Towards Insect Inspired Visual Sensors for Robots

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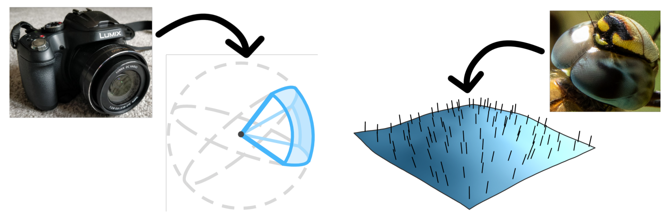
***Abstract*—Flying insects display a repertoire of complex behaviours that are facilitated by their non-standard visual system that if understood would offer solutions for weight- and power-constrained robotic platforms such as micro unmanned aerial vehicles (MUAVs). Crucial to this goal is revealing the specific features of insect eyes that engineered solutions would benefit from possessing, however progress in exploration of the design space has been limited by challenges in accurately replicating insect vision. Here we propose that emerging ray-tracing technologies are ideally placed to realise the high-fidelity replication of the insect visual perspective in a rapid, modular and adaptive framework allowing development of technical specifications for a new class of bio-inspired sensor. A proof-of-principle insect eye renderer is shown and insights into research directions it affords discussed.**

***Index Terms*—Novel sensing, Artificial Intelligence and Robotics, Bioinspired, Vision, Rendering**

I. Introduction

For engineers seeking to develop long-range autonomous micro unmanned aerial vehicles (MUAVs) weight and power constraints present a critical design parameter that currently limits their application [1]. Insects provide an existence proof that seemingly simple sensory systems are sufficient for solving complex tasks from navigating natural habitats in 3D; through detection and tracking of food, prey and conspecfics; to rapid flight control to avoid damaging impacts from static and moving objects [2]. We thus propose that novel solutions will arise through revealing the secrets of insect visual systems allowing for abstraction into a new class of low-power, low-weight bioinspired robot sensor.

Insects see the world through a fundamentally different mechanism than humans and most camera systems [2]. Their compound eyes are constructed from hundreds to thousands of self-contained "mini-cameras" known as ommnitidia: each comprising a lens, light-guide and light sensitive cells which are physically interlocked over a convex surface per eye (see Figure 1(b)). In addition, the surface structure (e.g. field of view), layout (e.g. density of ommatidia), and ommatidial function (e.g. sensitivity to specific properties of light: wavelength, polarisation) of compound eyes vary across eye regions and between caste, sex and species. Given the vastness of the feature space in which compound eye designs reside and the computational complexity involved in searching that space for possible solutions we define three criteria that any insect eye simulator must meet:



(a) The projection pyramid of a panoramic image, projecting the 3D environment onto a single uniform point or sphere.

(b) The sampling rays following the normal of an irregular projection surface, similar to that found on an insect eye.

Fig. 1: Regular and irregular surface projection diagrams. Insect eye photo credit to Matthew Barber, used with Permision.

1) Perform beyond real-time.
2) Allow arrangement of ommatidia on arbitrary 3D surfaces.
3) Allow configuration of individual ommatidial properties.

II. State Of The Art

Insect eye perspective renderers have tended to focus on recreating the panoramic field of view and low spatial resolution properties of compound eyes [3], [4]. Cube-mapping techniques, whereby a camera is rotated to sample images across six viewpoints which are then stitched into a single panoramic image (Figure 1b(a)) combined with downsampling and post-processing approximate these two properties in a computationally efficient way (e.g. [5]). These systems have been used to investigate the impact of these properties on navigational performance in simulated [6] and real-world studies that generate similar perspectives by augmenting standard cameras using convex mirrors [7], [8] or fish-eye lens imaging systems [9]. Yet as such models form images through the projection of a 3D scene onto a uniform viewing surface, they inherently violate *criteria 3*. Attempts to address this issue by modelling compound eyes using multiple small field of view cameras within hardware-accelerated modern game engines have proven unsuccessful due to performance constraints that violate *criteria 1*.

III. Insect Vision Using Ray-Based Methods

Raycasting and *raytracing* techniques are image rendering approaches that produce realistic imagery through the physically-based simulation of light rays, as opposed to the less realistic projection transform approaches commonly used in real-time graphics processes. By tracing the path of individual rays, ray-based rendering allows for the accurate simulation of optical effects, driving their realism. Technical development has been primarily driven by the film industry (e.g. see advances in the *Toy Story* movie franchise, with the most recent instalment including advanced camera lensing effects).

Due to demand in the video games industry for increasingly realistic graphics generated in real-time, dedicated hardware has been introduced to massively parallelise computationally expensive ray casting and tracing algorithms. These changes in graphics processing ability lend themselves very well to the simulation of compound eyes, as ray-based methods allow for the accurate sampling of light as if refracted through an ommatidium's optical system: something that traditional rendering pipelines struggle to achieve [10].

Moreover, as ray-based methods are inherently designed to handle the simulation of many rays at many locations within an environment, the source position of these rays are immaterial: any projection surface can be used to spawn rays with minimal additional overhead. That is, it should be feasible to render the perspective from any number of ommatidia on any surface.

Finally, modern raytracing hardware is capable of rendering tens of millions of rays per frame, owing to their real-time use on high-definition displays. In comparison, a drone bee's eye consists of only about 10,000 ommatidia [11], the view of each of which could be simulated with 81 rays [9] and the total number of rays would still be less than that used in a 1920-by-1080 pixel (standard HD screen size) rendering.

An initial study conducted by Polster et al. [12] demonstrates some of the benefits to be gained from ray-based simulation of the compound eye, providing support to the approach. Their work does not, however, run in real-time and also lacks tools to explore differing insect eye surface shapes.

IV. Proof Of Concept

Figure 2 shows sample images using our prototype raytracing-based insect eye renderer. Images were generated in a large 3D environment from an insect's visual perspective at 60 frames per second utilising raytracing hardware in modern consumer-grade NVidia graphics cards (NVidia GeForce RTX 2080Ti) successfully fulfilling *Criteria 1*. Figure 2 (upper) shows a simulated eye with equally spaced ommnitidia arranged on a sphere whereas Figure 2 (lower) has ommnitidia clustered around the horizon as observed in some insects, demonstrating the ability of the system to fulfil Criteria 3.

With the technical challenges of building a ray-tracing based insect eye renderer largely complete (open-source software release expected soon), we will now look to investigate the specific requirements for natural and artificial visual systems in shared tasks such as navigation. Insights gained from more thoroughly exploring the insect visual perspective—and it's design relative to visual feature extraction—will help guide the development of visual systems in robotics by considering not only visual post-processing steps, but also the intrinsic structure and design of the imaging sensor itself.

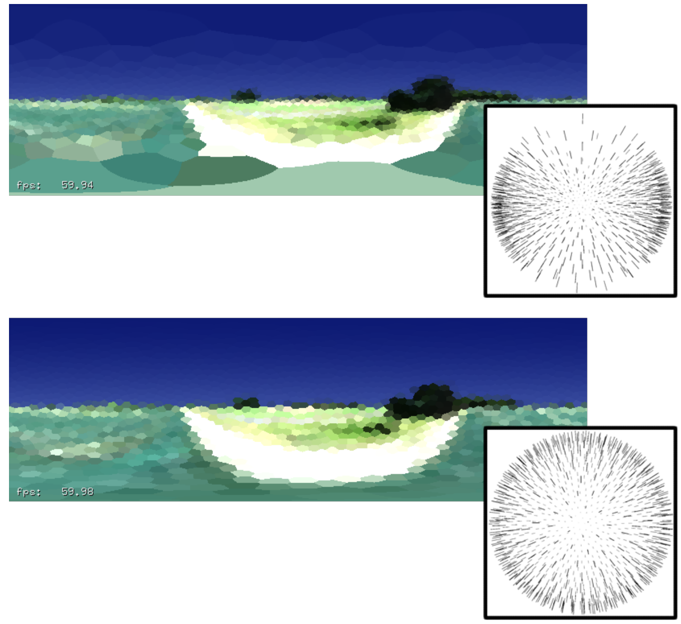


Fig. 2: Insect perspectives generated using a prototype raytracing-based renderer. Upper: Ommatidial distribution increased on horizon. Lower: Equidistant distribution.

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