



A lightweight, inexpensive robotic system for insect vision



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ARTICLE INFO

Article history:

Received 20 June 2016

Received in revised form

5 August 2017

Accepted 10 August 2017

Available online 1 September 2017

Keywords:

Embodiment

Insect vision

Honeybees

Robotics

Computational modelling

ABSTRACT

Designing hardware for miniaturized robotics which mimics the capabilities of flying insects is of interest, because they share similar constraints (i.e. small size, low weight, and low energy consumption). Research in this area aims to enable robots with similarly efficient flight and cognitive abilities. Visual processing is important to flying insects' impressive flight capabilities, but currently, embodiment of insect-like visual systems is limited by the hardware systems available. Suitable hardware is either prohibitively expensive, difficult to reproduce, cannot accurately simulate insect vision characteristics, and/or is too heavy for small robotic platforms. These limitations hamper the development of platforms for embodiment which in turn hampers the progress on understanding of how biological systems fundamentally work. To address this gap, this paper proposes an inexpensive, lightweight robotic system for modelling insect vision. The system is mounted and tested on a robotic platform for mobile applications, and then the camera and insect vision models are evaluated. We analyse the potential of the system for use in embodiment of higher-level visual processes (i.e. motion detection) and also for development of navigation based on vision for robotics in general. Optic flow from sample camera data is calculated and compared to a perfect, simulated bee world showing an excellent resemblance.

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1. Introduction

Recent improvements in sensors, processing, and batteries have made new technologies low-weight, low-power, and low-cost. This has allowed robots, particularly sUAVs (small Unmanned Aerial Vehicles), to be more accessible and users to broaden their applications. As robots decrease in size, they are subject to different constraints (limited power, size, GPS capabilities, etc.), more complex missions (such as searching buildings or other confined areas), and bigger disturbances due to small changes in the environment (i.e. wind or moving objects). Flying insects are of interest to the design of small robotic platforms, because they represent a complete working solution which is capable of the behaviours required for performing in challenging environments.

Flying insects are capable of sophisticated odometry, including estimating flight duration, integrating their course over time to generate a direct home vector ('path integration'), and regulating their flight speed (Srinivasan et al., 1996, 2015). They can perform

smooth landing on unfamiliar targets, and optimise routing around a set of target locations in a few flights (Lihoreau et al., 2012). All these capabilities are performed using primarily visual inputs and processing (Srinivasan et al., 2000; Esch et al., 2001; Barron and Srinivasan, 2006; Srinivasan, 2011), and thus, understanding insect vision is critical to understanding how these complex behaviours arise.

To understand how insects' neural systems perform their complex behaviours, it is important to create models of these behaviours and then embed them in physical systems, like robots. Many studies primarily focus on only simulating behaviours and cognitive processes within computing platforms (e.g. 'Blue Brain' Project (Markram, 2006)) while ignoring the implications of embodiment. In reality, neural processes are just a part of the computational loop where sensing and action play an equally critical role. Behaviour is not solely the result of a system's internal make up, and in fact, the body helps to shape the brain both physically and functionally. The environment in which a system senses and interacts in addition to the physical make-up of the system affects its behaviour (Pfeifer et al., 2007). For example, two different physical systems (e.g. one with a nose versus one with eyes and wheels versus limbs) will each have very unique experiences with different environments, which will produce very distinctive behaviours. In turn, this results in unique ways in which systems perceive the world and process

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information (Webb, 2013; Lungarella and Sporns, 2006). Robots can help to understand the underlying sensing, processing, and behaviour. Similarly, the sensory systems used to provide input data to cognitive and behavioural models should be as accurate to the biological source as possible. Otherwise, even a perfect model might not be able to replicate the performance of a biological agent.

In order to improve lightweight robotics and better understand flying insects, we try to replicate their behaviours, and therefore their sensory and cognitive processes, in robotic systems. Visual processing is the focus in this paper due to its significant role in flight behaviour. Expensive, bespoke cameras are impractical to use in everyday applications. For this reason, we propose a lightweight and inexpensive design for modelling insect vision for embodied mobile robotics. The methodology presented here allows for the flexible replication of a variety of insect visual systems on any hardware that meets the design requirements. This work goes on to outline a single implementation of this methodology as a proof-of-concept. The performance is evaluated against the camera and insect models. Additionally, the implementation is based on the suitability of the system for further embodiment of behaviour and cognition; that is, we calculated optic flow and compare it to a simulated bee world. In the conclusions and future work, we highlight advantages that could be gained through alterations to this proof-of-concept implementation. Ultimately, this design paradigm will help to improve both robotic capabilities and the understanding of insect behaviour.

2. Background information

The vision system in insects is linked to complex cognitive behaviours which are not currently understood (Srinivasan, 2011). In particular, there has been extensive research in recent years into honeybee vision and flight navigation, as bees are known to have impressive capabilities. For example, honeybees will seek out food over miles and directly return to their hive, provide navigational instructions to each other, use landmarks for location identification, distinguish colours to identify good sources of food, navigate in corridors and other, complex environments, and more. It has been shown that bees use their vision to regulate their velocity in flight, control their course, estimate distance travelled through path integration, avoid obstacles, and land smoothly (Srinivasan, 2011). Bees are able to accomplish these tasks through the estimation of angular velocity or optic flow of the visual world (Ibbotson, 2001; Thurrowgood et al., 2014). Current computational research (e.g. Green Brain Project and “Brains on Board” Project) is trying to model and embody these behaviours to show how bee’s physiology is able to accomplish these impressive tasks with such efficient coding and processing of information (Cope et al., 2013).

This section discusses the important physical aspects of insect vision and the state-of-the-art in embodiment of insect vision. While the methodology presented in this work can be applied to any insect vision model, the focus of implementation is on replicating honeybee vision as this is an ideal candidate for further study of navigation and cognition. As such, most of the details of the visual system discussed in this section relate to honeybees.

2.1. Insect vision

Insect vision can be characterised in three major dimensions, spatial organisation, temporal response, and chromatic response. We will now describe each dimension in turn, with special reference to the honeybee.

In terms of the spatial organisation of their vision, insects can have an extremely wide and deep Field-of-View (FoV) consisting of individual lensed units called ommatidia. Each ommatidium

detects light coming from a specific direction. Ommatidial numbers and density vary considerably across species: from almost 30,000 placements in some dragonflies (Zufferey, 2005) to approximately 800 or fewer placements in the fruit fly (Power, 1943). The honeybee FoV is almost panoramic and has a total of ~5500 ommatidia per compound eye (Seidl and Kaiser, 1981a). The fruit fly is similar in FoV despite less than 800 ommatidia (Power, 1943) leading to a much larger angular spacing between neighbouring ommatidia and thus, poorer spatial resolution. In many insect species including the honeybee, each ommatidium accepts light from an angle similar to the spacing angle between neighbouring ommatidia, and thus can be thought of as a single pixel element. In addition, the photoreceptors in each ommatidium lie along a single vertical axis below the lens. As such, the ommatidia form an array of single pixel elements with very little inhomogeneity in spacing compared to that found in mammalian vision but of much larger angular extent.

The spacing and acceptance angle of the ommatidia results in the large field of view and the spatial resolution of insect eyes. It has been found that the ommatidia are packed more densely near the centre of the eyes than at the edges. The central ommatidia have a visual angle of about 1°, whereas those furthest from the centre can be up to 3°. Additionally, the honeybee’s eye has greater resolution in the ventral to dorsal direction than in the anterior to posterior direction (Hecht and Wolf, 1929). It is these two parameters (spacing and acceptance angles) that produce the bee’s spatial resolution. While these exact parameters vary across insects, the pattern is comparable.

The two compound eyes have fixed focus as they cannot move with respect to each other and can only move as the insect head moves with respect to the body. There is, however, a region of overlap in the fields of view of the compound eyes which provides a fixed convergent zone, and this may be used for some insect species for specific purposes. For example, it is used for prey capture and pursuit in dragonflies (Olberg et al., 2000).

The temporal characteristics of the insect visual system are described by two main parameters, the speed of response and the latency of response. The response speed of the insect visual system varies largely between species depending on the requirements for detecting motion. For example, honeybees can reach flight speeds of up to 0.7 m/s in a 0.2 m wide corridor, and as such require higher temporal resolution than the slow flying fruit fly (Srinivasan et al., 1996, 2011). Studies have been done to try to determine how fast bees can actually see rapidly changing images. It has been behaviourally established that bees can only make decisions on stimuli up to frequencies of 165–300 Hz implying that they resolve images up to a maximum of 300 Hz (Autrum and Stoecker, 1950). In comparison, humans have a temporal resolution in the range of 20–70 Hz meaning that bee vision is roughly five to six times faster (Rabin, 2010).

The insect nervous system consists of several pathways from visual input to motor output, which determine the latency of behavioural responses. The shortest of these runs through the optic neuropils, then directly to the rear of the insect brain where the dendrites of neurons descending to the motor ganglion are found. This pathway therefore determines the minimum processing delay from sensory stimulation to motor response, which is an important factor for stable flight control. In the dragonfly, behavioural responses to environmental changes have been found to have latency as low as 30 ms (Olberg et al., 2007).

Finally insects are trichromats, possessing photoreceptors responding to three evenly spaced sections of the electromagnetic spectrum and covering a larger section overall than mammals, notably including the ultraviolet part of the spectrum (Dyer and Chittka, 2004).

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