Computational Efficient Circuitry for Detecting Shadows in Hexagonal Array of Compound Eye

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Summary

Abstract

Compound eyes in invertebrates are mostly arranged in hexagonal array for computational efficiency. Hexagonal arrangement provides geometric symmetry for efficient local computation of light-intensity level between adjacent ommatidia (photodetecting elements). Shadow motion detection circuitry for detecting critical velocity of light shadows for flight escape reflex is explored using a set of light-intensity comparers and time-delay circuitry. Motion of shadows is detected by comparing the light-intensity level between adjacent cells (ommatidia) using light-intensity difference comparers. Predation escape reflex is triggered by a critical velocity detector for shadow movements. Results show the time-delay local circuitry can be used in a hexagonal array to process local differences of light intensity efficiently for flight escape reflex in flying insects.

1. Introduction

Compound eyes of invertebrates (especially insects) are often arranged in hexagonal arrays to detect the direction of light source. The photodetecting elements of ommatidia (light sensing receptor cells) in the compound eyes are enclosed in a set of light-guides fanning out in a three-dimensional hemispheric direction. These light-guides limit a narrow incident angle of light received by the ommatidia for light direction detection. Thus, the compound eye arrangement is ideally suited for element detecting the incident angle of light sources.

2. Orientation Detection

Since the incident angle of the sun can be approximated as a constant at a given time independent of the distance traveled by an animal, the information provided by the incident angle of the light source can be used as the “compass” for spatial orientation without using earth’s magnetic field as directional guide. The 3-D directional bearing of the invertebrate can simply be mapped by the specific x-y coordinate of the ommatidium within the hexagonal array that is maximally stimulated because there is a one-to-one correspondence between the light direction and the hexagonal array element in the compound eye.

One of the interesting consequences of this orientation detect method for insects is that they tend to be “attracted” to the light source because of the assumption that the light source is a point source from the sun even at night when the light source is an electric light bulb rather than the point source of the sun at an infinite distance.

3. Light Shadow Detection

Given that the insect orientation can be deduced from the incident angle of the light source relative to the animal, the next computational challenge for insects is to compute the direction and velocity of moving shadows so they can escape from predation. It is well-known that insects, especially flying insects, can escape from predation by a simple escape reflex based on the direction of moving shadows. If the velocity of moving shadow exceeds a critical velocity, it triggers an escape response to fly away from the direction of that shadow.

Thus, a computational efficient method for detecting the direction and velocity of moving shadows is essential for the survival of flying insects. Hexagonal array arrangement of the compound eye provides the geometrical symmetry needed for local computation of light shadow cast between adjacent ommatidia.

4. Geometric Symmetry Considerations

Rectilinear (or octagonal) arrays are not suited for this purpose due to the fact that the center-to-center distance between neighboring cells are not equidistant from each other. In rectilinear array (using a Cartesian coordinate frame) the center-to-center distance between adjacent cells in the x and y direction is not the same as the center-to-center distance between diagonally adjacent cells.

In order to compute the movement direction of light shadows cast on adjacent cells, local comparison of light intensity information is needed. If the center-to-center distances are asymmetrical in the x-y and diagonal directions, it would require two different sets of local computational elements to process the neighboring light intensity information.

In contrast, since the center-to-center distance is equidistant in hexagonal arrays for all directions among its neighbors, including the diagonal neighbors (see Fig. 1), hexagonal arrays would provide the ideal geometrical arrangement for simplified computation of local light intensity differences with a single set of algorithm rather than two.

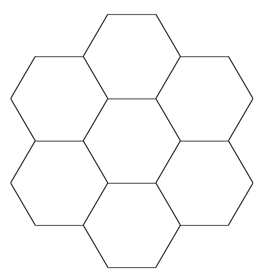

Figure 1. Diagram showing the geometric symmetry of center-to-center distant for hexagonal and rectilinear arrays.

5. Adjacent Neighbor Local Computation for Detection of Light Shadow Movements

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].

Hexagonal array provides the best candidate for contagious neighboring cell computation of local light intensity difference between adjacent cells without the complexity of an octagonal rectilinear array. The first-order computation of light intensity differences can be computed using the contagious neighboring cells at 60º angles (see Fig. 1).

Using this hexagonal configuration, finer angular differences, such as 30º angles, can be obtained using the second-order adjacent cells. Thus, this provides a means for symmetric computation using one set of computational algorithm, each having exactly 6 contagious neighbors.

The significance of this symmetrical geometry arrangement can be appreciated when the computation of light intensity difference between second-order and higher-order adjacent cells is required, such as the computation needed for finer angular increments, and velocity and acceleration computation (time-derivatives of second-order and third-order differences).

These geometric constraints have significance in the physical implementation and packing of ommatidium in the compound eyes that require local computation involving adjacent neighboring cells.

5. Algorithms for Performing Local Computation of Light Shadow Movements

Detection of light movement direction is essentially a "correspondence-problem" for light-level detection between adjacent array elements. In other words, when an object moves pass two adjacent-cells, it would produce the same light intensity at the adjacent cells sequentially. The task of the adjacent-cell computation is to determine the time-delay for the same light-level to reach the adjacent-cell pair. In order to provide a computational efficient method for adjacent-cell light-level comparison, a simple hardware circuit consisting of light-comparers and time-delay element can be used.

6. Light-Intensity Level Comparer

One of the most efficient design of the light-comparer is as follows: Instead of using a complex circuit for comparing different levels of absolute light-intensity, a simple circuit for subtracting the light difference between adjacent cells can be used. In other words, a "differencer" is used as the comparer. If the difference is zero, the light level at the adjacent cells is the same, independent of the absolute light intensity level. In other words, the light-comparer performs relative light-level comparison instead of comparing the absolute light-level values. This simplifies the hardware circuitry (or the complexity of physiological circuitry) for the compound eye.

7. Directional Light Increment/Decrement Detection

Furthermore, the direction of incremental/decremental light-level changes between adjacent cells can be derived simply by the positive/negative value resulted from the subtraction. Thus, when the light-level difference is positive, the light-intensity is increasing. When the difference is negative, the adjacent intensity-level is decreasing.

8. Light Shadow Movement Velocity Detection

The velocity of light shadow can be computed by adding time-delay elements between the adjacent light-level comparers. Since the center-to-center distance between adjacent cells is equidistant in all 6 hexagonal directions, the velocity of shadow can be derived from the time it takes for the correspondence shadow cast through the adjacent cells. 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,

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

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

9. Critical Velocity Detection for Triggering Escape Reflex

In order for the flying insects to escape from predation, the escape reflex is dependent on establishing the critical velocity of light shadow for escape-flights. Slow moving objects often do not trigger the escape reflex in flying insects, whereas fast moving objects signal the potential danger to escape. For computational efficiency, instead of establishing circuits for detecting various velocity-levels, detecting a single critical triggering velocity is sufficient for the escape reflex. In other words, a preset critical velocity is used for triggering the escape reflex. In this case, this critical velocity can simply be translated to a critical fixed time-delay between the comparers of adjacent cells. If the shadow passing through the adjacent cells is less than this critical time-delay, escape reflex is triggered. Otherwise, no escape is needed.

This implementation simplifies the escape circuitry to a set of time-delay elements and light-level difference comparer between adjacent cells.

10. Light Shadow Movement Direction Detection

In order for the insect to escape successfully, the direction of escape-flight needs to be determined, which is simply the same direction as the shadow movement so as to move away from the predator (rather than toward the predator). The direction of the shadow movement can simply be detected by determining which one comparer of the six adjacent cells in the hexagonal array has reached critical velocity of the shadow movement.

11. Implementation of the Light Detection Circuitry

We implemented this computationally efficient light-detection circuitry algorithmically to test the efficiency of the flight escape reflex. Results have shown that light shadow direction and velocity detection can be implemented efficiently using a minimal set of detecting elements based on the hexagonal geometric symmetry, difference-comparers and time-delay circuitry.

References

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