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Impulse response of a multiaperture vision system eyelet

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Abstract. Multiaperture vision systems are of interest in the area of robotic vision. A facsimile of the insect eye may be as useful for transmitting information to robotics as conventional cameras, which are analogous to the human eye. A physical model of one multiaperture vision system, the insect apposition ommatidia, has been successfully constructed. To provide an understanding of the multiaperture vision system, the impulse response of a single eyelet, or ommatidium, was developed. Experimental measurements of the impulse response were found to closely match theoretical results.

Subject terms: multiaperture vision; insect vision; robot vision; gradient-index lens application.

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1. INTRODUCTION

The multiaperture vision system (MAVS) is a concept that has been considered for computer vision applications.¹ The compound eye of the insect served as the inspiration for the MAVS concept.

Insect eyes are compound (multiocular) and do not image an object.² Various geometrical arrangements of the individual lens modules (ommatidia) optimize sensing performance for different applications. For instance, the sand wasp ommatidia arrangement is a diagonal crisscross pattern that is useful in tracking prey on a bland desert background, whereas the gomphid dragonfly's arrangement is highly dense in the area normal to the flight path for use in object recognition.

As in insect vision systems, different arrangements of MAVS eyelets will result in optimum performance for specific applications. The prelude to the study of these arrangements is the mathematical modeling of a single eyelet.³ This paper presents the development of the impulse response model of a particular MAVS eyelet. The individual eyelet consists of a quarter-pitch gradient-index lens coupled to a 200 μm step-index optical fiber that transfers light from the lens to a photodetector. The intensity leaving the optical fiber in response to a point source of light is taken to be the impulse response of the system. Two parameters are considered in this study: the fiber location at the rear surface of the lens and the angular offset of a point source from the lens optical axis (Fig.

1). Theoretical and experimental results are presented for the impulse response of the eyelet.

2. THEORETICAL MODEL

The intensity function at the rear surface of a quarter-pitch gradient-index lens⁴ can be represented by a circle function:

$$I(x, \theta) = A \text{ circ} \left[\frac{x - \left(\frac{1}{n_o \sqrt{a}} \right) \theta}{0.005} \right], \quad (1)$$

where A is the peak amplitude of the light leaving the lens; x is the distance, in millimeters, from the fiber center to the optical axis on the rear surface of the lens; n_o is the index of refraction on the optical axis of the lens; a is the quadratic constant that describes the parabolic decrease of refractive index to the periphery of the lens; θ is the angle, in radians, of the point source from the optical axis of the lens; and the 0.005 scaling factor is the diffraction limited spot size, in millimeters, at the focus of the lens. The circle function⁵ is defined to have a value of 1 when its argument is less than 1 and a value of 0 otherwise.

The maximum acceptance angle of a step-index fiber is usually greater than the maximum exiting angle of a ray leaving a quarter-pitch gradient-index lens. Under this condition, the intensity entering (and leaving the opposite end of) the fiber can be characterized by

$$I(x) = \text{circ} \left(\frac{x}{0.2} \right), \quad (2)$$

where the 0.2 scaling factor is the diameter of the fiber core in millimeters and x is, again, the distance from the fiber center to the lens optical axis. A coupling efficiency term is not included in this expression since the data presented in this paper are normalized.

The convolution of the function describing the gradient-index lens with the function describing the fiber model yields the system function

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Fig. 1. Eyelet configuration.

Fig. 2. Comparison of experimental data and theoretical model of intensity as a function of fiber location with discrete values of point source angular offset.

$$I(x, \theta) = A \text{circ} \left[\frac{x - \left(\frac{1}{n_o \sqrt{a}} \right) \theta}{0.005} \right] ** \text{circ} \left(\frac{x}{0.2} \right) \quad (3)$$

This equation does not account for vignetting or leaking of rays. The gradient-index lens has a loss of intensity at its rear surface that is a function of the angle subtended by the point source from the optical axis, given by⁶

$$I(\theta) = \sqrt{1 - \left(\frac{1}{n_o \sqrt{a}} \right)^2 \theta^2} \quad (4)$$

The equation that models the complete impulse response of the system now becomes

$$I(x, \theta) = I_o \left\{ \text{circ} \left[\frac{x - \left(\frac{1}{n_o \sqrt{a}} \right) \theta}{0.005} \right] ** \text{circ} \left(\frac{x}{0.2} \right) \right\} \times \sqrt{1 - \left(\frac{1}{n_o \sqrt{a}} \right)^2 \theta^2} \quad (5)$$

The dashed lines in Figs. 2 and 3 show this equation as a function of x and θ , respectively.

3. EXPERIMENTAL RESULTS

A pinhole illuminated by a 15 mW helium-neon laser beam focused with a microscope objective provided a variable location point source that was moved across the system field of view. The pinhole diameter and the microscope objective numerical aperture were 14 μm and 0.4, respectively. The pinhole was maintained at a constant distance of 3.4 m from the front surface of the gradient-index lens (see Fig. 1). The lens/fiber assembly was rotated with respect to the optical axis to simulate an angular offset. For each point source location, the fiber, held in a vacuum chuck, was moved across the rear surface of the lens with a micrometer stage. The micrometer stage allowed the distance from the gradient-index lens to the fiber to be held constant. The opposite end of the fiber was coupled to an S-20 photomultiplier tube that had a linear response over the range of intensities used. The solid lines in Figs. 2 and 3 show the experimental results of the eyelet system intensity output as a function of x and θ , respectively. The intensities shown are normalized to the photomultiplier output at $x, \theta = 0$.

Three types of discrepancies are apparent from the comparison of the theoretical and experimental results. The variation of the intensity value at the top section of each experimental function is the result of surface defects of the optical fiber end at the gradient-index lens. The curving phenomenon at the lower edges of the experimental functions results from the leaking of rays in the fiber cladding to the core when the diffraction spot is located on the cladding. Discrep-

Fig. 3. Comparison of experimental data and theoretical model of intensity as a function of point source angular offset with discrete values of fiber location.

ancies in the slopes at the edges are due to the tolerance in the focal point location. Although the diameter of the diffraction spot is specified by the manufacturer to be $5 \mu\text{m}$ at the focal point, $25 \mu\text{m}$ away from the focal point it increases to $30 \mu\text{m}$.

4. CONCLUSION

The theoretical model and the experimental measurement of the impulse response for a particular MAVS eyelet have been compared, and three discrepancies have been noted. Two of the discrepancies are important in selecting the type of location determination algorithm that can be used effectively with the eyelet.

The first of the two discrepancies is the variation in the crest of the function due to the fiber surface irregularities. Algorithms based on the intensity drop due to the point source angular offset would be difficult to use because of this variation. This problem may be alleviated by applying a smoothing algorithm to the crest of the function such that the angular intensity drop can be utilized in location determination. This improvement could be advantageous because it permits the use of large core fibers while maintaining good eyelet resolution.

The other discrepancy that could affect algorithm performance is the slope error in the edges of the function. Algorithms employing edge detection will be only slightly affected by the discrepancy since the slope error is small. Algorithm performance can be optimized by judicious choice of threshold intensity level. This choice should coincide with the crossing points of the theoretical and actual slopes. The fact that this discrepancy is small suggests the use of a large number of smaller core fibers to achieve high resolution with edge detection algorithms.

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