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VLSI Implementation of Bio-Inspired Elementary Motion Detector

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ABSTRACT: Compound eyes of insects gives a wide field of view, quick motion detection and sensitivity to variations of light. With little to none distortion, they accurately perceive shapes and distances which are crucial for things like flight. Some insects can even detect polarized light which in turn aids in navigation and communication. Overall, these eyes are tools which help insects to survive in various environments.

Insects detect light through their compound eyes, which consist of a lot of ommatidia, each of which have photoreceptor cells. These cells are sensitive to changes in the intensity of light and wavelength. When light enters the compound eye, it lands on the photoreceptor cells, causing a cascade of biochemical reactions which gives electrical signals. These signals are then processed by the insect's nervous system, allowing it to perceive visual information.

Elementary motion detection is the brain's ability to perceive and respond to objects in motion in its visual field. Starting from the retina, where changes in light intensity are found, signals are sent to specialized neurons which analyze direction, speed, and trajectory. In insects, this process is finely tuned which helps in tasks like avoiding predators and capturing preys. By rapidly detecting motion, organisms can make quick decisions important for survival in dynamic environments.

Compound eyes are excellent in detecting elementary motion because of their sophisticated structure. With numerous ommatidia, each having photoreceptor cells, insects can see movement across a broad field of view simultaneously. This lets them have rapid comparison of visual inputs, allowing swift detection and tracking of moving objects. The redundancy in ommatidia ensures reliability even if some units are damaged, enhancing motion detection in varied conditions. This capability is vital for tasks like predator evasion and prey capture, underscoring the compound eye's effectiveness in ensuring insect survival.

KEYWORDS: Compound eyes, ommatidia, photoreceptor cells, Elementary motion detection.

I. INTRODUCTION

Biological systems, especially the complex nature of for a long time. Despite their small size, insects are very good at perception and navigation, thanks to their very efficient sensory organs and neuroelectric systems. There are two types of eyes in insects: straightforward and complex. The compound eye is unique because it contains a variety of ommatidia, each of which functions as a separate functional unit.

Insects have a smaller cerebral capacity than vertebrates. It controls the insect's behaviour, coordinating intricate metabolic processes and sensory perception. Despite its tiny size, the insect's brain can remarkably analyse sensory information and guide behaviour with remarkable accuracy.

A fundamental feature of biological vision systems is motion detection, which enables organisms to navigate their environment and react effectively to stimuli. This project aims to develop and implement a VLSI-based elementary motion detector using the biomimicry approach, inspired by insect vision systems' remarkable efficiency and robustness. Motion detection, which allows organisms to move through their environment and respond efficiently to stimuli, is a fundamental feature of biology vision systems. Inspired by insect vision systems' remarkable efficiency and robustness, this project is aimed at developing and implementing a VLSI Based Primary Motion Detector using the Biomimicry Approach.

The main objective of this project is to develop and introduce a bioinspired motion detection system that can detect movement in the vicinity of neighbouring ommatidia, i.e. an artificial mechanism for detecting movements similar to those found in nature's compound eyes. The system aims to achieve directionally selective motion detection, enabling the detection of motion patterns in the visual field, by combining the output of the photoreceptors and using delayed signals.

We're inspired by the ingenious motion-sensing mechanisms used by insects when we look for biomimetics. We're replicating the insect's ability to detect the direction of the moving objects by using the timestamps to estimate the time of travel. We reveal information on time motion dynamics and demonstrate how slow objects linger in the sensory field, by calculating differences between neighbouring timing values.

Insects are adept at navigating the complex environment, sensing obstacles, and tracking a route with accuracy by analyzing visible motion in visual features. In modern autonomous systems, such as drones, where agile and obstacle-aware flight control is essential for safe and efficient operation, this technology is found to be applicable.

The proposed system uses the principles of elementary motion detectors, called EMDs, which compute movement by correlation with other photoreceptor's outputs. The response of the EMD is directionally selective, indicating either leftward or rightward motion. Full spatial motion can be detected when the responses of several EMDs are integrated. To detect the time change in visual input and to generate output signals indicating a direction of motion, the system relies on High Threshold Filters and Delayed Signal Processing.

Several applications, ranging from robotics to monitoring the environment, have great potential for convergence between biologically inspired sensor approaches and cutting-edge VLSI implementation. We aim at opening new frontiers of motion sensing and navigation, as well as laying the foundation for developing agile and adaptive systems through our examination of insect neurobiology and sensorimotor perception.

Circuit mechanism underlying chromatic encoding in drosophila photoreceptors:

Colour vision in insects is obtained by comparing the two photoreceptors' output of different spectral sensitivities. In drosophila colour vision and colour opponent signals are measured at the terminals of axons which are cone-like photoreceptors. These are light-sensing rhabdomeres of photoreceptors R7 and R8 on top of one another. Photons emanating from the same point in visual space are absorbed by the photoreceptors in the optical unit or ommatidium. The colour opponent signals are generated through the reciprocal inhibition between the pairs of R7 and R8.

There are 2 types of ommatidium, pale and yellow ommatidium. Pale ommatidium exhibit short UV-sensitive rh43 rhodopsin in R7 and long UV-sensitive rh4 rhodopsin in R7 and R6 green sensitive in R8.

R8 photoreceptors from single ommatidium. Specific and distinct wavelength opponents are displayed by photoreceptors R7 and R8.

II. RESEARCH GAP

The Hassenstein-Reichardt or correlational elementary motion detector (EMD) has been thoroughly researched in the context of motion perception in both biological systems and artificial vision systems. However, there are still significant research gaps that require attention.

There is a significant gap in understanding how EMDs function under varying environmental conditions and a need for more research into the neural implementation and plasticity of EMDs in biological systems. Another one is integrating EMD models with other sensory modalities and higher-level cognitive processes is a crucial area for further study. This integration will lead to a more comprehensive understanding of motion detection and its applications in robotics and artificial intelligence.

III. BLOCK DIAGRAM

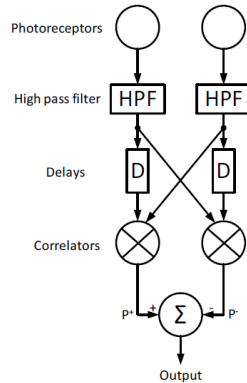


Fig. 1: The Hassenstein-Richardt or correlational elementary motion detector (EMD)

3.1 WORKING

The EMD has photoreceptors, high pass filters (HPFs), delay units (LPF), and correlators. All of these components together work to estimate the motion of a moving object or feature going through the two neighbouring photoreceptor cells.

An object moves between two photoreceptors, generating a noticeable temporal change that is detected by an HPF and effectively delayed with a constant of time. The delayed output of every HPF is correlated with the HPF output of the cell which is its neighbour; thus, each correlator generates an output when an object moves in a particular direction.

3.2 PHOTORECEPTORS

Artificial photoreceptors emulate the natural phototransduction process by transforming light into electrical signals through the absorption of photons by their light-sensitive materials.

Insects primarily use their compound eyes and ocelli as their main photoreceptive structures, enabling them to perceive and react to light. They transform light into electrical signals that the nervous system can interpret, allowing Insects to experience vision.

3.3 HIGH PASS FILTER

A High Pass Filter (HPF) isolates high-frequency motion components, filters out low-frequency noise, and enhances the accuracy of motion detection algorithms by emphasizing rapid changes in pixel intensity over time. This allows systems to effectively identify and track moving objects while disregarding static elements and environmental disturbances.

In insect vision, the medulla acts as an HPF, receiving visual input from photoreceptor cells to detect motion.

3.4 DELAY UNIT (LPF)

A Low Pass Filter (LPF) delays by smoothing out rapid changes in pixel intensity, reducing noise and transient fluctuations. This enhances the reliability of motion detection algorithms for accurate identification and tracking of moving objects in dynamic visual environments.

The lobule plate in the insect vision system acts as a low-pass filter (LPF), integrating visual information in the optic lobe to smooth out rapid changes in pixel intensity.

3.5 CORRELATOR

Cross-correlation is a technique used in elementary motion detection to compare successive frames of a video or image sequence, helping to detect motion by identifying shifts or displacements between the frames. In insects, the lobula complex functions like cross-correlation, comparing visual inputs from neighbouring photoreceptor cells to detect motion and help insects respond quickly to moving objects.

3.6 SUMMING UNIT

In an EMD calculates the output of the 2 cross-correlators of two neighbouring cells. In insects, the lamina combines visual signals from compound eyes' photoreceptor cells, enhancing brightness perception and facilitating the detection of changes, including motion, in the visual environment.

IV. SYSTEM LEVEL SIMULATION REQUIREMENTS

The MATLAB flow follows a sequential structure, starting from the photoreceptor and progressing to the tangential cell. This approach helps us understand the entire process, including algorithm development, simulation, and verification. The diagram below depicts this flow.

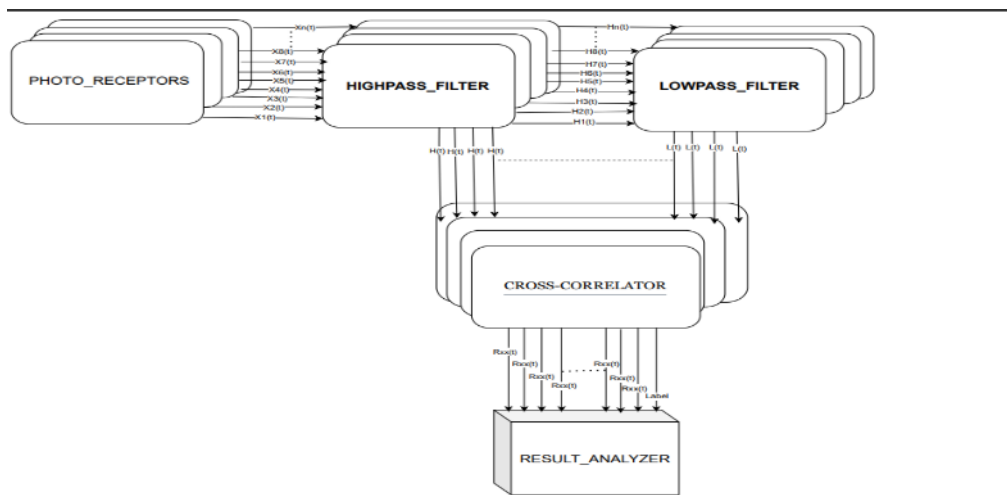


Fig 2: MATLAB Flow

4.1 PHOTO_RECEPTORS

This system functions like the retina. It captures temporal information from the environment by a hexagonal array to create a Region of Interest (ROI). The hexagonal size is 20-40 μm . The frame is captured at a rate of 0.001 seconds and converted into an RGB matrix. The red channel is removed because insects can only perceive green and blue colours.

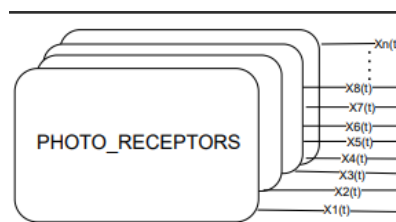


Fig 3: N*M matrix of photoreceptors

This process utilizes 8-bit encoding for the intensity range between 0-225, with the assistance of Lipetz transformation [26]

$$U = \frac{I^a}{I^a + I_0^a}$$

Where I is the intensity, \$I_0\$ mid reference, a (0.5-1) and U is the output, where for the insect a to 0.5, \$I_0\$ (0 to 10), the equation approximates log-linear response over the input dynamic data.

4.2 HIGHPASS FILTER

It receives input from the normalized photoreceptor and mimics the lamina cell region. Its main goal is to improve temporal information to detect smooth motion. We have created a second-order filter with a corner frequency of 0.4 Hz [3]. The transfer function is described as:

$$TF[s] = \frac{0.0253s^2}{0.0253s^2 + 0.4775s + 1}$$



Fig 4: High Pass Filter

The above transfer function with a specification zero [0 0], poles [186.6172, -2.118] the system is stable.

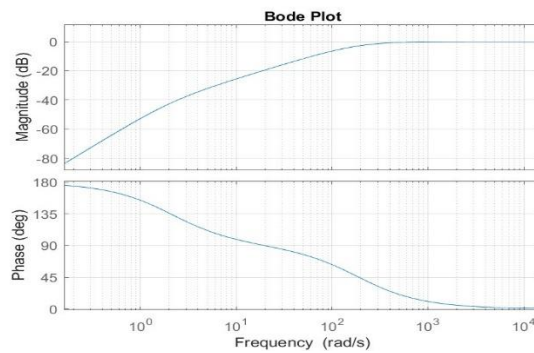


Fig 5: Bode and Phase plot

4.3 DELAY UNIT:

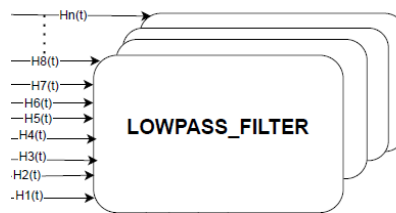


Fig 6: Low Pass Filter

It acts as a delay module but reduces the roll-off through the RC delay. It captures the temporal information signal when the capacitor begins charging. Once it reaches its peak value, it discharges based on the RC value. We created a first-order filter with a corner frequency of 40Hz [3], and the transfer function is described by:

$$TF[s] = \frac{1}{125.663s + 1}$$

The above transfer function with a specification zero [NAN], poles [-0.008] the system is stable.

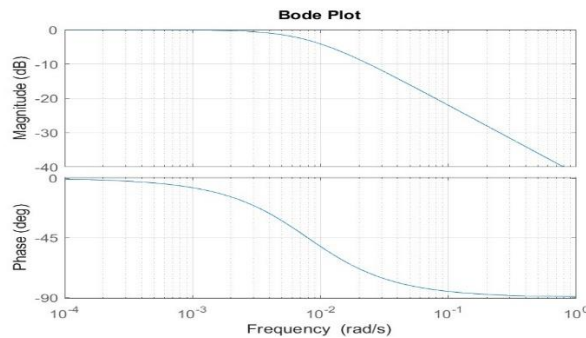


Fig 7: Bode and Phase plot

4.4 CROSS-CORRELATOR

This component acts like a lobule, it takes the input from the high-pass & low-pass filters. This component multiplies the delayed and undelayed temporal signal to give the directional and unidirectional polarisation based on the region and distance of ROI.

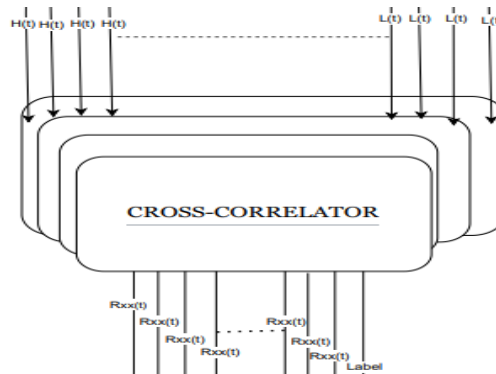


Fig 8: Cross-Correlator

V. RESULT & DISCUSSIONS

The verification of the HR model for operation In this project, we utilised MATLAB to simulate and evaluate the performance of our VLSI design. MATLAB is a robust tool for conducting in-depth modelling, simulation, and analysis of complex systems. This section provides an overview of the simulation setup, encompassing the test case and ideal case scenarios.

5.1 IDEAL CASE SIMULATION

In this, the model is given for the ideal condition of constant ambient light, and velocity, and limits the motion direction to dx, dy 1-d motion, where the point object starts the motion from some random position in the defined 2X4 hexagonal array as in Fig (9) the motion started from hexagonal structure (2,1) cell to (2,4) cell.

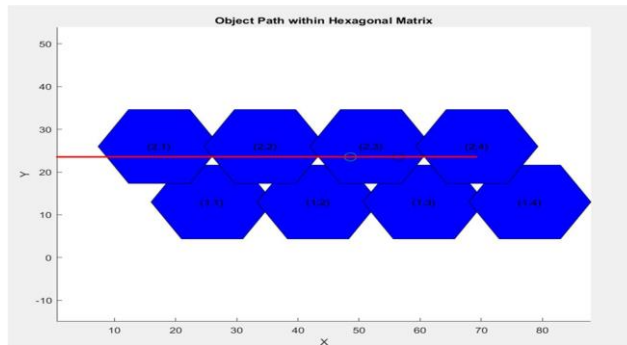


Fig 9: Object path tracking within the hexagonal structure

Figure b presents a pictorial representation of the intensity distribution of pixels inside the studied cells. The x-axis indicates the range of intensity values from 0 through 255, and the y axis shows how frequent each intensity value is.

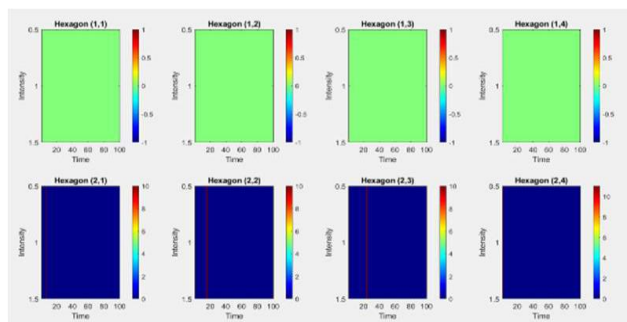


Fig 10: Intensity plot of each photoreceptor

This indicates there are two unique cell characteristics within the sample, possibly related to different biological marks. The vast array of intensity values and high peaks indicate a diverse sample with considerable disparity in cell composition. In this study, a Simulink model was devised to simulate the spread of intensity of data signals among various cell elements utilizing sub-blockages, each illustrating an H-R model. The input signal, outlined in MATLAB, was transported into the Simulink model utilizing a 'From Workspace' butter, ensuring precise representation of signals. Each sub-blockage, conceived as a substructure, enclosed the essential H-R blueprint equations, enabling the intricate simulation of ion channel dynamics and various other cellular compartments. The interconnected sub-blocks successfully modelled the movement and allocation of the input signal through the system. Visualizations of simulation results were executed utilizing 'Scope' butter, offering insights into the dynamic reaction and intensity fluctuations within the cellular model. This strategy highlights the potential of Simulink in modelling complicated biological systems and assessing the allocation of data signals in a structured and organized style.

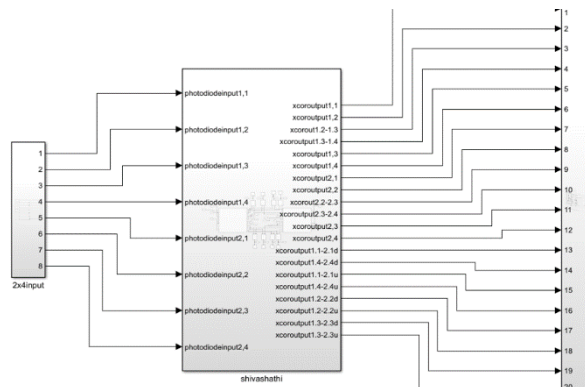


Fig 11: Simulink module

Fig (12) model's output permitted us to visualize and analyse the movie direction of the cellular components. This process demonstrates how Excel and Simulink can be effectively combined to model, simulate, and interpret complex biological systems, providing valuable insights into the dynamic behaviours and characteristics of the modelling objects. The successful extract and plotting of Simulink model's output from cell (2,1) to (2,4) allow us to visual and analyze the motion direction indicated by signal 1. This process demonstrates how MATLAB and Simulink can effectively combine for model, simulate, and interpret complex biological system, provide value insight into dynamic behaviour's and characteristic for model entities. By focusing on certain cells, we can understand detail of phenomena localised and their contribution to system behaviour overall.

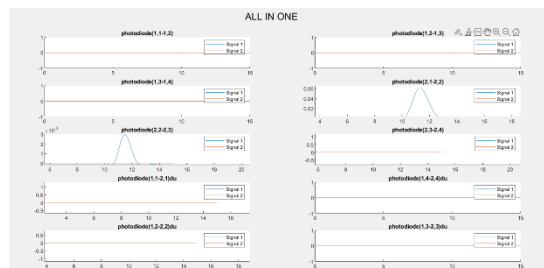


Fig 12: Correlator output

VI. CONCLUSION

The creation of an VLSI Implementation of Bio-Inspired Elementary Motion Detector marks an advancement within the Bio-medical and robotics sector. Using MATLAB and Simulink, this system effectively demonstrates the practical application of the EMD, a powerful neural model that precisely mimics the motion detection abilities found in the visual systems of flying insects. It correlates signals from neighbouring photoreceptor cells to accurately estimate the magnitude and direction of motion between these cells. The EMD model is very important in the development of bio-inspired optic flow sensors for MAVs. It serves as a biologically inspired process that efficiently detects motion, making it best suited for the constraints of small aerial vehicles. By leveraging the EMD model, researchers and engineers can design optic flow sensors that not only mimic biological processes but also offer practical and effective solutions for motion detection in the context of MAVs. This approach not only enhances the capabilities of small aerial vehicles but also opens up new possibilities for their applications in various fields, including surveillance, environmental monitoring, and search and rescue operations.

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