## Design concepts for a novel attitude sensor for Micro Air Vehicles, based on dragonfly ocellar vision<sup>\*</sup>

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Currently, two types of vision-based attitude sensing mechanisms are commonly used in MAVs. One approach computes a best fit of the horizon line from video images taken by an on-board camera, requiring time-consuming multipixel processing. An alternative approach estimates the centroid of incident illumination, obtainable with simple analog hardware. The latter strategy is strikingly similar to a classical model of the function of the ocelli of flying insects. Ocelli are simple lens eyes, occurring in addition to the primary visual system formed by the compound eyes. In a comprehensive study on dragonflies, we have found that those aerial predators have developed an ocellar system that is much more elaborate than previously thought. The dragonfly ocelli contain gradient-index lenses with extremely short focal lengths, thus forming images on the photoreceptor arrays. The photoreceptors are ultraviolet-sensitive and are sampled by second-order neurons with fields of view that cover a narrow streak along the forward half of the equator of the animal's viewsphere, apparently forming a template of the horizon. Thus, dragonflies have reduced horizon detection to a one-dimensional task, combining the accuracy of the best-fit approach with the simplicity of the centroid approach. The concept is suitable for a miniaturized biomimetic implementation.

### Nomenclature

FOV	=	field of view
IR	=	infrared
LED	=	light-emitting diode
L-neuron	=	large ocellar second order neuron
MAV	=	Micro Air Vehicle
UV	=	ultraviolet

### I. Introduction

**D**ragonflies, with a mass of < 1 g and a wingspan of < 100 mm, are amongst the most competent flying organisms or machines in existence. Their repertoire of flight modes is likely to be the envy of MAV designers for some time to come: it includes gliding, fast sorties in pursuit of prey and the ability to maintain hover with remarkable precision, even in the presence of strong wind gusts. This competence is supported by a complement of sensory systems that enables flight control. Of those systems, vision is the most strongly expressed one, although there are also mechanical sensors that measure airspeed and wing loading, as well as the equivalent of a gyroscope.

As in other flying insects, the visual system is composed of two independent subsystems, namely the paired compound eyes and a triplet of ocelli. In dragonflies, the compound eyes are composed of approximately 60,000 ommatidia, almost covering the entire viewsphere with a resolution in the order of 1°. The associated neuronal circuitry in the brain consists of multiple layers that extract complex information such as optic flow, the trajectories and sizes of moving objects, as well as cues for course control such as the e-vector of polarized skylight. Of a total of nearly  $10^6$  brain neurons, a substantial fraction is involved with the processing of data from the compound eyes. In contrast, the less conspicuous ocelli are simple lens eyes that are associated with

<sup>\*</sup> Supported by the Air Force Office of Scientific Research, special contract AOARD-03-4009.

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neuronal circuitry that consists of a few thousand photoreceptor neurons, feeding into a single layer neuronal network that contains about a dozen large second-order ocellar neurons (L-neurons).

The underlying reasons for the presence of a dual visual system have long been a mystery. One century-old hypothesis<sup>1</sup> is that the ocellar system would be eminently suited to detect deviations from level flight, both in pitch and roll, by monitoring the horizon. Later, it was demonstrated in wind tunnel experiments on flying dragonflies<sup>2,3</sup> and locusts<sup>4</sup> that manipulation of visual inputs to the ocelli evoked attitude changes that were consistent with the horizon hypothesis.

Recent developments in MAV-technology have led to a surge of interest in vision-based horizon sensors, attributable to the realization, now widespread, that achieving MAV flight stability presents some difficult challenges<sup>5</sup>: with a reduction in size, both moments of inertia and aerodynamic angular rate damping decrease, whereas wind gust speed will frequently exceed the total forward airspeed of the MAV. Another size-related problem arises if propulsion is generated by flapping wings: if the natural frequencies of oscillatory modes of the airframe are close to the wingbeat frequency, some form of active damping is necessary<sup>6</sup>. As dragonflies can cope with those problems exceedingly well, the function of their ocelli and other equilibrium sensors is relevant for MAV-technology.

That relevance has led us to a major re-examination of the dragonfly ocellar system, at the levels of optics, morphology and electrophysiology<sup>7-11</sup>. The result is that we are now able to present a comprehensive system identification of the biological circuitry, suitable for the implementation of a model that can be tested in a simulation or in the form of physical, flight-testable hardware. The main objective of this paper is a review of those results, covering the way in which the biological system achieves extreme miniaturization, and the way in which the visual world is mapped in space and time. This will be preceded by a section on current vision-based horizon sensors in MAVs, as well as an outline of general features of insect ocelli and their similarities to technical systems.

### II. Vision-based horizon sensors in MAVs

Human pilots detect the horizon by recognizing one part of the visual world as sky and another as ground. In formal terms, this process can be described as classifying all points on the viewsphere into either sky or ground, by criteria such as texture and color, and then estimating the line best separating those two classes. This algorithm was implemented by processing a video stream from a camera on a serial computer<sup>5,12</sup>. Another method uses a circular mask on the image and computes the centroids of all sky and ground pixels respectively<sup>13</sup>. Also, a CMOS based, analog 12×12 pixel VLSI array has been described<sup>14</sup>, finding a best-fit horizon line by parallel processing.

This classical machine vision approach incorporates multi-element imaging photodetector arrays, as well as



Figure 1. A: Tiled panoramic view, of a scene containing parkland and buildings, covering  $\pm 22^{\circ}$  of elevation, taken from 1 m above ground, 20 m from a 3-storey building. B: Parabolic mirror used to take panoramic views from the same location, shown in C to E. Camera was pointed vertically at the mirror, from below. Elevations covered were from  $-90^{\circ}$  to  $+45^{\circ}$  of horizon. Sun was within FOV. C, D, E: images taken through filters in the red, green and near UV respectively.

computationally demanding processes such as pixel classification and image segmentation. It may also incorporate an adaptive learning step whereby the rules for picture element classifications are determined immediately prior to usage. The latter classification step can be avoided if prior assumptions are made, for instance about the brightness distributions of sky and ground. Also, optimization of spectral sensitivity is quite helpful: In the red part of the visible spectrum (Fig. 1C), the ground is brighter than the sky but the sun is much brighter, causing substantial glare if it is in the FOV of the camera. In the green (Fig. 1D) the contrast between sky and ground is poor, in addition to the detrimental effect of the sun. However, acceptable results can be obtained at shorter wavelengths, where most objects on the ground are of low reflectance and indirect skylight is brighter relative to the sun. Thus, the optimal wavelength range is in the near UV, around 360 nm Fig. 1E) where the absolute amount of radiation is still sufficient.

For the machine vision approach, it is worth considering that a forward-looking camera is usually present anyway, obviating the need for extra hardware. However, such a camera will be primarily designed for high resolution, typically obtained at the expense of FOV. A typical camera that covers 60° of azimuth will thus see only a sixth of the horizon, meaning that its performance will be degraded in a cluttered scene where the horizon is not a straight line, as is the case at low altitude. As also demonstrated in Fig. 1, a panoramic detector is superior in this respect: the centre of the best fitting circle around the contour of the ground patch in Fig. 1E is within 5° of the true vertical.

For using a panoramic-vision method of horizon detection, the number of pixels used needs to be optimized. In the extreme, that number can be quite small, leading to a low-resolution alternative to the machine-vision approach. It is based on a 'matched filter' mechanism<sup>1</sup>, using prior knowledge such as the fact that the sky/ground contrast is best in the UV, and the notion that the sky-ground intensity distribution has its centre of gravity close to the zenith. The latter means that it is not necessary to identify the horizon in the first place if we subject the viewsphere to spatial band-pass filtering at a period of 360° and find the spatial phase of the overall intensity distribution, in the two dimensions of pitch and roll.

It has been suggested<sup>15</sup> that wide field detectors, assigning sinusoidal weight functions to the full

viewsphere, are optimal for the detection of pitch and roll (Fig. 2A). A schematic diagram of a pitch/roll controller using that principle is shown in Fig. 2B. Two pairs of wide field light sensors are used, without any focusing optics. They are aligned with the horizontal plane, such that a tilt leads to intensity differences between opposite sides. Simply feeding the difference signals from each pair to the control surfaces of the aircraft will close feedback loops for pitch and roll.

An autopilot for model aircraft, based on greensensitive photoresistors, has been commercially available for some time. Its specifications state that it is adversely affected by the presence of bright surfaces on



Fig. 2. A: Two-dimensional weighting functions of optimal pitch and roll detectors (adapted from Ref. 16). White signifies positive, black negative weights. B: The simplest possible panoramic attitude detector, viewed from above.

the ground and by a low sun. An improvement on the optical-wavelength approach<sup>16</sup> incorporated the notion that the contrast between sky and ground is low in the green, allowing the usage of this wavelength range as an overall luminance reference. Thus, pairs of UV- and green-sensitive detectors were used and the output ratios for each pair were formed (color opponency). Thereby, the system becomes robust against fluctuations of overall light intensity and the effect of a low sun is mitigated.

Optical-wavelength based attitude controllers can be extremely small and can have response times in the order of microseconds, but they suffer from the disadvantage that they depend on ambient light from an external illuminant. In the mid-IR part of the spectrum, at wavelengths above 5  $\mu$ m, this constraint does not apply because the sky is always colder than the ground. Consequently, it is not surprising that a standard method of attitude stabilization for orbiting satellites uses mid-IR sensors. Recently, miniaturized thermopile detectors have become available, with the result that the principle has found its way into the commercial market for model

aircraft. For the control of MAVs, the merits of the mid-IR based approach have been investigated<sup>17</sup> and a number of competition entries to MAV05 used this approach.

# III. General features of insect ocelli

Ocelli are present in many adult insects, usually in a group of 3. Often, they are strongly expressed in winged animals. Their positions on the head differ between species; for the example of the locust (Fig 3A), the median ocellus is located on the midline, between the two antennae, and the two lateral ocelli are next to the anterior rims of the much more conspicuous compound eyes. A cross section through an ocellus (Fig. 3B) reveals the typical design of a simple or lens eye, with lens, vitreous body and retina. However, an atypical



Figure 3. A: Portrait of a locust, with locations of the ocelli indicated by arrows. CE compound eye. *Scale bar: 5 mm.* B: Cross section of median ocellus, with lens L, vitreous body V and retina R. Asterisk indicates position of focal point F. *Scale bar: 0.2 mm.* C: Viewsphere projection with FOVs (10% contours) of L-neurons in the three ocelli (adapted from Ref. 18). Grey: part of viewsphere normally below horizon.

feature is that the refracting power of the lens is not sufficient to form an image at the plane of the retina. In addition, electrophysiological measurements<sup>18</sup> show that the FOVs of typical L-neurons cover fairly wide angles (Fig. 3C) and that their axes are aligned with the equator of the head, which is normally aligned with the horizon. The FOVs are distinct for different ocelli; together they cover a substantial part of the viewsphere. During level flight, half of each FOV is exposed to ground and the other half to sky. A further conspicuous feature is that the L-neurons have the largest axons of all insect brain neurons. A large diameter results in high conduction velocity of neural signals, indicating that the system is adapted for speed. Finally, the spectral sensitivity maximum is in the UV, a feature eminently suited to measure sky-ground contrast, as discussed above. Taken together, those observations strongly support the idea that ocelli are adapted to act as a 'rough and ready' horizon sensing system<sup>18</sup>, sacrificing spatial resolution for speed of response.

There is a striking parallelism between the described properties of the insect ocelli and those of the panoramic horizon detectors discussed above: it is possible that the existing differences are of minor relevance. One difference is the presence of three, rather than four, ocelli, which might be superficial because three points in space are enough to define a plane. The usage of mid-IR rather than visible light appears to be superior but might not be possible in insects. The main common feature is the presence of very wide FOVs that add up to a panoramic view, meaning that all or most points of the viewsphere are coverd.

However, it turns out that the dragonfly ocellar system has evolved in a different direction.

### IV. The dragonfly ocelli

The face of the dragonfly (Fig. 4A) is dominated by the large compound eyes, together with the forward-facing frons which is the cover for the mouth parts. In the remaining triangle, the forward-facing oval-shaped median ocellar lens is located in a groove



Figure 4. A: Portrait of a dragonfly, showing the positions of the median and the left lateral ocellus (arrows). CE compound eye, F frons, V vertex. *Scale bar: 1 mm.* B: Section in median (vertical) plane through median ocellus, with lens L and retina R. Asterisk indicates position of focal point F. *Scale bar: 0.2 mm.* 

formed by the frons below and the vertex above, and flanked by the antennae. The lateral ocelli are located on the sides of the vertex, facing sideways.

A vertical cross section through the median ocellus (Fig. 4B) reveals that the lens is much thicker than it is in the locust, and there is no vitreous body. Unlike the locust (and the majority of other insects), the focal point, as identified by direct observation<sup>10</sup>, is located within the retina, meaning that this eye is capable of image formation. In spite of its oval shape, the lens is not astigmatic, because the shape of the inner lens surface

compensates for astigmatism, albeit with the result that the image of an object that lies directly forward is duplicated in azimuth<sup>10</sup>. If the refractive index of the lens were homogenous, and of a value of 1.5 as is maximally obtainable by biological materials, its surface curvature would not be sufficient to account for the short focal distance. Instead, it is found that this short distance is achieved by the presence of a refractive index gradient<sup>10</sup>. Thus, it appears that the dioptric apparatus is specifically adapted to meet the prerequisites for image vision. An additional specific adaptation is present in the lateral ocelli, where the retinae are subdivided into focused dorsal and underfocused ventral parts<sup>11</sup>.

The median and lateral retinae are composed of approximately 2000 receptor neurons, converting photons into electrical signals, with a photon capture efficiency close to 1. This, combined with large apertures of the lenses, results in the system being functional down to a light intensity equivalent to a moonless night sky<sup>3</sup>.

The image information at the receptor neuron outputs is sampled by the L-neurons. There are 17 L-neurons in total. The median ocellus contains five pairs where each member is a mirror image of the other, and three pairs sample the lateral ocelli. In addition, there is an unpaired bilateral neuron that samples all three ocelli. Each neuron is distinct from all others by its shape, including the peripheral arborization pattern. Using two L-neurons as examples, from opposite sides, with each being a member of a different pair, Fig. 5 illustrates the way in which the median ocellar retina is sampled. In the projection on the horizontal plane (Fig. 5A), it is evident that the two neurons differ in their branching patterns, sampling different parts of the retina. When viewed from the front (Fig. 5B), it can be seen that the branching patterns are concentrated around a common horizontal line and that the width of either projection exceeds its height.

Those observations describe the spatial mapping of L-neurons onto the retina, but not the way in which the actual visual world is mapped onto the L-neurons. However, a more direct approach is available to achieve this. Due to their large sizes, L-neurons are easily accessible to electrophysiological recordings that measure the voltage across their cell membranes as a function of light stimuli. Recordings were taken from individual L-neurons in animals placed in front of a video display specifically designed to explore their spatiotemporal properties<sup>9</sup>. The display was an array of 108 pairs of green and UV LEDs, arranged on the surface of a sphere in 12 rows of 9 columns, with angular sampling



Figure 5. A: Schematic representation of spatial relationship between two of the L-neurons and lens/retina of median ocellus. View from above, at horizontal plane. Dashed line indicates plane of section in Fig. 4 B. *Scale bar: 0.2 mm.* B: Frontal projection of the same Lneurons.

densities of  $3^{\circ}$  in elevation and  $6^{\circ}$  in azimuth. Those sampling densities had been found to be sufficient in earlier measurements on ocellar receptor neurons<sup>8</sup>. All LEDs were independently addressable, at a refresh rate of 625 Hz. For the experiments described here, only the UV channels were used. The display enabled us to determine the spatiotemporal transfer functions of the L-neurons by the most parsimonious method available, namely white noise analysis.

The temporal transfer functions were determined by modulating all LEDs simultaneously with the same random sequence, evoking a transmembrane response, as shown in Fig 6A. By analyzing the correlation between stimulus and transmembrane voltage, the temporal impulse response or kernel was obtained (Fig 6B). The impulse response consists of a delay of 10 ms, followed by a biphasic response with a first peak after 18 ms. This time course is characteristic for a bandwidth-limited differentiator. There is also a sustained component, as the integral is nonzero. Thus, the output of the ocellar system, as a function of light intensity, contains both a proportional and a derivative component. Consequently, the system is capable of signaling the absolute position of the horizon, with an enhancement of fast changes, likely to enhance stability in a closed-loop situation.



Figure 6. A: Randomly modulated light stimulus (upper trace) and resulting transmembrane voltage of an L-neuron (lower trace); B: Temporal impulse response, derived from data as in (A) by white noise analysis; C: Set of impulse responses, for a range of angular positions of stimulus; D: contour plot derived from maximum responses in (C). Area with 50% or more of maximum response shaded in grey; best fitting ellipse shown in black.

For the determination of the spatial kernels, the light intensities of all LEDs were modulated simultaneously but independently by random sequences, followed by separate correlation analysis for each channel. In this way, a two-dimensional set of temporal kernels could be obtained, for each L-neuron investigated, as shown in Fig. 6C. Using the peak amplitudes of all those kernels, the contour plot shown in Fig. 6D was obtained. It represents the FOV of this particular neuron and shows that the maximum sensitivity occurred at an azimuth of 36° and an elevation of 9°, with half-widths of 15° and 34° respectively. The shape of the 50% contour plot can be reasonably well approximated by an ellipse as indicated.

Thus, this particular neuron is spatially much more selective than is the case for the optimal wide-field detectors (Fig. 2) and for the locust ocellus (Fig. 3).

This leads to the question whether other L-neurons are similarly selective and how the complete set of L-neurons maps visual space. To this end, recordings were made from many neurons and the morphological identity of each recorded neuron was determined by injecting a dye after recording. This enabled us to verify that the presence of 17 distinct morphological types does have a correlate in their physiological mapping of the



Figure 7. FOVs of 9 representative L-neurons in median and lateral ocelli. Best fits of ellipses to 50% sensitivity contours. Grey: part of viewsphere normally below horizon.

visual world. The result is presented in Fig. 7; for clarity, only a representative subset of 9 L-neurons is shown. Some of the remaining FOVs are duplicates.

With the exception of one pair, all FOVs in both median and lateral ocelli are closely aligned with the equator of the head<sup>11</sup>. In all cases, the elevation range is similar to that in Fig. 6, but different neurons cover a wide range of azimuths. A total of 180° of azimuth is covered, subdivided into 7 distinct sections. The extent of coverage in elevation is much narrower. The exception is the most lateral pair of FOVs that is not directed at the horizon at all: instead, it is cenered on azimuths of 110° and -110° respectively and on an elevation of 30°. Those FOVs are also the largest of all, which is consistent with evidence that they are associated with the underfocused ventral retinae of the lateral ocelli<sup>11</sup>.

### V. Discussion

The existence of vision-based attitude sensors for MAVs demonstrates that there has been a perceived need for them; equally, it is reasonable to assume that the equivalents in insects have evolved, albeit on a different time scale, because there is an advantage in carrying them. Beyond this, one must resist the temptation to carry the biomimetic argument too far and simply copy the biological system on the basis that it must be optimized by evolution: there are some fundamental constraints that apply to organisms but not to machines. With this in mind, the following paragraphs aim at considering the scope of biomimetic implementations of various aspects.

*Optics.* The range of FOVs observed (Fig. 7) proves that it is possible to construct a half-panoramic sensor, occupying a volume of less than 1 mm<sup>3</sup>, by using no more than 3 lenses of the sizes and shapes found in the dragonfly ocellar system, but it remains open whether a biomimetic reconstruction is superior to other approaches. For instance, a FOV of 180° can also be obtained by using a fisheye lens, and by using a parabolic mirror as in Fig. 1 a full panoramic FOV would be within reach.

*Phototransduction.* The retina (Fig 4B) contains the photoreceptor neurons which in turn contain the photopigment that transduces light into an electrical signal. It is inherent to the design of insect photoreceptor neurons that they must be of considerable length in order to achieve a high photon capture efficiency. This constraint does not apply to technical photodetectors, meaning that an electronic retina could be much thinner. On the other hand, the photoreceptor neurons are capable of adapting their sensitivities over a wide range of background light intensities, ranging from a moonless night<sup>3</sup> to full daylight. A biomimetic ocellus that uses an imaging array of thermopile sensors is potentially superior to a light-based system because it will be background-independent.

*Time course of L-neuron responses.* The earliest component of the impulse response (Fig. 6B) is a latency of about 12 ms. Of this, 8 ms are attributable to the photoreceptor latency<sup>8</sup> which is unavoidable because it is attributable to the phototransduction mechanism inherent to biological visual systems. The remainder of the latency is caused by the delay in signal transmission from receptor neuron to L-neuron, again unavoidable. This is followed by a bipolar transient, with a rise time to maximum of 10 ms, determined by the time constant of the L-neuron. Time constants of neurons decrease with increasing size, and it is noteworthy that L-neurons are he largest of all neurons in the insect central nervous system, suggesting that there is a premium on response speed. The speed argument has also been used to explain why there is a separate ocellar system in the first place: if the compound eyes were to perform the same function, processing by additional neuronal layers would increase the system delay by a factor of at least two. A biomimetic implementation of an ocellar system that uses UV could be much faster, because the response times of electronic components such as photodiodes are much shorter. On the other hand, the time constants of current thermopile sensors are in the order of 20 ms, meaning that an IR-based system would have no speed advantage.

*FOVs.* With the exception of the most lateral pair, all FOVs are aligned along a single horizontal line, close to the equator. In particular, where FOVs of different neurons overlap at a given azimuth, there is no evidence that they differ in elevation. Thus, the assembly of L-neurons is spatially quite selective for a narrow half-panorama along the equator of the animal, forming a one-dimensional image of the forward and lateral horizon during level flight. This leaves no room for the extraction of the slope of an oblique horizon line, such as in the machine vision approach. Rather, the geometry is easily derived from the simple sensor in Fig. 2B, by just increasing the number of detectors and decreasing their FOVs, while keeping the optical axes pointed at the horizon. This, in turn, leads to the question as to what the advantages of a multiple-sensor arrangement might be. First of all, we expect that the sensitivity to small deviations from level attitude is larger than it can be for a wide-field sensor assembly: small deviations from level flight will cause large changes in light intensity in some of the sensors. Dragonflies are very skilled at hover and station-keeping, when accurate maintenance of attitude is particularly important. The geometry might also be the dragonfly's answer to the problem caused by the presence of the sun, particularly when the latter is close to the horizon. That situation will lead to serious

degradation of the accuracy of a set of a few wide-field detectors, but for multiple detectors it is straightforward to apply a simple rule whereby an extreme reading in a single channel is ignored.

However, dragonflies are also very skilled at aerobatic manoeuvres, involving frequent and large deviations from level flight. At first sight, it might appear that the multiple sensor array in Fig. 7 is subject to the major disadvantage that the horizon can be out of view of the sensors. This notion is the result of the convenient but misleading usage of a cylindrical projection to represent spherical data: in fact, any linear sensor array that covers 180° or more must intersect the horizon, as illustrated in Fig. 8. In the limit, for an array that consists of a large number of sensors with very small FOVs (thick lines in Fig. 8), only one sensor will point directly at the horizon (except for exactly level attitude (all sensors) or precisely pure pitch (both end sensors)) and all others will either look at sky or ground. The point of transition from one to the other represents the axis around which the equatorial plane of the flyer is tilted against the horizon. This means that the magnitude of the tilt is not known but its direction is, which might be sufficient for a coordinated correction. The fact that the FOVs extend over 180° but not more suggests that nothing much is gained by covering more: a full circle would intersect the horizon at two points that are 180° apart, meaning that knowing one is sufficient.

*The z-sensor.* The most lateral pair of L-neurons looks sideways and upward, in a direction that is normally occupied by sky. If either or both FOVs are exposed to ground, the attitude must be extreme, requiring a fast corrective manoeuvre. Human pilots are sometimes taught that, in response to losing control, the best survival strategy is first to correct roll attitude. It is interesting to observe that a supplier of mid-IR based attitude controllers for model aircraft offers a z-sensor that is intended for the same purpose.

*Connection to actuators.* Our analysis has not yet been extended beyond the outputs of the L-neurons. It is known, however<sup>19</sup>, that they connect directly to descending neurons. The descending neurons also receive inputs from other modalities (compound eyes, wind) and then drive the flight motor control system. The analysis of this part of the circuitry will be subject to further research.

Overall conclusion. The dragonfly has designed an elaborate matched filter for horizon detection and it is tempting to speculate that this is related to the dragonfly's lifestyle as a competent aerial predator. The design derives its credentials from the usual Darwinian/ biomimetics reasoning that it must be optimized because it is the result of a long evolution process. We believe that our system identification effort has now sufficiently advanced to warrant consideration for practical application in MAVs.



Figure 8. Examples of projections of a 180° wide linear array of sensors onto an equal-area grid, for 3 different extreme attitudes. Grey: part of viewsphere normally below horizon.

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