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From Insects to Robots

Barbara Webb

Insects provide a compelling ‘proof of principle’ for what robotic engineering might hope to achieve. They display adaptive sensorimotor interactions to support survival in an enormous range of environmental conditions and tasks. Their operation is notably robust compared to any man-made technology, and includes the ability to deal with damage, altered circumstances and the natural variability inherent in interacting with the world. Their control systems are impressively compact and energy efficient, and support both rapid responses and longer term adaptation and learning. Understanding and replicating these mechanisms as machines has constituted a small but influential research agenda in robotics over several decades (e.g. Franceschini et al., 1992; Beer et al., 1997; Srinivasan et al., 1999; Möller et al., 2001; Webb, 2002; Delcomyn, 2004; Sitti, 2007; Harvey et al., 2008; Ma et al., 2013; Werfel et al., 2014; Bagheri et al., 2017).

This special issue presents a group of papers that reflect different aspects of the current state of the art in ‘insect robotics’, that is, research into capturing some of the capabilities of insects in robot hardware. Approaches differ but have a common pattern: identification of a key capacity in a biological system to be replicated; design of a complete sensor-motor loop; construction in hardware of the required interfaces (sometimes first in simulation); computational modelling of the sensory and subsequent processing (sometimes also realised in specialised hardware) to produce a motor output; analysis of the behaviour of the complete system; refinement of each stage, including, frequently, a return to biology to obtain a better characterisation of the initial capacity that was targeted. The developed system can thus also act as a testbed for the adequacy of existing biological hypotheses, often leading to new insights and new experiments (Webb, 2000).

A good example is provided by the paper in this issue from Sabo et al. The target to be replicated is visual control of flight, especially as observed in bees, and the aim is both to improve lightweight flying robots and better understand flying insects. Consideration of the physical properties of insect vision, such as the spatial layout of receptors and temporal response, are used to establish design requirements; but these are also influenced by practical issues such as expense, availability and flexibility. This leads to a specific selection of CCD cameras paired with compound-eye image filtering in software, rather than, e.g., utilising hardware compound eye designs (Jeong et al., 2006; Floreano et al., 2013; Li and Xiao, 2015). The cameras are mounted on board a small quadcopter, with off-board processing to test models for optic flow. The preliminary analysis shows good agreement of motion detection on the robot using a novel Angular Velocity Detector Unit model (Cope et al., 2016) with the theoretical (i.e. simulated) function of this model, but with much higher noise, which could impact the effectiveness in control.

The paper from Serres and Ruffier also focusses on optic flow, providing an overview of the issues arising in flight control using optic flow from both insect and robotics perspectives. The

concept of regulating optic flow to adjust speed and positioning relative to the surroundings has been frequently suggested for insects, and widely tested in robot implementations (e.g. Weber, Venkatesh and Srinivasan, 1996; Blanchard, Rind and Verschure, 2000; Beyeler, Zufferey and Floreano, 2009). Frequently, the robot research has helped to expose limitations in the hypothetical control mechanisms. For example, using the difference in optic flow on each side to steer along a corridor seems plausible, but can fail dramatically if there is an opening on one side, or other minor irregularities. Several alternative strategies have consequently been developed and shown to be robust and effective on a robot.

Graham and Philippides examine a different form of visual behaviour in insects, the ability found in many central place foragers to use the visual surroundings for navigation back to desired location. They focus specifically on solitary foraging ants, and review the key characteristics of this behaviour established over decades of behavioural experiments. This points towards a procedural algorithm, in which directional control is directly coupled to retinotopic matching of views (Collett and Cartwright, 1983; Zeil et al., 1996; Collett et al., 2013). They draw several lessons for robotics, e.g., it is not necessary (indeed potentially disadvantageous) to have high resolution vision for navigation. Their paper also describes how computational and robotic modelling of specific insect brain circuits can bridge the current gap between the extensive behavioural but very limited neurophysiological data on insect navigation, and may point the way to new solutions for robot engineering. This is a particularly hot topic as navigation in autonomous vehicles is a major technological growth area.

In Ando et al., the choice of target behaviour is odour tracking in the moth. As they discuss, this has the advantage of being a stereotyped behaviour, already well-studied at a number of levels from the ecological to the genetic, involving the multimodal combination of sensory information. Their work tackles the important issue that direct comparison of robot and insect behaviour is complicated by the difference in physical size and dynamics, which can be crucial in fast feedback control for tasks such as tracking. Their novel approach is to use a "robot in the loop" in their investigation of the insect's behaviour. The hybrid system uses a moth on a trackball to control the movement of a robotic platform (direct control from neural signals has also been explored (Kanzaki et al., 2013)). This allows a variety of experiments in which the availability of different information and the properties of the feedback loop can be altered. Further, it allows direct substitution of a model controller for the moth under the same physical conditions, enabling effective evaluation of hypothesised control circuits.

The issue of dynamics is also addressed in the paper from Szczecinski et al, who look at targeted body and leg motion for a robot modelled on the praying mantis. They note, in particular, that real sensors in a real system experience complex and noisy effects that can be hard to model accurately in simulation, but may be crucial to the effectiveness of a neural controller. They show that effective orienting responses to visual targets can be obtained by assuming the brain provides only high level commands (whether to walk or stand, and the target direction) that appropriately modulate the ongoing activity of thoracic circuits which establish the required individual joint motions. Such a distributed solution has been shown to be effective in a number of other insect-inspired walking robots, e.g. (Ferrell, 1995; Duerr et al., 2003;

Steingrube et al., 2010) Notably, this paper goes beyond simple reactive control to explore how proprioceptive signals and memory can be used in predictive saccades. The work provides an excellent illustration of how to combine bioinspired computational models with biomimetic hardware, which copies, in significant detail, a complete insect behavioural capability.

Collectively, these papers show how a 'robotic' mindset can provide a distinctive approach to understanding biological systems. It literally enforces a mechanistic view of function - hypotheses are expressed as actual physical machines - which can contribute to new experimental methods and theoretical developments. Often the motivation of construction has driven work towards more detailed and precise quantification of behaviour or physical structure, and contributed to novel analysis. As a consequence, in the field as a whole, it has been noticeable that the most significant advance tends to occur when there is a deep embedding of robotics researchers and research methods within a biologically-oriented research group, as many of these papers illustrate.

Looking towards the future, an important advance needed is to see more work beyond reflexive behaviours to understand how insects exhibit integrated and adaptive expression of behaviour according to context and history of experience. Indeed, this is an area where the translation to robotic control might turn out to be especially effective, as the highly conserved neural mechanisms point towards solutions that might have wide generality across adaptive behaviour tasks, even when the sensory and motor systems differ. It is also exciting to contemplate how rapid advances in many areas of biological research will contribute to building better grounded models. These range from new methods for unravelling, observing and manipulating neural circuitry (such as optogenetics) to new tools for behavioural observation (such as high speed video and automated behavioural analysis). Particularly in the latter case, the aforementioned integration of researchers with a computational or engineering background into insect research labs, has often made a direct contribution to methodological advance. It will also be important to see a continued convergence of modelling of 'sensory' and 'motor' systems, which are still too often treated as separate research fields, even in biology. Here again the robotic approach can make a useful contribution, as it requires some form of loop closure through real interaction with the world, and thus highlights the need to treat behaviour as an integrated whole.

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