Electronic Compound-Eye Image Sensor: 
Construction and Calibration

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ABSTRACT

Compound eyes are a highly successful natural solution to the issue of wide field of view and high update rate for vision systems. Applications for an electronic implementation of a compound eye sensor include high-speed object tracking and depth perception. In this paper we demonstrate the construction and operation of a prototype compound eye sensor which currently consists of up to 20 eyelets, each of which forms an image of approximately 150 pixels in diameter on a single CMOS image sensor. Post-fabrication calibration of such a sensor is discussed in detail with reference to experimental measurements of accuracy and repeatability.

Keywords: artificial compound eye sensor, CMOS camera, wide field of view, object tracking, calibration

1. INTRODUCTION

As a result of millions of years of trial and error, biological organisms reach optimum adaptations for life in their particular environment. Engineers have long sought to learn from observations of the natural world, and to apply the knowledge gained about nature’s optimal solutions to artificial systems. An important part of this concept is that the solutions are optimized for differing applications (e.g. customized data acquisition and processing), performance goals (e.g. resolution, speed, field of view) and “cost” (e.g. power consumption, physical dimensions).

Compound eyes are possessed by a large majority of all individual animals on earth today, including insects, crustaceans, and arthropods [1]. Each eye is composed of a multitude of small lenses (up to 300,000 for a dragonfly) arranged on a convex surface. Typically, each lens illuminates eight photosensors of differing spectral sensitivity. The principal drawback of such a scheme is the limiting effect of diffraction on resolution for such small lenses. Puzzling exceptions to this norm are the trilobites, which flourished around 400 million years ago, and strepsipteran insects alive today. These creatures have fewer facets per eye, but each lens forms an image on a retina of around 100 receptors [2, 3]. In this paper we discuss the design, implementation, results, and applications of an electronic compound eye sensor similar to those of the trilobites and strepsipterans.

A three-dimensional compound eye structure of this type has not, to the authors’ knowledge, been demonstrated previously. Implementation of compound-eye sensors representing a circular cross section with up to 118 elements have been reported [4, 5], as well as a sixteen-element linear ‘compound eye’ with moveable fields of view [6]. In all of these cases, each facet of the sensor contained a single discrete photosensor, directly analogous to typical insect compound eyes. The rationale for investigating artificial compound eyes has been articulated clearly by Sanders and Halford in their theoretical study of compound eye sensors for robot collision avoidance [7], including expansion of the field of view and the potential for parallel image processing. With the increasing prevalence of CMOS single-chip cameras [8] and the associated availability of custom sensor design services, the practical implementation of sophisticated electronic compound eyes is now possible.

While the present implementation of the compound eye sensor – here named the DragonflEye – employs a single standard CMOS camera, we expect that a major strength of this approach lies in replacing or augmenting this sensor with one or more custom imagers. In such a distributed system, the choice of the individual sensor characteristics, optics and geometrical layout enables unparalleled flexibility in system optimization.
In the following sections (§2 & §3), the application scenario, design and construction of the prototype DragonflEye sensor will be discussed and sample images presented. For high-precision applications, post-construction calibration of the optical axes and fields of view of the individual elements may be required, as discussed in Section 4. The paper concludes with a discussion of future developments of the design (§5).

Important figures of merit for the DragonflEye sensor include sensitivity, resolution, field of view, power consumption and update rate. For the current single-camera system, a trade-off exists between field of view and resolution (number of pixels in each sub-image). This in turn influences the design of the optical components and, to some extent, also affects the sensitivity. Update rate and power consumption are influenced by the electronic camera; the use here of a CMOS sensor allows programmable region-of-interest readout, so selected portions of the field of view can be read out at a higher frame rate and power usage optimized. These issues are addressed in Section 2 below.

2. SCENARIO-SPECIFIC DESIGN CONCEPT

Figure 1 shows the scenario of interest for the baseline compound-eye imager. The emphasis is on a very large field of view, which can approach 4 pi steradians. The coverage is obtained by $n_{\text{eyelet}}$ cameras - “eyelets” - with independent optical elements. Each eyelet has a lens and a detector array. The degree of overlap of the fields of view of the eyelets is a design choice that flows from the system requirements. Multiple eyelets may share a common detector array.

Figure 1: Compound eye sensor (DragonflEye) operational scenario

The classical tradeoff among bit rate, field of view, angular resolution and update rate dominates the design and is expressed by Equation (1).

$$bit \_ rate = n_{\text{bit}} \times n_{\text{rows}} \times n_{\text{cols}} \times f_{\text{update}}$$

(1)
where $n_{\text{bits}}$ is the number of bits per pixel, $n_{\text{rows}}$, $n_{\text{cols}}$ are the average number of rows and columns in a single ‘eyelet camera’, $n_{\text{cams}}$ is the number of eyelets and $f_{\text{update}}$ is the average camera update rate. With $(n_{\text{bits}}, n_{\text{rows}}, n_{\text{cols}}, n_{\text{cams}}, f_{\text{update}}) = (8,100,100, n_{\text{cams}}, f_{\text{update}})$, the bit rate is shown in Figure 2. For the baseline system, a wide field of view and fast update rate are the main criteria of interest, so that bit rate of interest is in the upper right of the graph ($10^{12}$ Hz or greater). Because such high bit rates are not available in a conventional system, the compound-eye concept is intended to allow many cameras and on-chip parallelism of readout to increase the effective bit rate of the system.

![Image](image.png)

Figure 2: System bit rate versus update rate and camera number

With localized, simple objects that are well separated from the background, a “pixel-binary” imager organization [11] allows an update rate of $10^4$ to $10^6$ Hz or more by using a comparator on each pixel and a parallel readout of rows and columns. For the above model, $(n_{\text{bits}}, n_{\text{rows}}, n_{\text{cols}}, n_{\text{cams}}, f_{\text{update}}) = (1,1,1, n_{\text{cams}}, f_{\text{update}})$ in this case, resulting in a $10^4$ to $10^5$ reduction in effective bit rate that can be applied to faster update rate, higher angular resolution or a larger coverage area, with a manageable bit rate per camera.

### 3. DRAGONFLEYE PROTOTYPE INSTRUMENT

“DragonflEye”, a prototype compound-eye imager, was built to evaluate various calibration and object-tracking options (Figure 3). The main element of DragonflEye is a mechanical ‘dome’ structure covered with ‘eyelet’ lenses. Each eyelet lens has a coherent fiber bundle to bring the image to a common plane, the ‘fiber interface plane’, which is re-imaged onto the detector array by the ‘re-imaging lens’. The re-imaging lens was in C-mount format, for convenience, and was selected to have a flat field and sufficient resolution that it was not the limiting factor in system resolution. By de-magnifying the fiber interface plane, the re-imaging lens allows more eyelets for a given diameter of fiber bundle, and reduces the effect of fiber diameter on resolution.

The number and focal lengths of the eyelet lenses, $n_{\text{eyelet}}$, could be chosen in the range $10^0$ to $10^3$, depending on the resolution and coverage desired and the dome dimensions. For the work reported here, $n_{\text{eyelet}} = 25$ was typical and the total system field of view was large in azimuth (about 150 deg) but restricted in elevation (about 10 deg). Because the primary interest was fast-moving objects, overlapping coverage of adjacent eyelet fields of view was not required.

A commercial monochrome CMOS detector array with 1280 x 1024 pixels was selected, for the initial tests. Each pixel was a square of side 7.5 um. The update rate of the system was limited by the serial readout of the detector array to approximately 10 Hz (at full resolution and reading out the full array). Replacement of the single commercial imager
with a cluster of pixel-binary imagers [11] is planned, and is expected to allow a dramatically faster update rate, as discussed in Section 5 below. Hence, the emphasis in this work is on field of view rather than update rate.

The coherent fiber bundles were glass with a softening point near 704 C. Bend angles between 0 deg and 70 deg were used to cover the wide field of view of the system. The optical quality of the bent fibers was a potential source of performance degradation in the compound-eye instrument. Distortion was thought to result primarily from overheating. To achieve a reproducible bend geometry with minimal heating, a fiber bundle was installed in a jig to control sag and then placed in a temperature-controlled furnace. The furnace temperature was ramped to the above softening temperature over a period of about 100 minutes to ensure that the desired temperature profile across the bundle was maintained throughout the bending period. A small temperature gradient was applied to ensure that the ends of the fiber were heated less than the center regions, in order to avoid the formation of a meniscus at a fiber end, which would degrade the optical properties and necessitate optical polishing. A region of at least 5 mm in extent near each end of the fiber bundle was kept straight. To verify the optical quality after bending, each bent fiber bundle was inspected visually by use of an array detector and a standard target. Qualitatively, the bent fibers used in DragonflEye were optically no different from unbent fibers. Crosstalk is a secondary parameter for the scenario of interest here, so that the quantitative measurement of crosstalk in bent fibers is not discussed.
To achieve a wide field of view, coherent fiber bundles transfer each eyelet image to the input plane of a “re-imaging lens”. This plane was projected onto a detector array with a demagnification of about 2 to 5. Separate circular fiber bundles were used for each eyelet, so that the eyelet image regions on the detector array were also circular. The bend angle in each fiber bundle provided the desired angular coverage while still mapping the eyelet output onto the “re-imaging plane”. The degree of demagnification was made adjustable by the use of a zoom re-imaging lens.

Resolution can be affected by the focal length and aberrations of the eyelet lenses, diffraction, the diameter of the fibers in the coherent bundles, the demagnification ratio of the re-imaging lens and the size of the pixels in the detector array. The focal length of the eyelet lenses also affects the field of view of each eyelet. For the current DragonflEye prototype, the eyelet lenses are identical plano-convex acrylic components, with 15 mm focal length and 6 mm effective diameter. Each eyelet lens was mounted on a nylon structure linking it to a coherent fiber bundle. A threaded adjustment allowed the eyelet lens to be imaged onto the fiber bundle during instrument integration. The working distances were determined by the properties and focal adjustments of the eyelet lenses.

Various types of coherent fiber bundle were available. The default bundles (“high resolution”) had approximately $5 \times 10^4$ glass fibers, each with a diameter of 10 microns. The total dimension of the fiber bundle was 3.2 mm. The bundle diameter served as the field stop for the eyelet lens. The dimension of the (square) detector pixels was 7.5 mm. With the zoom re-imaging lens, the demagnification was used to vary the resolution and alter the relative importance of fiber and pixel dimension on resolution. The length of the fiber bundle was a design parameter, and was typically about $10^2$ mm. As the number of eyelet lenses increases, the lengths of the fiber bundles (and the dimension of the dome support structure) must increase in order to accommodate the lenses without overlap.

Alignment of the fiber bundles was performed as follows. Firstly, each eyelet lens was adjusted for desired focus with respect to the input end of the fiber and the nylon subassembly was glued in place on the end of the fiber bundle. Then, the output end of the fiber bundle was inserted into a machined guide in the “fiber output plane” support structure, adjusted for focus using the detector array and re-imaging lens, and fastened in place with glue. Before the glue was dry, the fiber bundle subassembly was rotated to point in the desired direction. The process was repeated for all fiber bundles, starting with ones in the center of the pattern to facilitate convenient access. To allow experimentation with different arrangements of fiber bundles, closely-machined Teflon fiber output support structures were also available, for which the fiber bundles could be inserted and removed.

With the above fiber bundle dimension and demagnification, a 1280x1024 array detector can readily contain up to 100 eyelet images or so, in which each eyelet image contains about $10^4$ pixels. (Note that the circular cross section of the fiber bundles leaves dead space on the imaging array.) A 15 mm focal length for the eyelet lens provided an eyelet field of view of approximately 0.036 sr or 0.56 % of the hemisphere. The corresponding eyelet cone angle was 213 mrad. For full coverage of the hemisphere using the above lens and other parameters, 300 to 600 eyelets are generally needed, depending on the allowable gaps in coverage. The number of eyelet lenses is limited in the present DragonflEye by the maximum demagnification and the field of view of the re-imaging lens. The angular extent of the fiber output plane as seen by the re-imaging lens is constrained by lens off-axis optical quality, vignetting and the angular distribution of light emitted by each fiber in the bundles (numerical aperture of 0.53 was used). With fiber bundles of smaller diameter or square cross section, more bundles could be used and the amount of ‘dead space’ in the fiber output plane could be reduced. The number of eyelet lenses that can be imaged onto the detector array is an additional constraint. Multiple detector arrays can be used. The “high resolution” fiber bundles described above could be replaced with “low resolution” bundles or individual optical fibers. All of the work described here was performed with the “high resolution” fiber bundles and a single detector array, as described previously.

In an alternative implementation, “low resolution” fiber bundles of 1.6 mm diameter were used. For these bundles, approximately $3 \times 10^3$ fibers of 25 microns diameter were present. In this case, the number of eyelet lenses could approach $10^5$, but with coarser angular resolution in each eyelet image. The physical dimensions of the prototype were scaled to accommodate the desired number of eyelets. Low-resolution fiber bundles and discrete fibers could be placed in the ‘dead space’ between high-resolution fiber bundles. For convenience in fabrication, the prototype DragonflEye used in the present measurements had its eyelet lenses arranged in a rectangular array with extensive angular coverage only in the azimuthal direction. Objects of interest were then restricted in elevation. This restriction does not limit the generality of the conclusions presented.
Table 1 lists important design options for the compound eye sensor.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Options for Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Coverage and overlap of fields of view of eyelets</td>
<td>Total field of view and overlap of eyelet fields influence the angular resolution and the gaps in coverage among eyelets for a given number of eyelets; fiber bundle dimension and lens focal length</td>
</tr>
<tr>
<td>Number of detector arrays</td>
<td>Total field of view and update rate can be scaled by increasing the number of detector arrays, without sacrificing angular resolution.</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>Diffraction, lens aberrations, point spread function, fiber diameter, pixel dimension, stray light, crosstalk.</td>
</tr>
<tr>
<td>Update rate</td>
<td>Number of pixels, number of cameras, row- and column-parallel readout, number of bits/pixel, on-chip processing, adaptive operation in a region of interest.</td>
</tr>
</tbody>
</table>

Selected system and performance parameters of the prototype DragonflEye are summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuthal field of view</td>
<td>degrees</td>
<td>150</td>
</tr>
<tr>
<td>Elevation field of view</td>
<td>degrees</td>
<td>10</td>
</tr>
<tr>
<td>Eyelet resolution</td>
<td>mrad</td>
<td>1</td>
</tr>
<tr>
<td>Number of eyelets</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>Update rate</td>
<td>Hz</td>
<td>10</td>
</tr>
<tr>
<td>Inter-eyelet calibration accuracy/precision</td>
<td>mrad</td>
<td>0.1</td>
</tr>
<tr>
<td>Dimension of optics dome</td>
<td>mm</td>
<td>100</td>
</tr>
<tr>
<td>Number of useful pixels</td>
<td>-</td>
<td>$3 \times 10^5$</td>
</tr>
</tbody>
</table>

Of particular interest is the number of eyelets. A large number of eyelets is generally preferable, in order to enhance resolution and increase the total field of view. Constraints on the number of eyelets include the dimensions of the optics, the aperture per eyelet lens, the diameter of each coherent fiber bundle, the space between eyelets for mechanical structures, the time needed for readout (if serial) and the time needed for processing. Inter-eyelet communication can be a factor as well. The salient optical parameters of an eyelet lens are diffraction at the entrance aperture, aberrations, depth of field and focus, throughput and positioning accuracy of the optic axis relative to the center of the corresponding coherent fiber bundle. The prototype DragonflEye is intended for laboratory use, so that the effects of temperature on alignment have not been incorporated into the design. Baffles have not been used. Stray light and crosstalk are expected to be important for low-light applications with complex scenes, but are less important for the baseline scenario of a dominant object moving through the scene.

Figures 4(a) and 4(b) are photographs of a DragonflEye prototype with a partial population of eyelets in two different arrangements and no cosmetic dome cover. The optics is a compact structure, while most of the volume of the prototype is needed for the re-imaging function. This version of DragonflEye was assembled from individually-aligned eyelets, each of which had a coherent fiber bundle and a lens. For large numbers of eyelets, integration of the eyelet lenses into a dome structure before alignment is an option that could reduce assembly/test time. An example of images recorded on the CMOS camera using ten eyelets in two parallel rows is shown in Fig. 4(b); each eyelet image is approximately 150 pixels in diameter.
4. INTER-EYELET CALIBRATION OF LOCATION

Selected alternatives for the calibration of DragonflEye are itemized in Table 3, along with salient features.

Table 3 Calibration Alternatives

<table>
<thead>
<tr>
<th>Calibration Alternative</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision angular motion and optical point source</td>
<td>Accuracy depends on precision translation/rotation system. Sensor- or scene-centred coordinates could be appropriate.</td>
</tr>
<tr>
<td>Large-angle target</td>
<td>Accuracy determined by target geometry and illumination. Scene-centred coordinates are most appropriate.</td>
</tr>
<tr>
<td>Vanishing points [10]</td>
<td>Reduced dependence on target and actuator specifications. Sensor-centred reference coordinates are most appropriate.</td>
</tr>
<tr>
<td>Motion of a standard object</td>
<td>Empirical calibration, localized validity, can be ‘stitched’ to cover full scene. Scene-centred coordinates are most appropriate.</td>
</tr>
</tbody>
</table>
The appropriate calibration method is dependent on the application and operational scenario as well as the availability of test equipment. For the present situation, the information of interest was the position of a fast-moving object in a scene-fixed reference frame, and the position of the image sensor was secondary. The “motion of a standard object” method of calibration was used for this work. Figure 5 shows the calibration scenario. The basic idea of the use of the ‘standard object’ is to select an object that is readily identified and precisely located both within the sensor image and in the fixed scene that is being imaged. The standard object is placed in various positions in the scene that are accurately known in the external reference frame of interest. Measurements of the corresponding locations on various eyelet images are converted into empirical calibration constants that allow the position in the scene to be determined from the measured positions in the image. Because only two parameters ($x_{image}$ and $y_{image}$, for instance) are measured in the image and 3 coordinates are needed for scene position, the problem must be constrained. For convenience in the present measurements, the scene object is constrained to move in a plane that is designated as the $x_{scene}$ $y_{scene}$ plane. This plane can have an arbitrary orientation with respect to any reference plane in the DragonflEye sensor.

![Figure 5: Use of a known object for calibration](image)

For each eyelet field of view, about $10^2$ locations on the reference plane were used. A least-squares fit of the measured positions on the image plane (for these known object locations) provided the coefficients of a linear fit for the determination of position on the “reference surface”. This method achieved a calibration accuracy of better than $\pm 0.05$ pixel (0.1 mrad), limited by the precision of the ‘known object locations’, nonlinearity in the calibration function and the random noise of the centroid location. For the measurements reported here, the reference surface was planar and the calibration object was a white disc that was placed in locations defined by a precision xy translator. Although this empirical calibration can be extended, in some multi-camera systems, to allow 3 dimensional motion of the calibration object, such measurements are not described here.

Angular or translational movement of the sensor during the measurements can change the calibration. This method is best applied to static placements of a sensor suite in a scene. Each sensor is separately calibrated with respect to scene-fixed coordinates, and the calibration coefficients provide the object position in the scene coordinates. This approach is similar in principal to that used in [9] where multiple video cameras were calibrated using a ‘wand’ with an LED [9]. By comparison, the ‘vanishing point’ method provides calibration constants that are best expressed in sensor-centred coordinates [10].

The x- and y-positions of the centroid of the image were measured with a precision of $\pm 0.02$ pixel (1-$\sigma$). With this level of precision, nonlinearity was less than 0.1 pixel over the measurement region of 20 mm (in scene coordinates). Figure 6
shows typical measurements for a scene approximately 1000 mm from DragonflEye. The abscissa is the scene position in millimeters while the ordinate is the image location in pixels (x-position and y-position in (a) and (b) respectively). The linear least-squares fit has an $r^2$ value of 0.99. The segment shown is approximately 10% of the field of view of a single eyelet and the expanded region shows a motion in the image plane of one pixel-length. For larger scene regions, aberrations of the eyelet lens and multiple eyelet lenses may require a piecewise linear calibration or a nonlinear calibration function. In Figure 6(b), the reduced slope allows the measured deviation from linearity to be observed. Care is needed to match both the calibration function and its derivative when using piecewise-measured functions.

Reproducibility of the calibration is illustrated in Figure 7, which shows histograms of a large number of repetitions of the centroid determination for a fixed scene target. The overall shape of the distribution is Gaussian, and the full width at half maximum is reduced as groups of data points are averaged, indicating low drift of the mean. Structure in the profiles reflects the collection of data into histogram bins and the expected shot noise. In the narrowest profile (each measurement an average of 1000 centroid locations), the small number of measurements and bins increases the variability. The laboratory temperature was constant to $\pm 1^\circ$C and vibration events were rare.
Significant anomalies – not associated with the primary (Gaussian) statistical distribution of the measurements – occurred every $10^4$ to $10^6$ image frames, were attributed to ionizing radiation events and ignored. From the above histograms of measured centroid values, the aforementioned spot-location precision was estimated. The precision depends on the number of measurements co-added, typically 100, and has the expected root(n) dependence on the number of measurements that is characteristic of random noise. Careful control of drift and other sources of systematic error during the measurement period is essential. The accuracy of object location for tracking purposes will generally be limited by object motion (which constrains the number of co-adds), calibration errors, field curvature, temperature drift and other systematic errors.

Drift in environment and other parameters during averaging can cause the histogram of position measurements to deviate from a Gaussian profile. While the histogram in Figure 7 is a good fit to a Gaussian profile, a suitable scatter plot can identify very low levels of drift (Figure 8). In Figure 8, each point represents 100 measurements, acquired over a time period of approximately $10^2$ seconds. The trend is suggestive of temperature or a similar drift during the measurement period, which is verified by plotting the same data against time. Drift may set an upper limit to the useful number of repetitions of a measurement for random noise reduction. Since the drift is often time dependent, a high frame rate can enhance precision through averaging the same number of frames in a shorter time.

![Figure 8: Scatter plot of position in pixels](image)

Calibration is described above with reference to object position. The corresponding calibration of object velocity requires, in addition, an accurate time stamp for each image. The exposure duration can be the limiting factor in the determination of object velocity. The derivation of tangential linear velocity in the scene from image motion assumes a knowledge of the range. For the DragonflyEye configuration described here, the displacement of the eyelet lenses was small, so that range estimation using triangulation in the imagery from different cameras had large uncertainties. The determination of range or motion along the line-of-sight can be useful but is not reported here.

With the “standard object” method of calibration, DragonflyEye could be used to direct the precise illumination of an insect or other rapidly moving object by a remote scanning light source. The location and orientation of the DragonflyEye instrument are not explicitly needed, but are implicit in the calibration coefficients. While highly accurate and convenient for applications where the sensor is fixed and the plane of motion of the target is known, the “standard object” empirical calibration described here lacks the generality of some other calibration approaches.
5. DESIGN EVOLUTION

The compound eye sensor discussed above forms the baseline prototype system used to establish essential techniques for construction, operation and calibration. Future implementations of the DragonflyEye are developing in a number of ways. It is expected that the need for high readout speed will result in a system in which both sensors and optics are distributed, i.e. many sensor chips, each with multiple optic inputs and parallel image paths. This will enable true parallel processing of the images from each sensor/optics module. At the same time, custom application-specific CMOS imager chips can also be employed – either wholly or partially – to further increase update rate. Examples of pixel-parallel sensors which would be well suited to the applications discussed here have been developed in this laboratory [11, 12]. High-speed detection and location of objects that are distinct from their background, and the resulting location of an analog “region of interest” for readout, are key attributes of those sensors.

In conjunction with sensor improvements, enhancements to the design and implementation of the optics are also desirable, such as the investigation and correction of eyelet lens aberrations, as well as optimization of the field of view shape, focal ratio, and other lens characteristics. In the present system, high-resolution coherent fibres are used, representing one solution to a general trade-off between resolution, eyelet number (limited by the fibre bundle diameter) and optical transmission coefficient. Regions in the compound eye sensor specialized for sensitivity, resolution or motion detection are expected to result in high-performance sensor systems tailored for individual applications.

The compound eye architecture also facilitates novel image processing approaches. For the object tracking application discussed here, selective readout of areas of the image sensor corresponding to salient view directions will lead to higher speeds and to optimized search strategies for locating the arrival of a new object of interest. When commercial CMOS cameras are used, there can be a relatively large delay in repositioning the readout window, so target prediction may play an important role in maximizing the performance of the system. The relative timing of eyelet readout can also be used for fast correlations and modified “phase sensitive detection” to extract the eyelets of interest (or targets therein) from the background.

By varying the optical design, the degree of overlap between eyelet fields of view can be adjusted. In the case where significant overlaps exist, objects will be imaged from two or more spatially separated locations, leading to the possibility of extracting depth information.

An interesting trend in autonomous system design is towards clusters of robots or satellites, where many individual devices cooperate to solve a task. An extreme example is nano-robots beloved of science fiction. In space applications, an associated trend is towards micro-, nano- and pico-satellites which are cheap to construct and launch but simple in function. For such ‘swarms’ of machines, techniques derived from the proposed compound eye research are expected to be valuable for image acquisition and processing.

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7. REFERENCES


