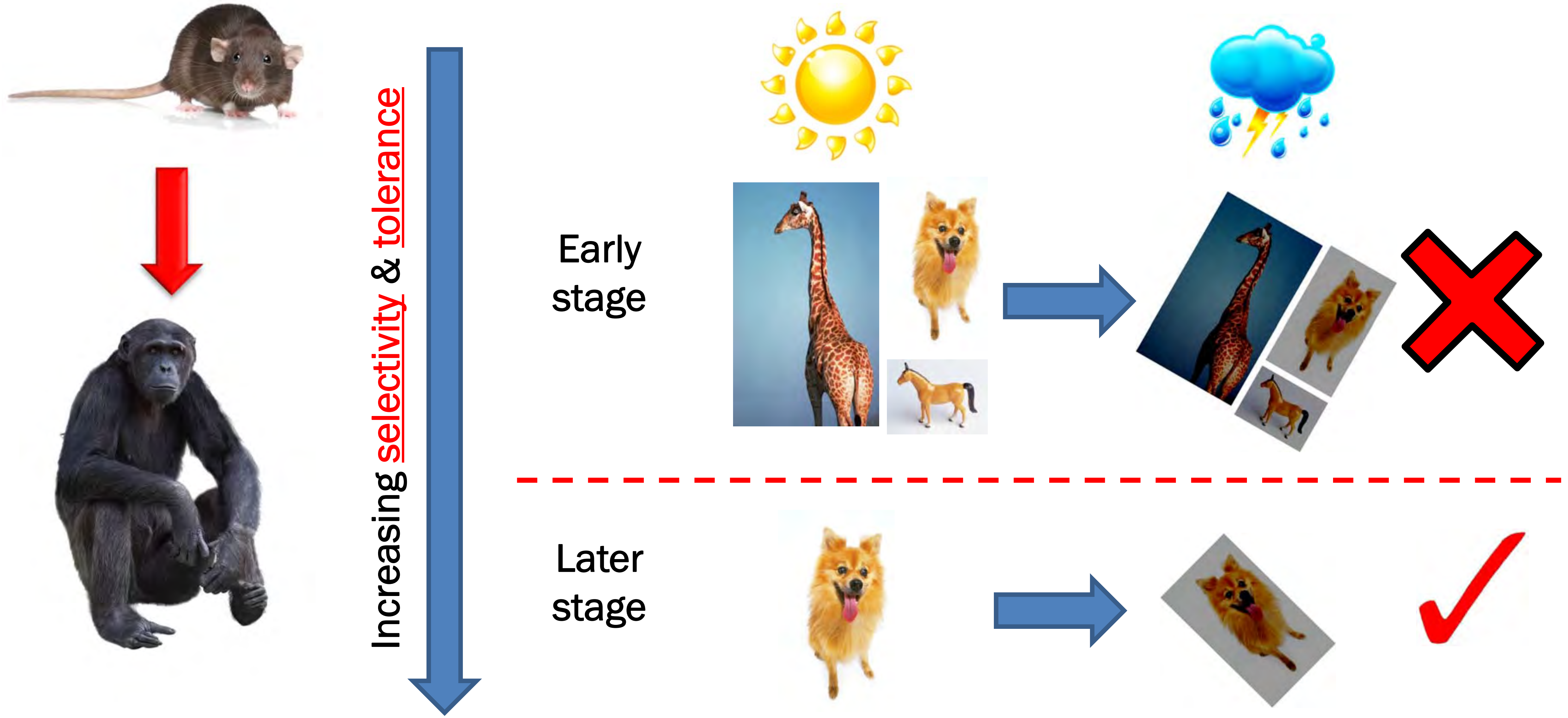
Some papers from 2018-2019

- J Mount, L Dawes, M Milford, “Automatic Coverage Selection for Surface-Based Visual Localization”, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 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
- Sourav Garg, V Babu, Thanuja Dharmasiri, Stephen Hausler, Niko Suenderhauf, Swagat Kumar, Tom Drummond, Michael Milford, “Look no deeper: Recognizing places from opposing viewpoints under varying scene appearance using single-view depth estimation”, *IEEE International Conference on Robotics and Automation*, 2019
- S Hausler, A Jacobson, M Milford, “Multi-Process Fusion: Visual Place Recognition Using Multiple Image Processing Methods”, *IEEE Robotics and Automation Letters* 4 (2), 2019.
- S Garg, N Suenderhauf, M Milford, “Semantic–geometric visual place recognition: a new perspective for reconciling opposing views”, *The International Journal of Robotics Research*, 2019
- J Mao, X Hu, X He, L Zhang, L Wu, MJ Milford, “Learning to Fuse Multiscale Features for Visual Place Recognition”, *IEEE Access* 7, 5723-5735, 2018
- S Garg, N Suenderhauf, M Milford, “Don't look back: Robustifying place categorization for viewpoint-and condition-invariant place recognition”, *IEEE International Conference on Robotics and Automation*, 2018
- Y Latif, R Garg, M Milford, I Reid, "Addressing challenging place recognition tasks using generative adversarial networks”, *IEEE International Conference on Robotics and Automation*, 2018
- S Garg, N Suenderhauf, M Milford, “Lost? appearance-invariant place recognition for opposite viewpoints using visual semantics”, in *Robotics Science and Systems*, 2018
- L Yu, A Jacobson, M Milford, “Rhythmic representations: Learning periodic patterns for scalable place recognition at a sublinear storage cost”, IEEE Robotics and Automation Letters 3 (2), 811-818, 2018

QUT Queensland University of Technology

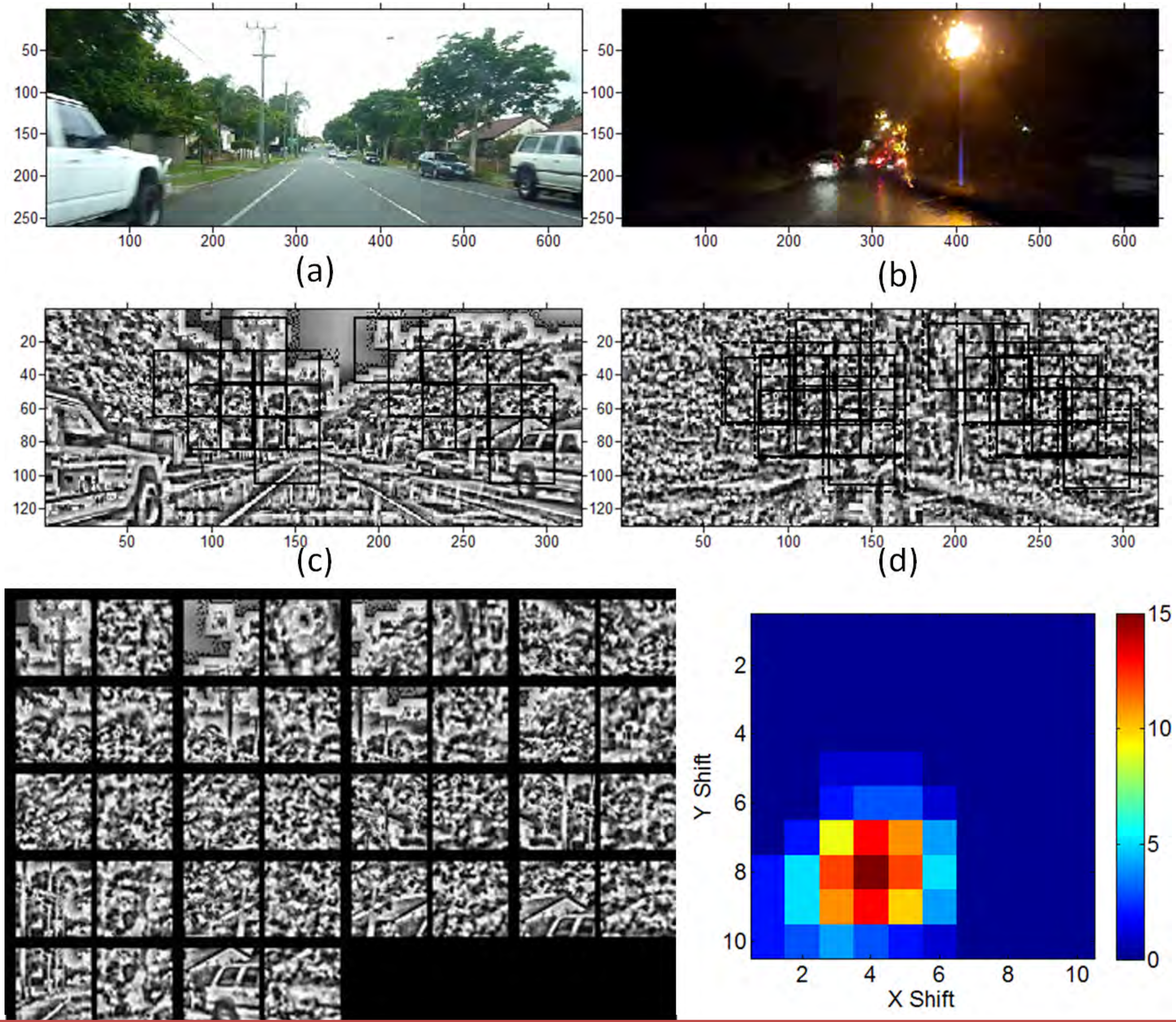
HARVARD UNIVERSITY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA



N. C. Rust and J. J. DiCarlo, "Selectivity and Tolerance (“Invariance”) Both Increase as Visual Information Propagates from Cortical Area V4 to IT," *The Journal of Neuroscience*, vol. 30, pp. 12978-12995, 2010

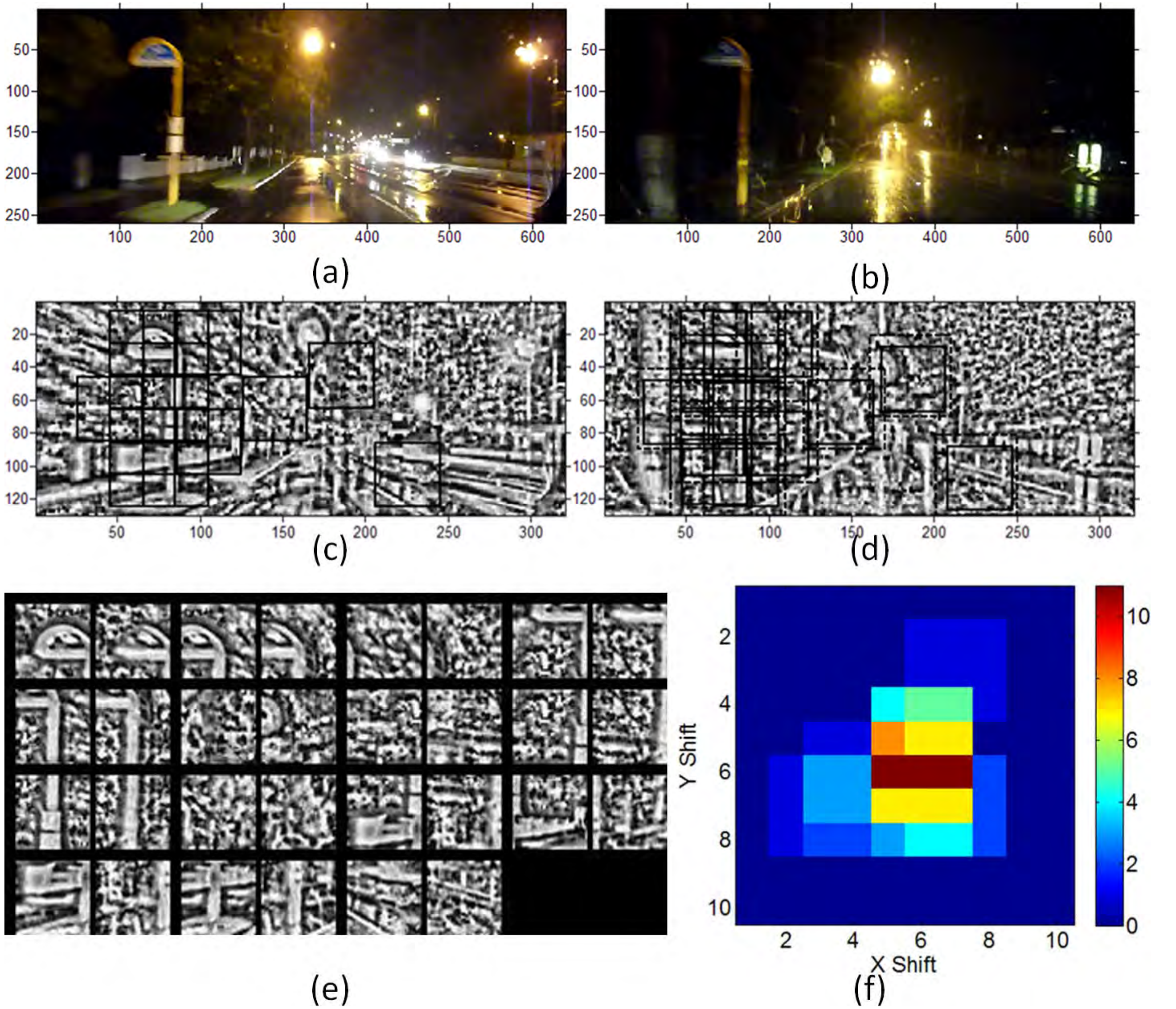
Correctly **confirmed** match: true positive



- Michael Milford, Eleonora Vig, Walter J. Scheirer, David D. Cox, “Vision-based Simultaneous Localization and Mapping in Changing Outdoor Environments”, in *Journal of Field Robotics*, 31 (5), 2014.
- Michael Milford, Walter J. Scheirer, Eleonora Vig, Arren Glover, Oliver Baumann, Jason Mattingley, David D. Cox, "Condition-Invariant, Top-Down Visual Place Recognition,“ *IEEE International Conference on Robotics and Automation, 2014*

Correctly rejected match hypothesis: true negative

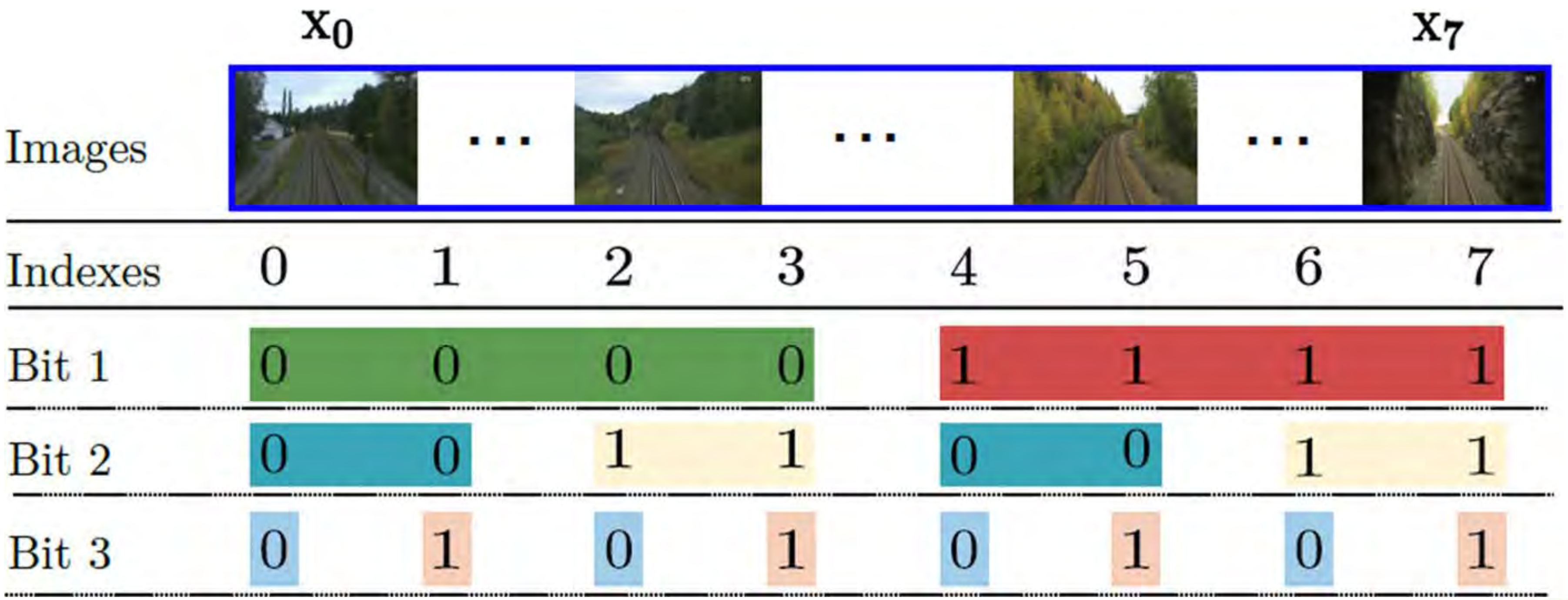
Beat the Machine Game



- Michael Milford, Eleonora Vig, Walter J. Scheirer, David D. Cox, "Vision-based Simultaneous Localization and Mapping in Changing Outdoor Environments", in *Journal of Field Robotics*, 31 (5), 2014.
- Michael Milford, Walter J. Scheirer, Eleonora Vig, Arren Glover, Oliver Baumann, Jason Mattingley, David D. Cox, "Condition-Invariant, Top-Down Visual Place Recognition," *IEEE International Conference on Robotics and Automation, 2014*

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[1], Tuan Hoang[2], and Michael Milford[3]

Contact: Professor Michael Milford, michael.milford@qut.edu.au

[13]Chalmers University of Technology, [2]Singapore University of Technology and Design, [3]QUT

The Nuances of Compression & Storage

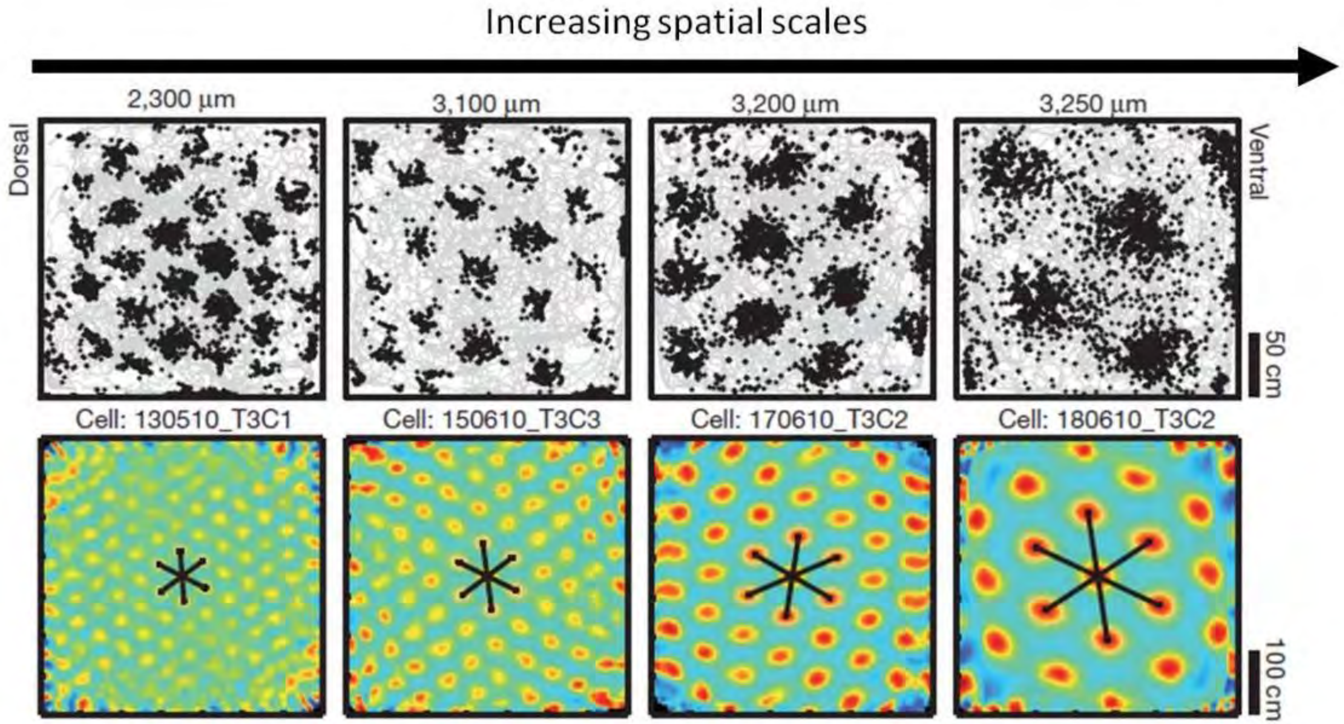
- Early days of robotics: critical factors for deployment & feasibility
- Recent years: move towards focus on maximal recall / accuracy / precision / other performance
- All other things being equal, better compression & storage enables:
  - Cheaper, less bulky / power hungry compute hardware
  - On-board 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?

Grid Cells (2004/2005)

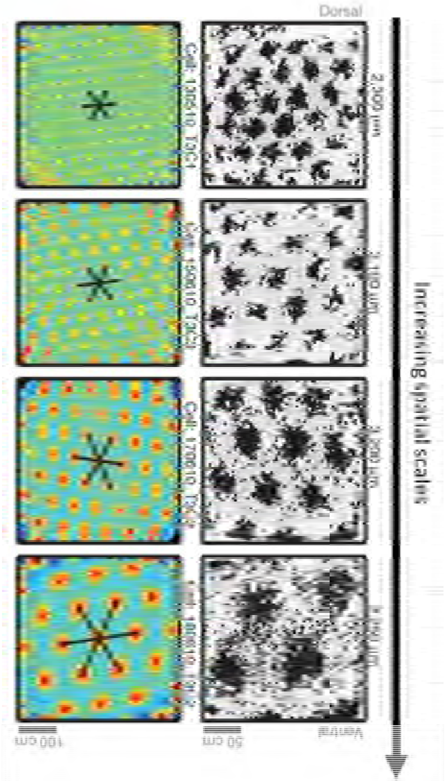
- Multi-scale grid cell mapping. ~5+ scales, √2 scaling



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

[2] H. Stensola, T. Stensola, T. Solstad, K. Froland, M. Moser, and E. Moser, "The entorhinal grid map is discretized," *Nature,* vol. 492, pp. 72-78, 2012

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?

H. Stensola, T. Stensola, T. Solstad, K. Froland, M. Moser, and E. Moser, "The entorhinal grid map is discretized," Nature, vol. 492, pp. 72-78, 2012

- Huu Le, Tuan Hoang, Michael J Milford, "BTEL: A Binary Tree Encoding Approach for Visual Localization", in *IEEE International Conference on Intelligent Robots and Systems*, 2019
- A Jacobson, Z Chen, M. Milford, Biological Cybernetics, 2018
- Litao Yu, Adam Jacobson, Michael J Milford, "Rhythmic Representations: Learning Periodic Patterns for Scalable Place Recognition at a Sub-Linear Storage Cost", in *IEEE Robotics and Automation Letters*, 2018
- Huu Le, Anders Eriksson, Thanh-Toan Do, Michael Milford, "A Binary Optimization Approach for Constrained K-Means Clustering" in *Asian Conference on Computer Vision*, 2018.
- Chen Fan, Zetao Chen, Adam Jacobson, Xiaoping Hu and Michael Milford, "Biologically-inspired Visual Place Recognition with Adaptive Multiple Scales", in press in Robotics and Autonomous Systems, 2017.
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- Z Chen, A Jacobson, UM Erdem, ME Hasselmo, M Milford, "Multi-scale bio-inspired place recognition," IEEE International Conference on Robotics and Automation, 2014.
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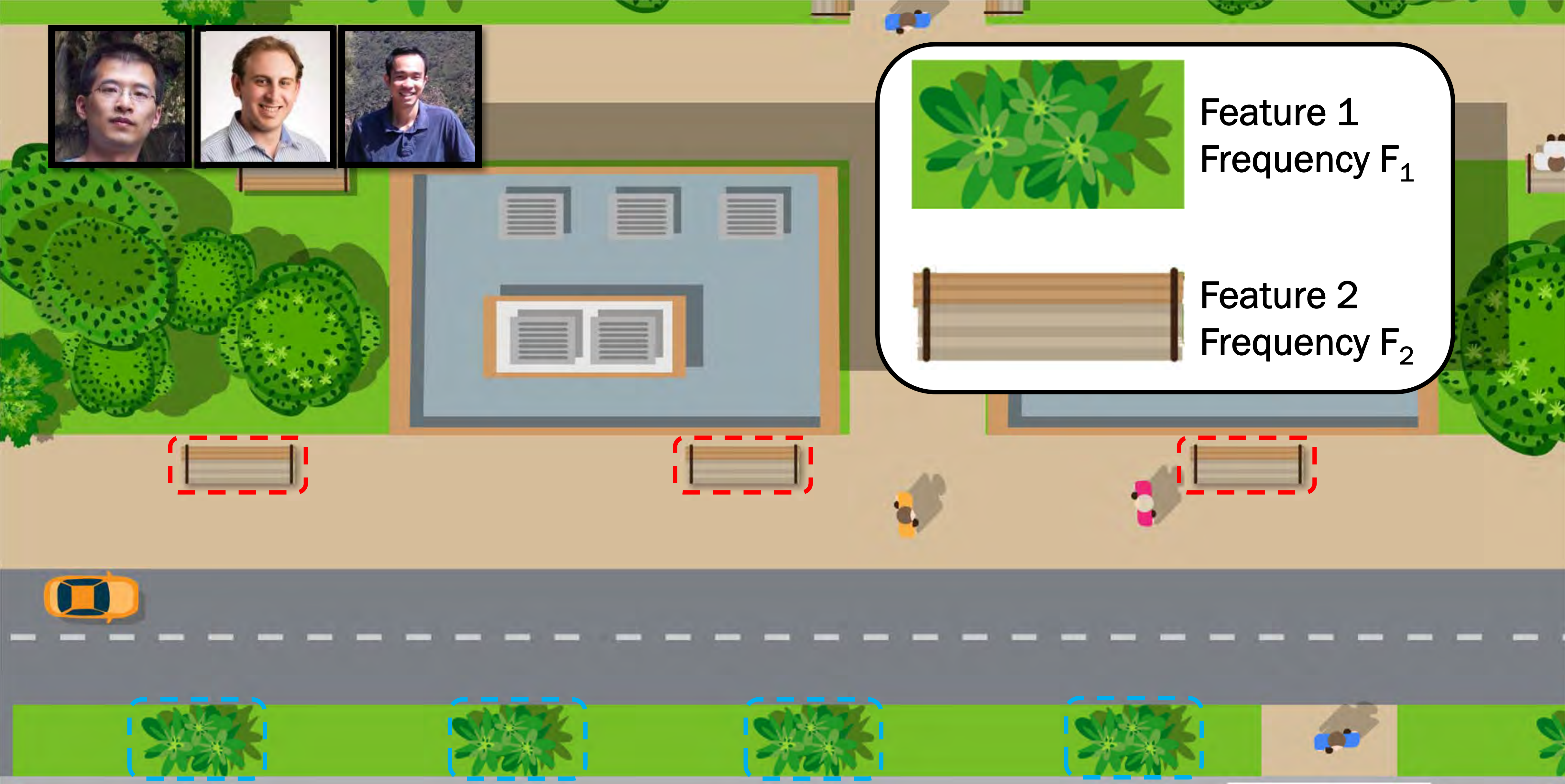
Exploiting a Cyclic World



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

Memory collision

6 places, 5 units of storage

Feature 1: [0 1]

Feature 2: [0 1 2]

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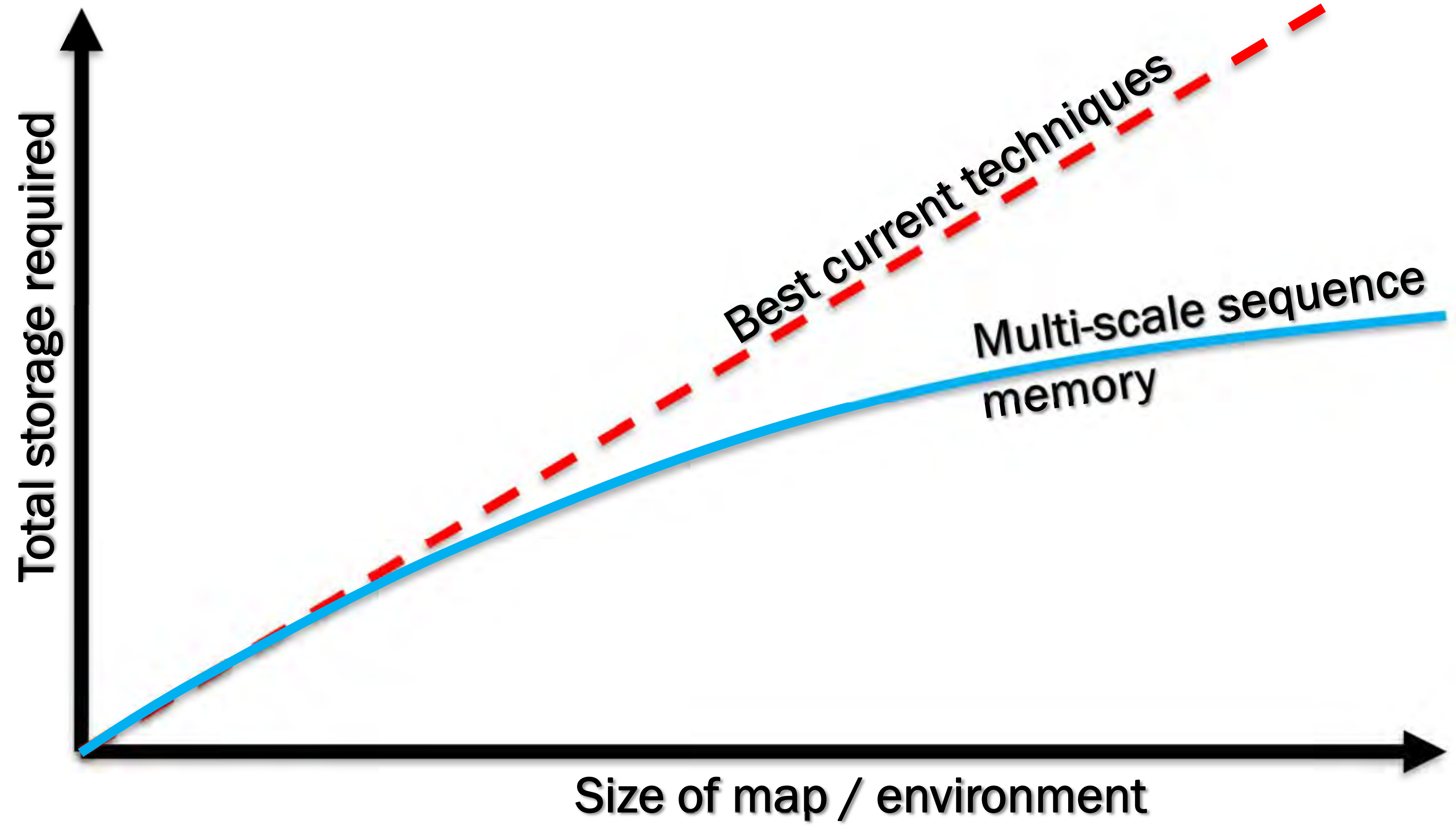
Real World Sub-Linear Dataset Compression



(b)

- Huu Le, Tuan Hoang, Michael J Milford, “BTEL: A Binary Tree Encoding Approach for Visual Localization”, in *IEEE International Conference on Intelligent Robots and Systems*, 2019
- Litao Yu, Adam Jacobson, Michael J Milford, “Rhythmic Representations: Learning Periodic Patterns for Scalable Place Recognition at a Sub-Linear Storage Cost”, in *IEEE Robotics and Automation Letters*, 2018
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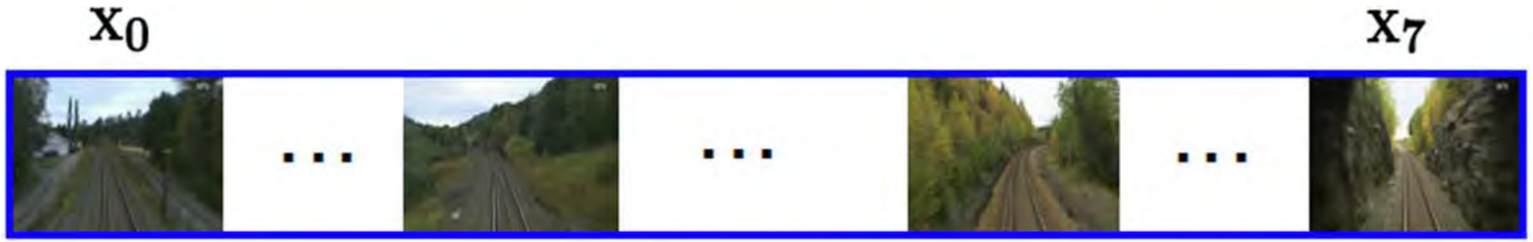


Images								
Indexes	0	1	2	3	4	5	6	7
Bit 1	0	0	0	0	1	1	1	1
Bit 2	0	0	1	1	0	0	1	1
Bit 3	0	1	0	1	0	1	0	1

BTEL: A Binary Tree Encoding Approach for Visual Localization

Huu Le[1], Tuan Hoang[2], and Michael Milford[3]

Contact: Professor Michael Milford, michael.milford@qut.edu.au

[13]Chalmers University of Technology, [2]Singapore University of Technology and Design, [3]QUT

Future Work

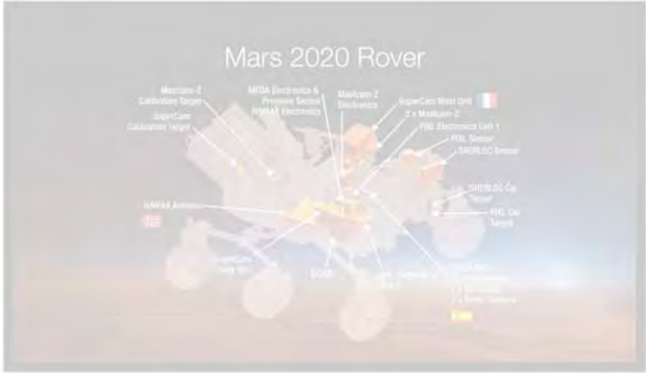
IROS2017 → IEEE RA-L 2018 / ACCV 2018 → IEEE RA-L/IROS2019 / ICCV2019 → ONGOING & FUTURE RESEARCH

- 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 multimodal toolpoint positioning

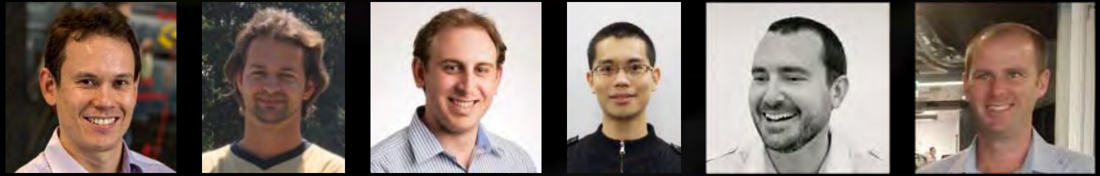
How Automated Vehicles Will Interact With Road Infrastructure Now and in the Future

Robust hazard detection on construction and mining sites

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

- Fan Zeng, Adam Jacobson, David Smith, Nigel Boswell, Thierry Peynot, Michael J Milford , “TIMTAM: Tunnel-Image Textually-Accorded Mosaic for Location Refinement of Underground Vehicles with a Single Camera”, in *IEEE/RSJ International Conference on Intelligent Robots*, Macau, China 2019.
- Fan Zeng, Adam Jacobson, David Smith, Nigel Boswell, Thierry Peynot, Michael J Milford , “LookUP: Vision-Only Real-Time Precise Underground Localisation for Autonomous Mining Vehicles”, in *IEEE International Conference on Robotics and Automation*, 2019.
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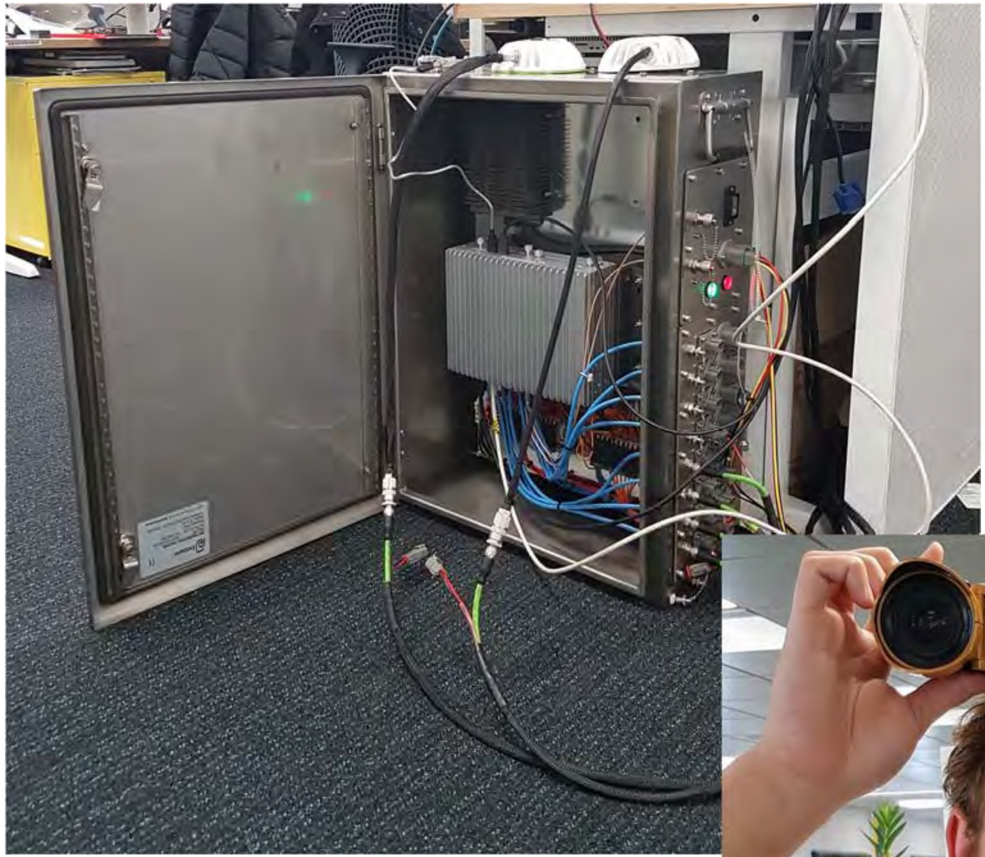
The Early Days…

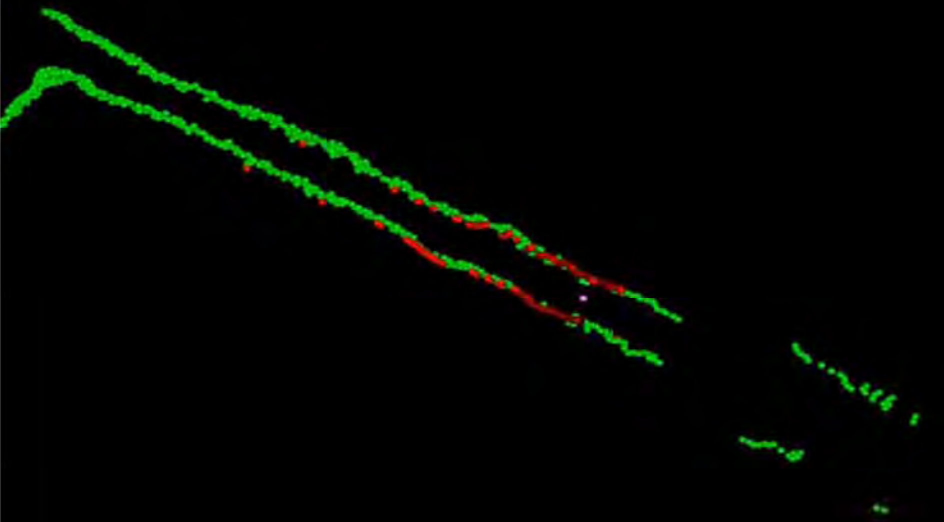


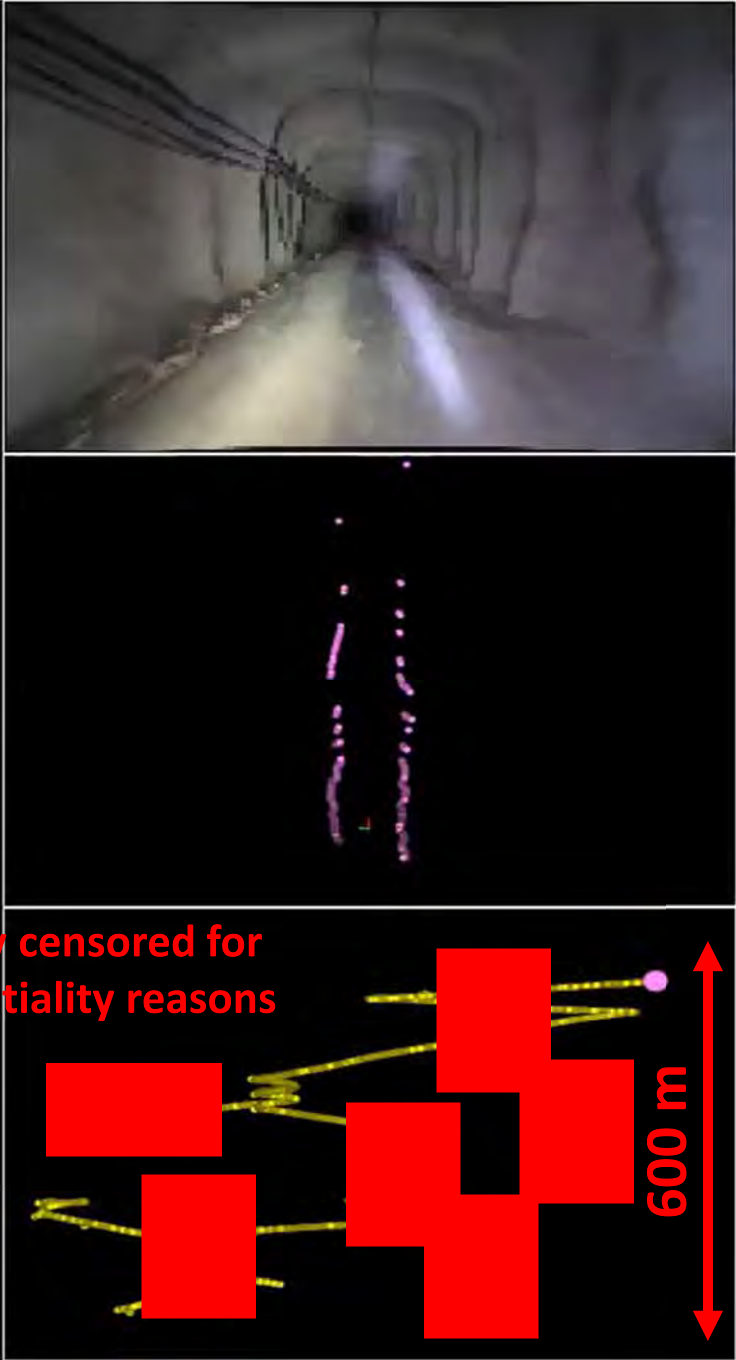
“Octobox”

Cameras

Adam


SICK
NOT FOR PRODUCTION
SICK
SICK





Partially censored for confidentiality reasons

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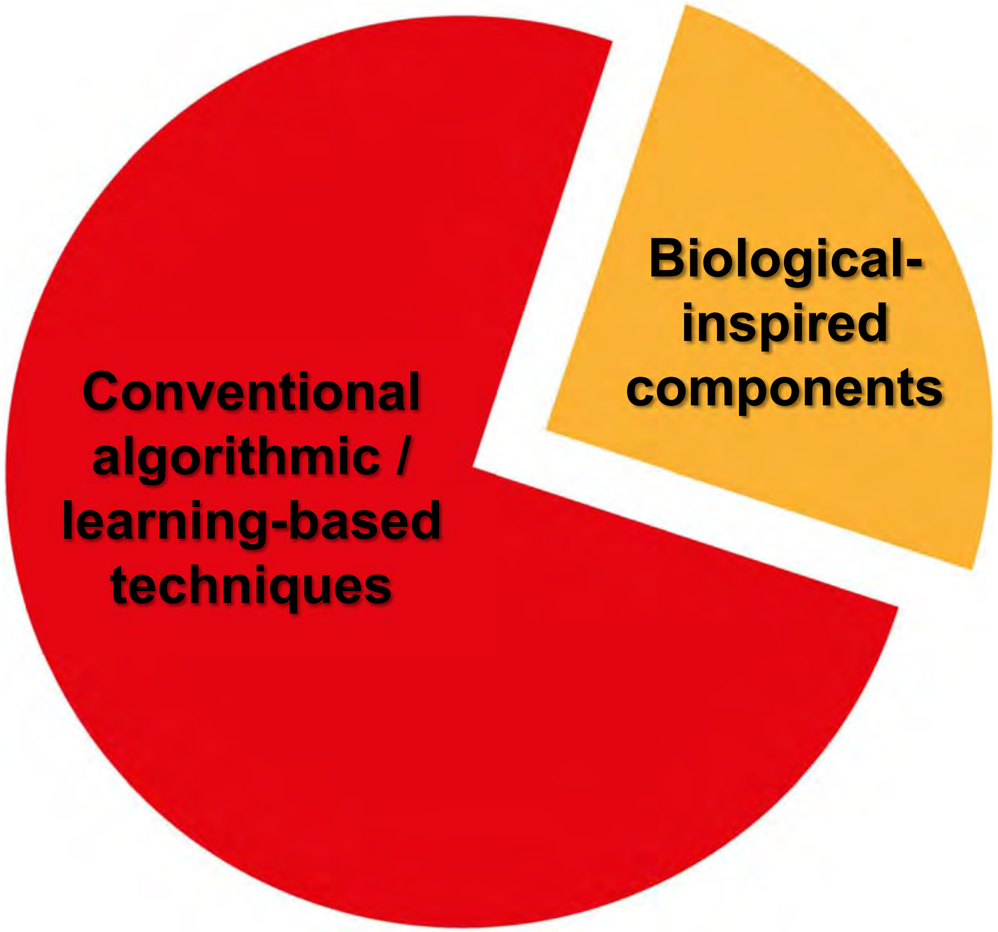
Going from biological inspiration to deployment



- 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

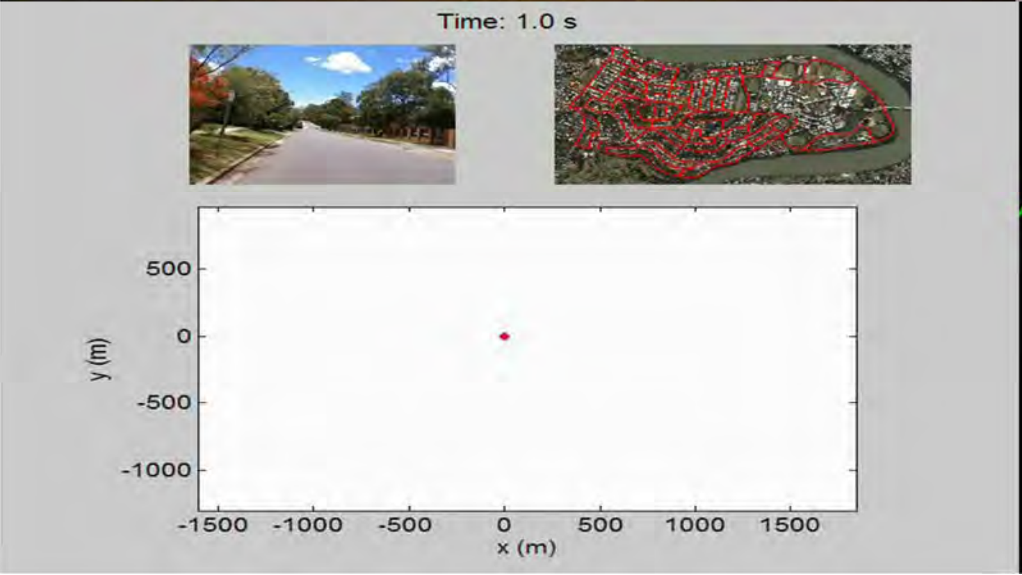
- Image processing techniques partially derived from bio-inspired research
- Short bespoke sequence-matching techniques
- Topological mapping techniques partially derived from bio-inspired research
- Image matching techniques derived from fundamental primate-inspired vision research several years ago

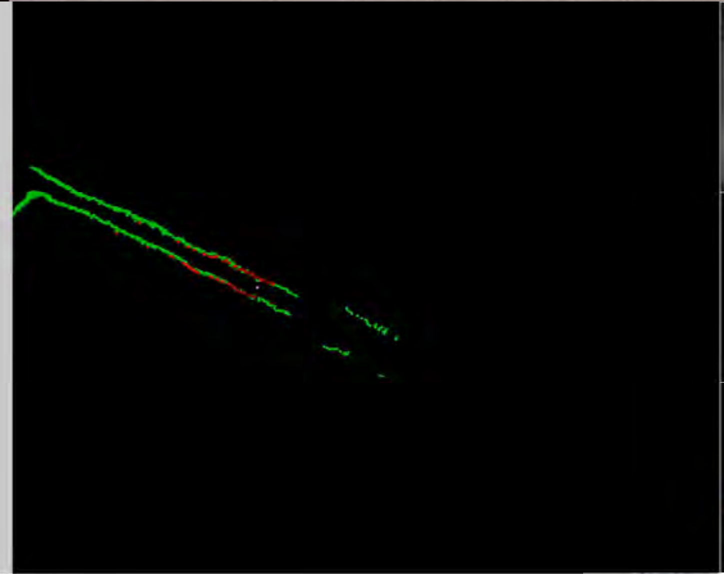

We are hiring!
Current and upcoming roles including PhDs, Postdocs, Research Engineers, and Academic Roles
We work here
E-mail: michael.milford@qut.edu.au
QUT

Collaboration Opportunities

Some groups we have published with or held joint grants with

- 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…





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Australian Government National Health and Medical Research Council NHMRC
Queensland Government Department of Transport and Main Roads
Queensland Government
sicsa* The Scottish Informatics & Computer Science Alliance
Australian Government Department of Defence Science and Technology

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