Position detection with hyperacuity using artificial compound eyes

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Inspired by the natural phenomenon of hyperacuity, redundant sampling in combination with the knowledge about the impulse response is used to extract high resolution information like the position of simple objects out of low resolution images received with an artificial apposition compound eye objective.

1 Motivation

The examination of the multi-aperture imaging systems of diurnal insects recently led to the development of artificial apposition compound eyes [1]. It consists of a micro-lens array (lens diameter D, focal length f) replicated on top of a thin, planar substrate and an optoelectronic detector array with a different pitch in the focal length of the micro-lenses (Fig.1). To increase resolution the size of the detector pixels is narrowed down by a pinhole array on the substrate backside. The pitch difference enables different viewing directions of each optical channel. Artificial compound eyes have a low volume, large field of view (FOV) and are easy to fabricate but lack from their low spatial resolution [2].

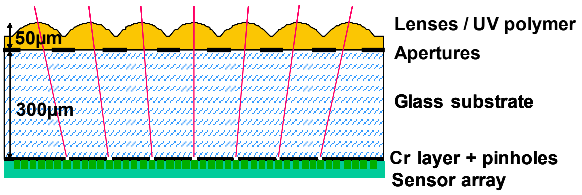
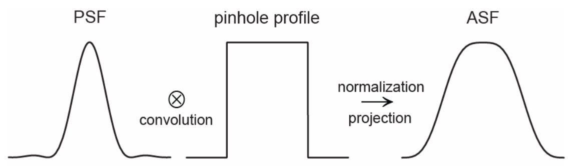


***Fig. 1** Planar artificial apposition compound eye.*

Each channel contributes to one image point by collecting light from a finite angle Δφ given by the angular diameter of the Airy disk convolved with the geometrical projection of the pinhole diameter d (Fig.2). The acceptance angle Δφ approximates the smallest resolvable feature size in the image. Increasing resolution for a given f-number means that the diameter of the pinholes d has to be decreased but then sensitivity decreases with d^2.



$$\frac{\lambda}{D} \otimes \frac{d}{f} \longrightarrow \Delta\varphi = \sqrt{\left(\frac{\lambda}{D}\right)^2 + \left(\frac{d}{f}\right)^2}$$

***Fig. 2** Origin of the angular sensitivity function (=ASF) and its FWHM (= approx. acceptance angle Δφ).*

For achieving high resolution information without losing sensitivity we may again learn from Mother Nature itself.

2 Using hyperacuity for position detection

Insects have the ability to extract high resolution information from a coarse matrix of photoreceptors so that they are capable of detecting movements of a fraction of their photoreceptor diameter. This ability was termed hyperacuity [3].

A linear imaging model is used with the assumptions that the total impulse response of the system (ASF), which is the efficiency expressed as a function of angular distance to the optical axis of each channel, is space invariant and free of aberrations. Furthermore incoherent illumination is assumed. As a key feature the ASFs of neighboring channels overlap with an amount given by the pitch difference Δp between micro-lens and pinhole array. One object point then gives rise to different optical fluxes within the shared part of the FOV of adjacent channels [4]. The difference depends on (1) the amount of overlap given by Δp and Δφ, (2) the absolute irradiation of the object point and (3) its position between the optical axes.

Using the ratio of fluxes between two adjacent channels provides a unique and analytical expression for the position of the object within the FOV of one channel, assuming the ASF is known. Because of its specific formulation the method is limited to the cases of point sources and edges or objects that are formed only by straight edges (e.g. a stripe). But here low computational load is needed to calculate the position information that is independent of background illumination and the total irradiation of the source from the measured fluxes of only three channels.

3 Experimental setup

The artificial compound eye objective and relay optics to image the pinhole layer onto a CCD are fixed on a goniometer (Fig.3). During the measurement they are rotated stepwise about the z-axis with respect to the object simulating object movement through the FOV. The comparison of the measured angular distance between two steps ($\Delta\phi_m$) with the change of the goniometer reference angle ($\Delta\phi_{ref}$) gives the error or acuity (δ_a) of the method (Fig.4). Therefore a high resolution measurement of the change of angular position between two measurement points is achieved.

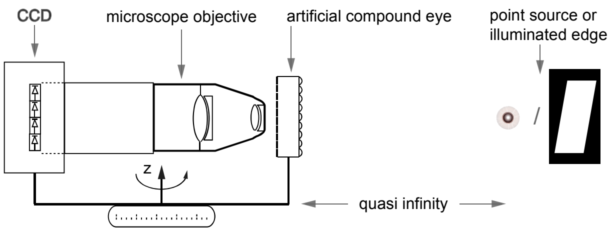


Fig. 3 *Experimental setup for position detection with hyperacuity. A point source or an edge is used as object. Illuminated pinholes on the backside of the artificial compound eye are imaged upon a CCD.*

4 Results

A reproducible acuity up to 0.03° which is an improvement of the factor 25 compared to the acceptance angle $\Delta\varphi$ was achieved for the measurement of the position of a point source and an edge. It was found that the region for hyperacuity within the FOV of each channel is limited to less than 1°. But hyperacuity regions of adjacent channels can be linked to expand the high acuity throughout the whole FOV. Using a slightly alternated method the angular width of a homogeneously illuminated stripe on dark background extending over several degrees was measured with a resolution 11 times superior to that of its image.

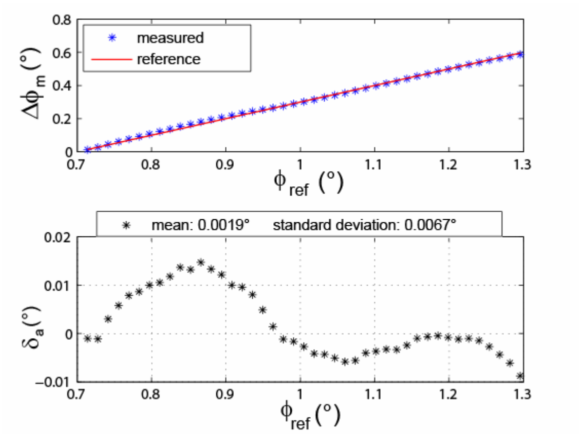


Fig. 4 *Example of measured angular distances (blue) compared with reference values (red). The difference of both gives the error or the acuity of the method (black).*

5 Conclusion and outlook

The demonstrated method is seen as a new approach to access high resolution information despite the number of pixels within the image is small. Three major conclusions result from the experimental investigations: (1) Large overlap between neighboring ASFs cause dense sampling of the object space which improves hyperacuity but leads to a small overall FOV for a given number of channels. (2) The signal-to-noise ratio states the final limitation for the maximum acuity. (3) Increasing sensitivity also improves the maximum acuity that can be achieved.

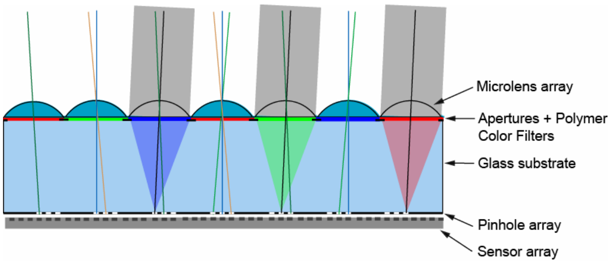


Fig. 5 *Artificial neural superposition compound eye with integrated color filters. As each object point is seen through 3 different color filters a color image of the scene is formed by re-arranging the pixels of the image.*

Especially point (1) and (3) have lead to the design of a new kind of artificial compound eye inspired by the neural superposition eye as known from the fly. Each object point within the FOV is imaged onto several (e.g. three) different pixels in different optical channels. Thus an increased sensitivity or even color vision (using an additional layer of polymer color filters) without losing resolution is feasible (Fig.5). Allowing the conjugated pixels to look in slightly different directions causes a dense sampling of the object which improves hyperacuity without decreasing the overall FOV. Averaging the signals received in pixels with a common viewing direction also improves the signal-to-noise ratio.

The future of hyperacuity methods for achieving an integrated imaging sensor is seen in the potential of combining the imaging principle of artificial compound eyes with on-chip parallel, analog pre-processing (e.g. by smart pixels). Future work is also going to examine and prove the advantages of the proposed multiple-pixels-per-channel system which is being fabricated at the moment.

Further Reading

[1] J. Duparré and P. Dannberg and P. Schreiber and A. Bräuer and A. Tünnermann: „Artificial apposition compound eye fabricated by micro-optics technology " in *Applied Optics*, **43**(22): 4303-4310 (2004)

[2] J. Duparré and P. Dannberg and P. Schreiber and A. Bräuer and A. Tünnermann: „Thin compound-eye camera" in *Applied Optics* **44**(15): 2949-2956 (2005)

[3] G. Westheimer: „Visual acuity and hyperacuity" in *Investigative Ophthalmology*, **14**(8): 570-572 (1975)

[4] J. S. Sanders and C. E. Halford: „Design and analysis of apposition compound eye optical sensors" in *Optical Engineering*, **34**(1): 222-235 (1995)