Motion Detection in Hexagonal Arrays of Insect Ommatidia

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Abstract

The photodetecting elements of the insect compound eyes (ommatidia) are often arranged in hexagonal arrays. We will show this hexagonal arrangement provides a computational efficient symmetric geometry for visual signal processing without needing for high-level processing. The geometric symmetry also allows additional computational efficiency for not only detecting visual gradients, but also movement velocity of visual objects. We proposed a computational model of a simplified circuitry for efficient processing of visual signals by neighboring cells that can be used to detect both visual gradients and motion detection with a flight escape reflex circuitry using a trigger threshold for critical motion velocity detection.

1. Introduction

Ommatidia are the photodetecting elements of compound eyes in insects, which are often arranged in hexagonal arrays. Unlike lensed eyes in vertebrates, the compound eyes are formed by ommatidia, which are basically light-guides fanned out in a hemispherical direction. Although no focused images are formed in the compound eyes, insects do have a hemispherical visual field provided by the converging light guided by the ommatidia light-guides. The angle of incidence of light is provided directly by the angle of the ommatidia, since they filter the light in a narrowly defined angle. The ommatidia arrays are often arranged in hexagonal lattice rather than rectilinear lattice, which we will show that the hexagonal symmetry will provide a geometric means for simplifying the computational efficiency of adjacent photodetecting elements for visual processing.

2. Hexagonal Geometric Symmetry

We will show that rectilinear (or octagonal) lattice arrays (e.g., Fig. 1B) of photodetecting elements will produce two sets of "center-to-center distances" between adjacent cells that are not equidistant to each other. Using a Cartesian coordinate to represent the rectilinear center-to-center distance between horizontal and vertical adjacent cells (in the x- and y- direction), the center-to-center distance between diagonally adjacent cells are not the same as the horizontal and vertical ones. Thus, in order to compute the visual gradient cast on adjacent cells, comparison of light intensity information of neighboring cells is needed. If the center-to-center distances were asymmetrical in the x-y vs. diagonal directions, it would require two different sets of parameters to compute the neighboring visual gradient information depending on the orientation of the visual stimuli. Thus, rectilinear lattice arrays are not computational efficient for processing visual gradient information that are orientation-dependent.

In contrast, hexagonal lattice arrays provide a set of symmetrical center-to-center distances that are equidistant in all visual orientation, including the diagonal neighbors (see Fig. 1A). Thus, hexagonal arrays provide a symmetrical geometrical arrangement for simplifying the processing circuitry for computing the visual gradient of neighboring cells with a single set of algorithm rather than two.

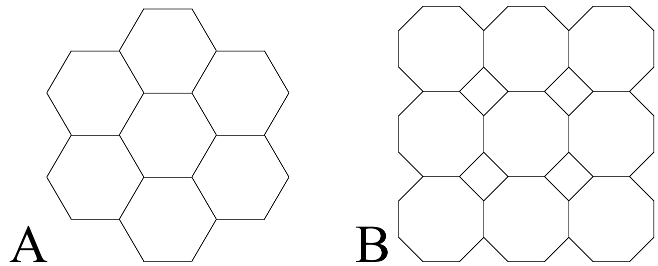

Figure 1. Diagram showing the differences between various hexagonal and rectilinear orthogonal array arrangements, with equidistant center-to-center distance for hexagonal arrays but two different equidistant center-to-center distances for rectilinear arrays depending on the visual orientation direction.

3. Visual Gradient Orientation Detection

The angle of orientation of the visual stimulus is defined by the light intensity gradient of the visual object. Thus, the visual orientation can be detected by computing the visual gradient of the neighboring photodetector cells. In order to compute the visual orientation, the light intensity of the adjacent cells can be compared. The visual gradient is simply the difference between the light intensity level of adjacent cells. Thus, having a hexagonal array provides symmetrical equidistance from center-to-center to its neighbor in all six directions. The second-order center-to-center distance is also equidistant to its second-order neighbors, filling in the orientation direction that is bisecting the first-order neighbors. This shows that hexagonal geometric arrays greatly simplify the visual gradient calculation by computing the light intensity difference between its first- and second-order neighbors.

4. Light Incident Angle Detection

The incident angle of a distant visual object can be approximated by the angle of the ommatidia detecting that light source. Since the ommatidia are arranged in a hemispherical dome, the location of the cells in the hexagonal lattice array is directly proportional to the incident angle of the light source. Thus, the incident angle of the light source is easily estimated by the geometry of the compound eye, simplifying the computational requirement of the visual processor without any high-level processing. This information can be used subsequently for the flight escape reflex response when the incident angle of the visual object (predator) is known. Furthermore, insects also rely on this incident angle of light source as a directional guide for their flight by assuming the direction of the sun is a constant for a given time. This provides the directional bearing for the insect to seek food or shelter.

5. Shadow Detection

With the incident angle and orientation angle of the visual object known relative to the insect's body, the next computational challenge for the insect is to compute the direction and velocity of moving visual object in order to escape from predation. Flying insects often escape from predation by a simple flight escape-reflex by detecting the direction of the moving shadow. When the velocity of moving shadow exceeds a minimal critical velocity, it will trigger an escape reflex to fly away from the direction of that moving object.

Computation of the moving shadow is directly dependent on the detection of the visual gradient and orientation of that object, thus, having a efficient algorithm for detecting the direction and velocity of predating moving shadows is essential for the survival of flying insects. The geometric symmetry of hexagonal array provides the needed simplicity for the neural circuit to provide local computation of light shadows.

6. Local Computation of Adjacent Neighbors for Detection of Shadow Movements

It has been known that motion detection in compound eyes can be computed based on the local difference of light intensity between adjacent neighboring cells [2, 4, 5] of the ommatidia [1] using lateral inhibitions [2, 3]. As shown above hexagonal array provides the ideal scheme for computing the light intensity difference of neighboring cell without the complexity of octagonal or rectilinear arrays. The 60º angle orientation can be computed by the first-order neighbors by subtracting the light intensity differences between them (see Fig. 1A). Finer angular orientation differences, such as 30º angles, can be computed using the second-order neighbors. This provides a simplified computational efficient method for symmetric computation using one set of computational algorithm, each having exactly six first-order neighbors and six second-order neighbors. The significance of this symmetric arrangement can be appreciated when the computation of light intensity difference between second-order and higher-order adjacent cells is required, especially the computation needed for finer angular orientation, and for computing velocity and acceleration (time-derivatives of second-order and third-order differences) of the moving target.

7. Computational Algorithms for Detecting Shadow Movements

The algorithm for detecting the direction of light movement is basically a "correspondence-problem" for light-level detection between neighboring cells. That is, when an object moves pass two adjacent-cells, it produces the same light intensity at the adjacent cells sequentially. The task essentially becomes the computation of time-delay between adjacent-cells that reach the same light-level at adjacent-cell pair. To provide a computational efficient method for light-level comparison of adjacent-cell**s**, a simple hardware circuit consisting of light-comparers and time-delay element can be used, which we will propose here.

8. Computational Efficient Circuitry using Light-Intensity Level Comparers

The computational efficient circuitry for comparing light-intensity difference of adjacent cells is as follows: Rather than using a complex circuit for comparing different levels of absolute light-intensity, a simple circuit for subtracting the light difference between adjacent cells is implemented. A "differencer" is used as the comparer of light intensity difference between neighboring cells.

If the difference is zero, the light level at the adjacent cells is the same, independent of the absolute light intensity level. This means that the light-comparer performs relative light-level comparison instead of comparing the absolute light-level values. This greatly simplifies the neural circuitry (or the complexity of physiological circuitry) for the compound eye.

9. Detection of Moving Visual Orientation Direction

The direction of moving object orientation can be estimated by the incremental (or decremental) light-level changes between adjacent cells. This value is derived simply by the positive (or negative) value resulted from the subtraction of the adjacent cell differences. Simply put, when the light-level difference is positive, the light-intensity is increasing; when the difference is negative, the adjacent intensity-level is decreasing.

10. Detection of Moving Visual Object Velocity

The circuitry for detecting the velocity of visual object is built by adding time-delay elements between the adjacent light-level comparers. The velocity of moving object is derived from the time it takes for the correspondence shadow cast through the adjacent cells, since the center-to-center distance between adjacent cells is equidistant in all six hexagonal directions.

The time-delay is inversely proportional to the velocity of movement for the equidistant adjacent cells. That is, if Δx = center-to-center distance between adjacent cells, and Δt = time difference, then the velocity, v, is

$$v = \frac{\Delta x}{\Delta t}$$

Since Δx = constant (equidistant for the center-to-center distance), therefore,

$$v = \frac{k}{\Delta t} \propto \frac{1}{\Delta t} \text{ where } k \text{ is a constant,}$$

then the velocity of shadow movement is inversely proportional to the time-delay difference between the adjacent cells reaching the corresponding light-intensity level.

11. Escape Reflex Implementation by Triggering on a Critical Velocity

Flying insects escape from predation by triggering the escape reflex that is dependent on establishing the critical velocity of visual object casting a shadow on the ommatidia. If the motion velocity of the moving object is too slow, it will not trigger the escape reflex in flying insects. In contrast, if the moving object exceeds the critical detection velocity, it will signal the potential danger to escape.

In order to implement a computational efficiency escape circuitry for evading predation, instead of establishing circuits for detecting various velocity-levels, a single critical triggering velocity is sufficient for the escape reflex. We predefined a preset critical velocity for triggering the escape reflex. This critical velocity detection is simply implemented by a critical fixed time-delay between the comparers of adjacent cells. When the visual object passes through the adjacent cells is less than this critical time-delay, the critical velocity is exceeded, and escape reflex will be triggered, otherwise, no escape is needed. This implementation greatly simplifies the escape circuitry needed by utilizing a set of time-delay elements and light-level difference comparer between adjacent cells.

12. Escape Direction Determination

Finally the direction of escape-flight needs to be determined if the insect is to escape successfully. The escape direction is simply the same direction as the visual object movement so that it moves away from the predator instead of toward the predator. The direction of the moving visual object (presumed predator) is determined by one comparer of the six adjacent cells in the hexagonal array that has reached the critical velocity of the escape response.

References

[1] Blum M, Labhart T. Photoreceptor visual fields, ommatidial array, and receptor axon projections in the polarisation-sensitive dorsal rim area of the cricket compound eye. J Comp Physiol [A] (2000) 186:119-128

[2] Coleman BD, Renninger GH. Theory of delayed lateral inhibition in the compound eye of limulus. Proc Natl Acad Sci U S A (1974) 71:2887-2891

[3] Laughlin S. A simple coding procedure enhances a neuron's information capacity. Z Naturforsch [C] (1981) 36:910-912

[4] Schultz AM, Wilcox MJ. Parallel image segmentation using the L4 network. Biomed Sci Instrum (1999) 35:117-121

[5] Srinivasan MV, Bernard GD. The effect of motion on visual acuity of the compound eye: a theoretical analysis. Vision Res (1975) 15:515-525

Biosketch

Dr. David C. Tam is an associate professor at the University of North Texas. He holds a Ph.D. in physiology, and three B.S. degrees in computer science, physics and astrophysics, all from the University of Minnesota. His current research projects are focused on deriving computational principles in autonomous decision-making process made in natural central nervous system (CNS) and artificial robotic systems, developing statistical multiple spike trains analysis techniques to decode the signal processing functions used in the CNS, and investigating the contribution of emotions for integrating sensory data into the behavior outputs.