Brains on Board Project Showcase Report

The University Of Sheffield.
University of Sussex
Queen Mary University of London
UKRI Engineering and Physical Sciences Research Council

Foreword

As the Brains on Board project ends its final year, I am happy to share with you this final overview of the project, to summarise its objectives and achievements. It has been my pleasure to lead the project during its five years. These years have seen a number of highlights, such as groundbreaking research papers, and the formation of a successful deep tech university spinout. Inevitably the years have also given us some notable lowlights, particularly the COVID-19 pandemic which was so disruptive to people's lives, and of the work of the project, for a prolonged period.

Brains on Board set out with a bold and broad ambition, to simultaneously conduct basic research into the behaviour of insects and how their brains generate that behaviour, and into reverse engineering insect brains to design novel artificial brains for robotics and autonomous systems, that function much more robustly and efficiently than existing approaches. In doing so, advances in both experimental and modelling techniques would also be required. We thus set our team a series of challenging targets. In reading this report I hope you will agree with my assessment, that the hard work and ingenuity of its researchers has made substantial progress to realising the original lofty goals of the Brains on Board research project.

Choosing highlights from a project of the scale of Brains on Board is always challenging; here, alongside the overview of the project, we present five highlights, one for each year of the project, that represent the breadth and ambition of the work done. I hope you will find reading about the Brains on Board project as interesting as it has been to see it developing first-hand.

Professor James A. R. Marshall
University of Sheffield

Image credit: UKRI

Introduction

What if we could design an autonomous robot brain with the navigational and learning abilities of a honeybee? Such a computationally and energy-efficient autonomous system would represent a step-change for robotics technology, and is precisely what the 'Brains on Board' project set out to achieve. Autonomous control of mobile robots requires robustness to environmental and sensory uncertainty, and the flexibility to deal with novel environments and scenarios. Animals solve these problems through having flexible brains capable of unsupervised pattern detection and learning. Even 'small'-brained animals like bees exhibit sophisticated learning and navigation abilities using very efficient brains of only up to 1 million neurons, 100,000 times fewer than in a human brain. Crucially, these mini-brains nevertheless support high levels of multi-tasking and they are adaptable, within the lifetime of an individual, to completely novel scenarios; this is in marked contrast to typical engineering solutions.

Funded by EPSRC as a £4.8m, five year Programme Grant, the Brains on Board project drew together the Universities of Sheffield, Sussex and Queen Mary University of London, in fusing computational and experimental neuroscience, animal behaviour, and robotics in order to develop a ground-breaking new class of highly efficient 'brain on board' robot controllers, able to exhibit adaptive behaviour while running on very lightweight, low power computing hardware.

The Brains on Board project was structured around five research projects, distributed across the three partner universities, integrating into a sixth research project taking the form of a robot demonstrator for the developed technology.

RESEARCH PROJECT	DESCRIPTION	PARTNERS
1	**Investigate the neural bases of honeybee visual perception and flight control, using virtual reality simulators**	**Sheffield, QMUL**
2	**Investigate what bees see and how they move during exploration and learning, using 3d harmonic radar and high speed videography**	**QMUL, Sheffield, Sussex**
3	**Derive efficient algorithms for appearance-based visual learning and navigation**	**Sussex, QMUL**
4	**Develop and test neural models of multi-modal sensory learning and action selection**	**Sussex, Sheffield**
5	**Build hardware- and model-aware neural simulation tools for GPU processors**	**Sussex, Sheffield**
6	**Build an on-board real-time controller for autonomous flying robots**	**Sheffield, Sussex, QMUL**

The University of Sheffield

Sheffield was the lead institution for Brains on Board, having responsibility for experimental work with free-flying bees undertaking behavioural experiments, tethered bees interacting with virtual reality environments (see Highlight 1) and neural recordings from the bee visual system. Leading the final integrative Research Project 6, Sheffield also worked on the development of a bespoke quadcopter platform suitable for mounting GPU-based brains-on-board controllers, including the design and fabrication of a sophisticated new stabilised multi-camera system. Other contributions were made in the area of insect-eye modelling (see Highlight 3), and in commercialisation of Brains on Board research via the establishment of Opteran Technologies (see Highlight 4).

The University of Sussex

Sussex was the key informatics project partner alongside The University of Sheffield, while also providing critical biological expertise on insect navigation, and learning. As well as developing and refining brain-inspired algorithms in these areas, Sussex made key contributions in demonstrating the utility of GPUs for large-scale neural simulation (see Highlight 2), in developing a framework for streamlined integration of brain models with robotic platforms ('BoB Robotics'), and in developing ground-based platforms for proof-of-principle demonstrations of its navigation algorithms, including integrating technology from project spinout Opteran Technologies.

Queen Mary University of London

Queen Mary provided the Brains on Board project with expertise in bee flight and learning behaviour, and developed cutting edge technology to track free-flying bees in landscape-scale natural environments (see Highlight 5). Key contributions included data on bee flight traces from this harmonic radar system, which shed light on a number of questions such as what large-scale landscape features bees use during navigation, as well as small scale high-speed video data helping uncover the visual information bees use to control their flight behaviour. Further contributions included studies on social transfer of learned behaviour between bees, and what simple tricks bees are likely to use when apparently doing cognitive tasks such as 'counting'.

Media Highlights

Coverage of the project and of Opteran Technologies:

- 'Die as a human or live forever as a cyborg': Will robots rule the world? *Sydney Morning Herald*, July 19th 2021
- ABC Radio, May 3rd 2021

Coverage of the paper 'Non-numerical strategies used by bees to solve numerical cognition tasks':

- Bees able to solve maths tests despite not understanding numbers, researchers find. *The Independent*, February 17th 2021
- Honeybees can solve maths tests without using numbers. *The Engineer*, February 3rd 2021
- BBC Radio Sheffield, February 17th 2021

Coverage of the paper 'Larger GPU-accelerated brain simulations with procedural connectivity':

- Video game graphics cards can simulate monkey brains on the cheap. *New Scientist*, February 1st 2021
- Researchers run monkey brain simulation usually restricted to supercomputers on commercial PCs. *iNews*, February 2nd 2021
- Video games were 'Eureka!' moment that helped boffins simulate neural activity on a single commodity GPU. *The Register*, February 3rd 2021

Coverage of the project's attendance at the UKRI VIP Reception at the AAAS Meeting, Seattle:

- Scientists look to bees to develop drone technology. *The Financial Times*, February 16th 2020
- Bees help drones to find their bearings. *The Times*, February 17th 2020
- Bees are being mapped to help develop driverless cars and drones by scientists gluing tiny antennas to their heads. *The Telegraph*, February 17th 2020
- Tiny antennae that record how bees navigate between flowers may help perfect steering systems for driverless cars and drones, scientists reveal. *The Daily Mail*, February 17th 2020
- Sky News, February 18th 2020

Coverage of the project:

- *Jimmy's Big Bee Rescue*, Channel 4, September 5th 2020
- *The One Show*, BBC, March 6th 2020
- RAI 2, November 4th 2018
- Reuters, June 5th 2018
- CBC News, April 10th 2018
- BBC World Service, February 8th 2018

Team

Past and present members of the Brains on Board team:

INVESTIGATORS

Prof James Marshall,
University of Sheffield

Prof Mikko Juusola,
University of Sheffield

Prof Lars Chittka,
Queen Mary University of London

Prof Thomas Nowotny,
University of Sussex

Prof Andrew Philippides,
University of Sussex

Prof Paul Graham,
University of Sussex

Prof Eleni Vasilaki,
University of Sheffield

Dr Mike Mangan, University of Sheffield

RESEARCHERS

Dr James Bennett,
University of Sussex

Dr Alex Cope,
University of Sheffield

Dr Alex Dewar,
University of Sussex

Dr Jamie Knight,
University of Sussex

Dr HaDi MaBouDi,
University of Sheffield

Dr Neveen Mansour,
University of Sheffield

Dr Jouni Takalo,
University of Sheffield

Dr Joe Woodgate,
Queen Mary University of London

RESEARCH STUDENTS

Joanna Brebner,
Queen Mary University of London

Alice Bridges,
Queen Mary University of London

Norbert Domcsek,
University of Sussex

Vincent Gallo,
Queen Mary University of London

Fadl Isa, University of Sheffield

Efstathios Kagioulis,
University of Sussex

Joni Kemppainen,
University of Sheffield

James McManus,
University of Sheffield

Stefan Meyer, University of Sussex

Blayze Millward,
University of Sheffield

Keivan Razban Haghighi,
University of Sheffield

Ben Scales, University of Sheffield

Fabian Steinbeck,
University of Sussex

PROJECT ADMINISTRATOR

Joanne Seal, University of Sheffield

TECHNICAL SUPPORT

Neville Dearden,
University of Sheffield

Amelia Kowalewska,
Queen Mary University of London

FORMER MEMBERS

Mark Kelly, University of Sheffield

Lucy Moffatt, University of Sheffield

Georgios Parthymos,
University of Sheffield

Michael Port, University of Sheffield

Chelsea Sabo, University of Sheffield

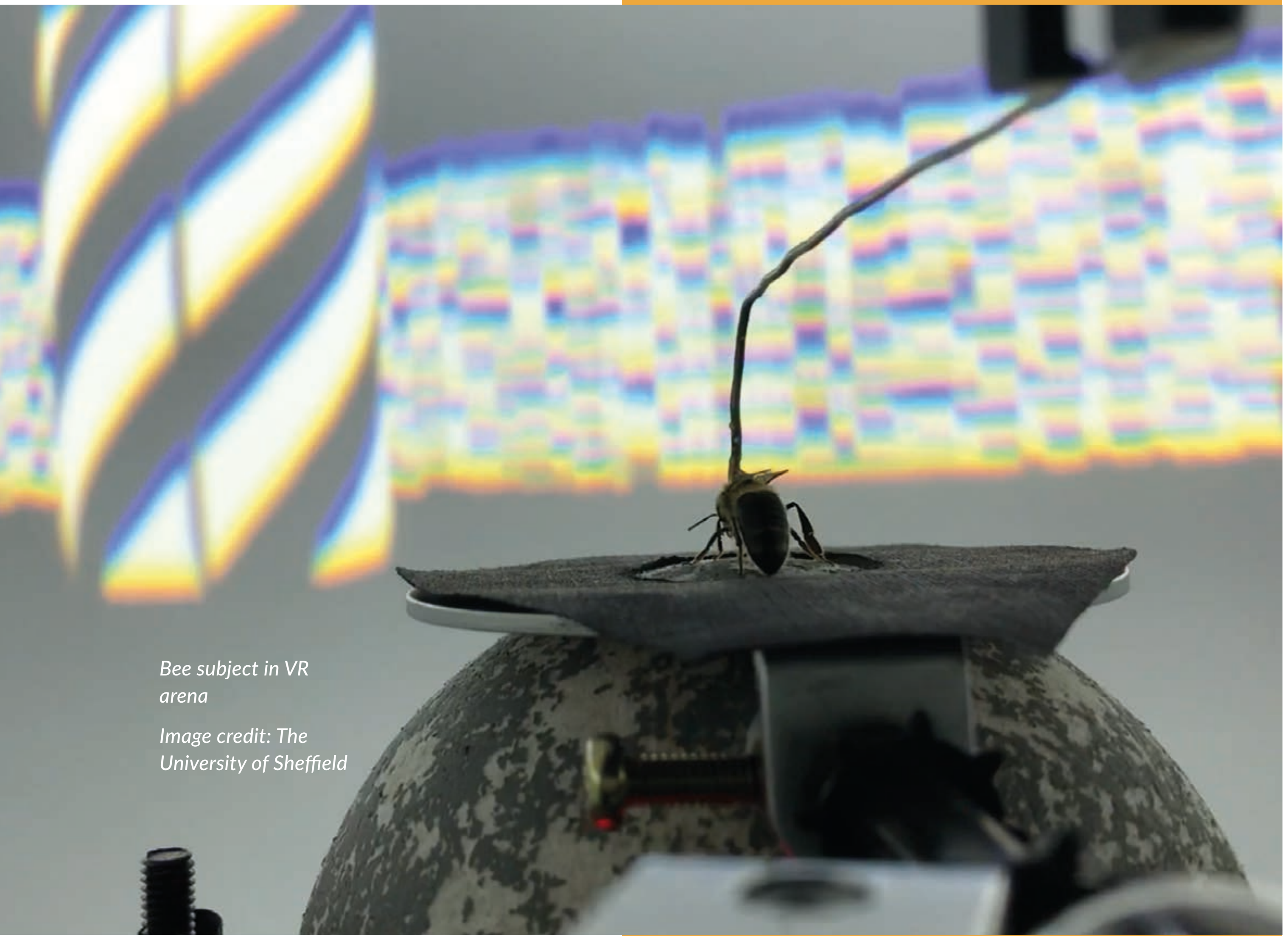
Dr Qingshan Shan,
University of Sheffield

Carla Teale, University of Sheffield

Dr Vera Vasas,
Queen Mary University of London

The Brains on Board team in summer 2019, Kenwood Hall, Sheffield

Image credit: The University of Sheffield



Bee subject in VR arena

Image credit: The University of Sheffield

Physical arena for subjects to explore before going into VR

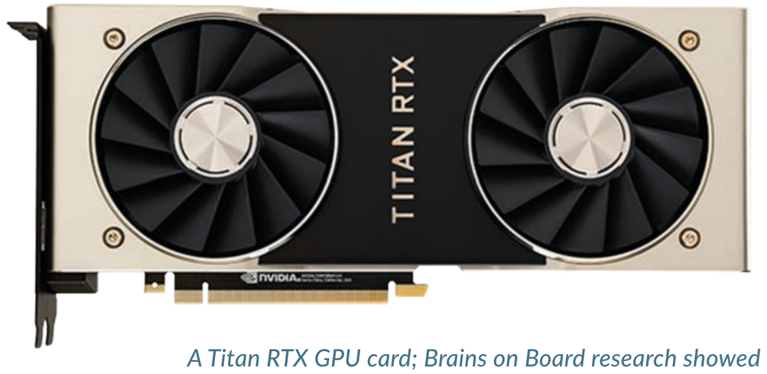
Image credit: The University of Sheffield

HIGHLIGHT 1

Bees in VR

The study of animal navigation behaviour in virtual reality brings a number of advantages; behaviour can be tracked in greater detail, manipulations of the world to test navigation models, such as teleportation, can be done in a way that cannot in the real world, and neural recording from navigating animals becomes much more feasible. Accordingly, the Brains on Board project developed an advanced VR projection system for walking bees, and a plan to move this towards a flight simulator environment.

Subjects for the VR apparatus are taken from a lab colony, and have access to a physical analogue of the VR environment for exploration and familiarisation. Movable physical landmarks corresponding to those used in VR enable bees to localise rewarding sucrose solution, or punishing heat, in order to learn the desired task - this can then be tested in VR.



A Titan RTX GPU card; Brains on Board research showed how one of these could equal the performance of 8 custom neuromorphic processor boards from a dedicated brain simulation supercomputer.

Image credit: NVidia

HIGHLIGHT 2

Supercomputer-beating neural simulation

Much of the recent deep learning revolution was enabled by faster simulations, in particular using Graphics Processing Units (GPUs) as general purpose accelerator hardware for simulating artificial neural networks.

Though it is an obvious idea to do the same with biologically more plausible spiking neural networks (SNNs), developers of existing SNN simulators have struggled to add GPU accelerator support. During Brains on Board we further developed the GeNN software that optimizes and deploys spiking neural network models for GPU accelerators.

We were able to show that a cortical microcircuit benchmark model runs as fast on a single GPU as on the fastest classical HPC configuration and faster than on the SpiNNaker neuromorphic supercomputer. Subsequently, we extended the capabilities of GeNN to also support even larger models by just-in-time connectivity generation, and ran the so-called multi-area model with 4 million neurons and 24 billion synapses on a single GPU - something previously only possible on large supercomputers.

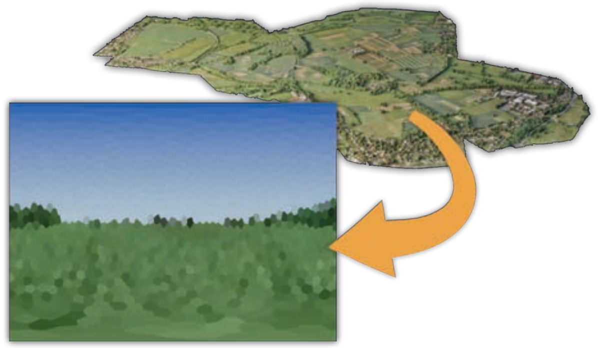
GeNN models can be deployed on a wide range of systems from supercomputers to embedded systems. The embedded systems support can underpin live robotics, allowing us to emulate bio-inspired brains-on-board algorithms in real time and in the real world.

HIGHLIGHT 3

Insect-eye rendering

Have you ever wondered what an ant sees? Or perhaps pondered the sights a bumble bee experiences as it weaves its way around towering buildings? Or maybe you have found yourself quoting the ubiquitous phrase “to be a fly on the wall”. It is easy to imagine that an insect sees the world much as we do, but just somehow smaller.

However, in reality insects see a vastly different world to us, and yet insects can understand this information with ease using brains smaller than a grain of rice. To do this they use a myriad of tricks - for instance, did you know that it can actually be easier to work out where you are when you look at something through a blurry lens as opposed to a super-high definition image? As scientists, we want to understand these tricks so that we can use them in our own autonomous robots. To do this we built an open-source computer graphics program that uses state-of-the-art raytracing hardware to accurately re-create the view from any compound eye imaginable, allowing us to search through thousands of eye designs to find out what makes them tick. The things we learn can then help us design better, more efficient robotic vision systems, as well as forward our understanding of one of the most successful groups of animals on the planet.



A 3d reconstruction of the field site where we track real bees (see Highlight 5) enables us to reproduce insect-eye views of what they see during flight.

Image credit: University of Sheffield

HIGHLIGHT 4

Commercial impact

The Brains on Board impact plan included the proposal to establish a spinout from project research. In March 2020 this was successfully realised, with the spinout of Opteran Technologies Ltd from the University of Sheffield, co-founded by team members James Marshall and Alex Cope, complemented with the recruitment of CEO David Rajan. Opteran closed over £2m of seed funding in November 2020, led by IQ Capital, alongside Seraphim, Episode 1 and Join. At eighteen employees already, including a number of former project members, Opteran is on a steep growth trajectory, showing how human-engineered approaches to autonomy will be outperformed by reverse-engineering natural brains.

The 'Green Hornet' drone flies fully autonomously under the control of the Opteran Development Kit, which deploys algorithms initially derived during the Brains on Board project.

Image credit: UKRI

A bee with harmonic radar tag attached.

Image credit: Queen Mary University of London

HIGHLIGHT 5

Bee tracking

Bees face a daunting navigational challenge, which has much in common with the challenges facing humans and robots: to explore an unpredictable landscape, discover and learn the locations of places of interest - such as the nest, food sources, etc - and devise efficient, robust ways to move between them. Learning how and where bees move helps us understand the strategies they use to meet these challenges with only a tiny brain - but keeping track of small insects over large distances poses quite a challenge to us.

We have recently developed a new type of harmonic radar, which tracks movement in three, not just two dimensions. We use our harmonic radar to track bee flight at a landscape scale. The radar scans through 360° every three seconds, emitting a powerful radio signal. A lightweight transponder attached to the bee emits a response signal allowing us to pinpoint its location.

We tracked bumblebees as they explored the landscape on their first ever flights, then challenged them to find their way home from an unfamiliar location. Examination of 3D flight paths will allow us to look at how they learn what their nest looks like from different heights and how that affects their homing ability (see Highlight 3).

An example of a bee's long-distance flight path, captured with harmonic radar tracking technology.

Image credit: Queen Mary University of London

Publications

de Croon, G.C.H.E., Dupeyroux, J.J.G., Fuller, S.B. & Marshall, J.A.R. (in review) Insect-inspired AI for autonomous robots. *Science Robotics*

Marshall, J.A.R. (2021) Borrowing bee brains. *New Scientist* 249(3322), 23 https://doi.org/10.1016/S0262-4079(21)00279-7

Husbands, P., Shim, Y., Garvie, M., Dewar, A., Domcsek, N., Graham, P., Knight, J.C., Nowotny, T. & Philippides, A. (2021) Recent advances in evolutionary and bio-inspired adaptive robotics: Exploiting embodied dynamics. *Applied Intelligence* 51, 6467–6496 https://doi.org/10.1007/s10489-021-02275-9

Turner, J.P., Nowotny, T. (2021) Arpra: An arbitrary precision range analysis library. *Frontiers in Neuroinformatics* 15 https://doi.org/10.3389/fninf.2021.632729

Bennett, J.E.M., Philippides, A. & Nowotny, T. (2021) Learning with reinforcement prediction errors in a model of the *Drosophila* mushroom body. *Nature Communications* 12, 2569 https://doi.org/10.1038/s41467-021-22592-4

Knight, J.C. & Nowotny, T. (2021) Larger GPU-accelerated brain simulations with procedural connectivity. *Nature Computational Science* 1(2): 136-42 https://doi.org/10.1038/s43588-020-00022-7

Knight, J.C., Komissarov, A. & Nowotny, T. (2021) PyGeNN: A Python library for GPU-enhanced neural networks. *Frontiers in Neuroinformatics* 15 https://doi.org/10.3389/fninf.2021.659005

Manneschi, L., Lin, A.C. & Vasilaki, E. (2021) SpaRCe: Improved learning of reservoir computing systems through sparse representations. *IEEE Transactions on Neural Networks and Learning Systems* https://doi.org/10.1109/TNNLS.2021.3102378

Manneschi, L., Ellis, M.O.A., Gigante, G., Lin, A.C., Del Guidice, P. & Vasilaki, E. (2021) Exploiting multiple timescales in hierarchical echo state networks. *Frontiers in Applied Mathematics and Statistics* 6 https://doi.org/10.3389/fams.2020.616658

Song, Z., Zhou, Y., Feng, J. & Juusola, M. (2021). Multiscale 'whole-cell' models to study neural information processing – new insights from fly photoreceptor studies. *Journal of Neuroscience Methods* 357, 109156 https://doi.org/10.1016/j.jneumeth.2021.109156

Brebner, J., Makinson, J., Bates, O., Rossi, N., Lim, K., Pasquaretta, C. Dubois, T.,Gomez-Moracho, T., Lihoreau, M., Chittka, L. & Woodgate, J. (2021) Bumblebees strategically use ground-level linear features in navigation. *Animal Behaviour* 179, 147-160 https://doi.org/10.1016/j.anbehav.2021.07.003

Woodgate, J.L., Makinson, J.C., Rossi, N., Lim, K.S., Reynolds, A.M., Rawlings, C.J. & Chittka, L. (2021) Harmonic radar tracking reveals that honeybee drones navigate between multiple aerial leks *iScience* https://doi.org/10.1016/j.isci.2021.102499

Gallo, V. & Chittka, L. (2021) Stigmergy versus behavioral flexibility and planning in honeybee comb construction. *PNAS* 118 (33) e2111310118 https://doi.org/10.1073/pnas.2111310118

MaBouDi, H., Barron, A.B. , Li, S., Honkanen, M., Loukola, O.J., Peng, F., Li, W., Marshall, J.A.R., Cope, A., Vasilaki, E. & Solvi, C. (2021) Non-numerical strategies used by bees to solve numerical cognition tasks. *Proceedings of the Royal Society* Series B 288, 20202711 https://doi.org/10.1098/rspb.2020.2711

Brebner, J.S. & Chittka, L. (2021) Animal cognition: the self-image of a bumblebee. *Current Biology* 31(4): R207-R209 https://doi.org/10.1016/j.cub.2020.12.027

Nityananda, V. & Chittka, L. (2021) Different effects of reward value and saliency during bumblebee visual research for multiple rewarding targets. *Animal Cognition* 24, 803–814 https://doi.org/10.1007/s10071-021-01479-3

Manneschi L and Vasilaki E (2020) An alternative to backpropagation through time. *Nature Machine Intelligence* 2(3), 155-156 https://doi.org/10.1038/s42256-020-0162-9

MaBouDi, H., Marshall, J.A.R. & Barron, A.B. (2020) Honeybees solve a multi-comparison ranking task by probability matching. *Proceedings of the Royal Society* Series B 287, 20201525 https://doi:10.1098/rspb.2020.1525

MaBouDi, H., Galpayage, Dona, H.S., Gatto, E., Loukola, O.J., Buckley, E., Onoufriou, P.D., Skorupski, P. & Chittka, L. (2020) Bumblebees use sequential scanning of countable items in visual patterns to solve numerosity tasks. *Integrative and Comparative Biology* 60, 929-942 https://doi.org/10.1093/icb/icaa025

MaBouDi, H., Solvi, C. & Chittka, L. (2020) Bumblebees learn a relational rule but switch to a win-stay/lose-switch heuristic after extensive training. *Frontiers in Behavioral Neuroscience* 14(137) https://doi.org/10.3389/fnbeh.2020.00137

Solvi C., Gutierrez Al-Khudhairy S. & Chittka L. (2020) Bumble bees display cross-modal object recognition between visual and tactile senses. *Science* 367, 6480 https://doi.org/10.1126/science.aay8064

Steinbeck, F., Adden, A. & Graham, P. (2020) Connecting brain to behaviour: A role for general purpose steering circuits in insect orientation? *Journal of Experimental Biology* 223(5), https://doi.org/10.1242/jeb.212332

Stimberg, M., Goodman, D. & Nowotny, T. (2020). Brian2GeNN: accelerating spiking neural network simulations with graphics hardware. *Scientific Reports* 10, 410 https://doi.org/10.1038/s41598-019-54957-7

Steinbeck, F., Graham, P., Nowotny, T. & Philippides A. (2020) Can small scale search behaviours enhance large-scale navigation? *Lecture Notes in Computer Science* 12413, 338-341 https://doi.org/10.1007/978-3-030-64313-3_32

Kagioulis, E., Philippides, A., Graham, P., Knight, J. & Nowotny, T. (2020) Insect inspired view based navigation exploiting temporal information. *Lecture Notes in Computer Science* 12413, 204-216 https://doi.org/10.1007/978-3-030-64313-3_20

Meyer, S., Nowotny, T., Graham, P., Dewar, A. & Philippides, A. (2020) Snapshot navigation In the wavelet domain. *Lecture Notes in Computer Science* 12413, 245-256 https://doi.org/10.1007/978-3-030-64313-3_24

Dewar, A., Graham, P., Nowotny, T., Philippides, A. (2020) Exploring the robustness of insect-inspired visual navigation for flying robots. *Artificial Life Conference Proceedings* 32, 668-677 https://doi.org/10.1162/isal_a_00307

Li, X., Abou Tayoun, A., Song, Z., Dau, A., Rien, D., Jaciuch, D., Dongre, S., Blanchard, F., Nikolaev, A., Zheng, L., Bollepalli, M.K., Chu, B., Hardie, R.C., Dolph, P.J. & Juusola, M. (2019). Ca2+-activated K+ channels reduce network excitability, improving adaptability and energetics for transmitting and perceiving sensory information. *Journal of Neuroscience* 39 (36), 7132-7154 https://doi.org/10.1523/JNEUROSCI.3213-18.2019

Perry, C. & Chittka, L. (2019). How foresight might support the behavioural flexibility of arthropods. *Current Opinion in Neurobiology* 54, 171-177 https://doi.org/10.1016/j.conb.2018.10.014

Vasas, V., Peng, F., MaBouDi, H. & Chittka, L. (2019) Randomly weighted receptor inputs can explain the large diversity of colour-coding neurons in the bee visual system. *Scientific Reports* 9, 8330 https://doi.org/10.1038/s41598-019-44375-0

Makinson, J.C., Woodgate, J.L., Reynolds, A., Capaldi, E.A., Perry, C.J. & Chittka, L. (2019) Harmonic radar tracking reveals random dispersal pattern of bumblebee (Bombus terrestris) queens after hibernation. *Scientific Reports* 9, 4651 https://doi.org/10.1038/s41598-019-40355-6

Vasas, V. & Chittka, L. (2019) Insect-inspired sequential inspection strategy enables an artificial network of four neurons to estimate numerosity. *iScience* 11, 85-92 https://doi.org/10.1016/j.isci.2018.12.009

Knight, J.C, Sakhapov, D., Domcsek, N., Dewar, A.D.M., Graham, P., Nowotny, T. & Philippides, A. (2019) Insect-inspired visual navigation on-board an autonomous robot: Real-world routes encoded in a single layer network. *Artificial Life Conference Proceedings* 31, 60-67 https://doi.org/10.1162/isal_a_00141

Cope, A.J., Vasilaki E., Minors D., Sabo C., Marshall, J.A.R. & Barron, A.B. (2018) Abstract concept learning in a simple neural network inspired by the insect brain. *PLoS Computational Biology* 14(9) https://doi.org/10.1371/journal.pcbi.1006435

Knight, J.C. & Nowotny T. (2018) GPUs outperform current HPC and neuromorphic solutions in terms of speed and energy when simulating a highly-connected cortical model. *Frontiers in Neuroscience* 12, 941 https://doi.org/10.3389/fnins.2018.00941

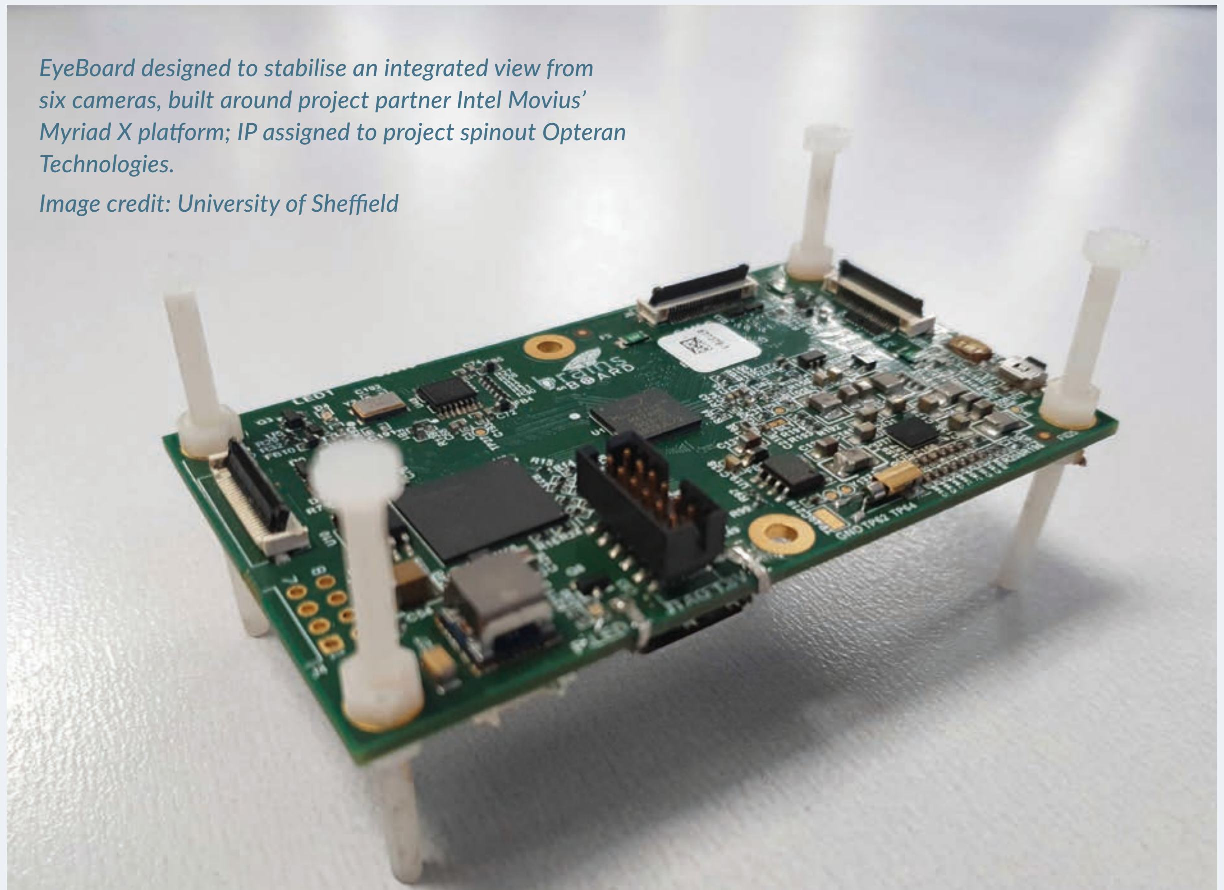
Guiraud M., Roper M. & Chittka, L. (2018) High-speed videography reveals how honeybees can turn a spatial concept learning task into a simple discrimination task by stereotyped flight movements. *Frontiers in Psychology* 9, 900 https://doi.org/10.3389/fpsyg.2018.01347

Gallo, V. & Chittka, L. (2018) Cognitive aspects of comb-building in the honeybee? *Frontiers in Psychology* 9, 1347 https://doi.org/10.3389/fpsyg.2018.00900

Woodgate, J.L., Makinson, J.C., Lim, K.S., Reynolds A.M. & Chittka, L. (2017) Continuous Radar Tracking Illustrates the Development of Multi-destination Routes of Bumblebees. *Scientific Reports* 7, 17323 https://doi.org/10.1038/s41598-017-17553-1

Sabo, C., Chisholm, R., Petterson, A. & Cope, A. (2017). A lightweight, inexpensive robotic system for insect vision, *Arthropod Structure & Development* 46(5), 689-702 https://doi.org/10.1016/j.asd.2017.08.001

Cope, A., Sabo, C., Vasilaki, E., Barron, A. B. & Marshall, J. A. R. (2017). A computational model of the integration of landmarks and motion in the insect central complex. *PLoS One* https://doi.org/10.1371/journal.pone.0172325



EyeBoard designed to stabilise an integrated view from six cameras, built around project partner Intel Movius' Myriad X platform; IP assigned to project spinout Opteran Technologies.

Image credit: University of Sheffield

Open Source Software

The Brains on Board project has developed, or contributed to, a number of open-source projects. Highlights include:

- BoB Robotics: provides code for interfacing with various robot platforms and other associated hardware, as well as code for running simulations and visualising data (https://brainsonboard.github.io/bob_robotics/)
- Compound Ray: cutting edge ray-tracing technology to accurately recreate the visual perspective of different insect eyes at unprecedented speed (https://github.com/BrainsOnBoard/compound-ray)
- GeNN: GPU-enhanced Neuronal Network simulation environment based on code generation for Nvidia CUDA (http://genn-team.github.io/genn/)
- SpineML / SpineCreator: modelling language and graphical tool for neural modelling; code generates to a variety of platforms including GeNN (http://spineml.github.io)

Data Availability Statement

- Metadata describing data collected by the Brains on Board project were logged at DataCite, with open access datasets being published via FigShare

Cover image: BeeBot v2, designed to carry an NVidia Jetson mobile GPU and bespoke panoramic camera system reproducing insect vision.

Cover image credit: AMRC


SPONSORED BY
Opteran®