Future Directions for Motion Detection Based on the Parallel Computational Intelligence of Insects.

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Abstract

The visual system of insects consists of distributed neural processing, inherent parallelism and fuzzy collision avoidance algorithms. This forms the basis for artificial vision systems that exploit these computational intelligence schemes for anti-collision tasks. Insects tend to detect motion rather than images and this together with the parallelism in their visual architecture, leads to an efficient and compact means of collision avoidance. A family of VLSI smart microsensors that mimic the early visual processing stage in insects has been developed. The system employs the 'smart sensor' paradigm in that the detectors and processing circuitry are integrated on one chip. The IC is ideal for motion detection, particularly collision avoidance tasks, as it essentially detects the speed, bearing and time-to-impact of a moving object. Fuzzy algorithms may then be employed for decision making. The Horridge model for insect vision has been directly mapped into VLSI and therefore the IC truly exploits the beauty of nature in that the insect eye is so compact with parallel processing, enabling compact motion detection without the computational overhead of intensive imaging, full image extraction and interpretation. This world-first has exciting applications in areas such as anti-collision for automobiles and autonomous robots. The status and future directions of this work are outlined.

1. Introduction

For collision avoidance tasks, where full imaging is uneccessary, simple motion detection of object boundaries offers an efficient solution. A world-first single-chip device, based on insect vision principles, has been developed [1, 2, 3, 4, 5, 6] that outputs the time-to-impact, bearing and velocity of a detected object. The processing power of a commercial microcontroller is then sufficient for making decisions based only on such simple variables.

The insect vision model we have adopted is that of Horridge [7, 8], which is named the 'template model.' This model is motivated by the desire to produce signals which can be readily interpreted by digital systems, and hence readily lends itself for mapping onto a VLSI chip. The edge of an object presenting a difference in contrast with the background, and moving in front of an array of receptors, elicits distinctive patterns of contrast changes which are consistent with the direction of motion. The receptor outputs are sampled and compared with their previous values, yielding signals which locally indicate an increase, decrease, or no change in contrast. The combination of two adjacent receptor responses at consecutive sampling times form a 'template,' and hence, since there are three possible receptor responses. there are 81 possible templates. The VLSI implementation and detailed description of this scheme is described elsewhere.

In this paper, we firstly review the template model and compare this with the biological insect eye architecture. We then proceed to discuss some of the implementation problems, developments that have occurred to solve them and the future vision.

2. Overview of insect vision

Insects, compared to humans, possess a relatively simple visual system, yet are capable of performing complex visual tasks. The insect visual system has a highly parallel structure – the visual ganglia in the optic lobes are organised into columns and strata. The lamina is the first optic ganglion and contains a large number of identical channels. The photoreceptors, in the retina, sample the visual field and

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perform adaptation using a gain control mechanism for efficient operation in varying light conditions. The role of the large monopolar cells, the main output cells of the lamina, is coding of contrast to enable vision with large variation in background intensity.

Conventional robotics systems often utilise measurements such as range and velocity which require further interpretation in order to determine a course of action. In contrast, insect vision provides readily interpreted visual information, or 'percepts,' which are represented qualitatively (eg. obstacles are 'close,' 'moving fast,' or 'looming') instead of being expressed in terms of precise metric measurements. This implies that the approach to designing the control structure of an insect vision based system should differ from traditional computational schemes, where sensing and control are clearly distinct.

In fact, it appears that in some biological species, sensors and motor control are directly linked, at least at a low level, as exemplified by the insect's optomotor response [9]. For instance, the response observed in a number of insect species is generally in a different direction from that of the detected pattern motion [10, 11], while guard bees seem to control a stable "hovering" position by responding to the small positional changes of a fixated pattern [12]. Moreover, psychophysical evidence suggests that primates may extract heading direction and depth information simultaneously [13].

Finally, many species, including humans, make use of the rate of expansion of an object relative to the visual receptor to estimate the time-to-impact. Mathematically, the time-to-impact is a function of the ratio of the angle subtended at the receptor by an object, to the rate of increase of that angle. Experimental studies (eg. [14, 15]) suggest that channels of the visual pathways are sensitive to this 'looming' effect. Considering that neither the receptor's motion nor the distance between the observer and the object are known, the result is quite remarkable, as it can be utilised directly by collision avoidance mechanisms. However, it should be pointed out that it is unclear if the collision avoidance mechanism is itself triggered by the time-to-impact having decreased to a particular value. In fact, experimental studies on locusts show that the insect may alter its flight path when an obstacle subtends more than ten degrees of the field of view, apparently irrespective of the time-to-impact [16]. This is the most rudimentary example of fuzzy-logic algorithm for collision avoidance.

3. Insect vision model

The advantage of a smart-sensor that can mimic insect vision is that the image processing is simplified and can be integrated on the detector chip, creating a compact device ideal for mobile applications. In addition, insects operate

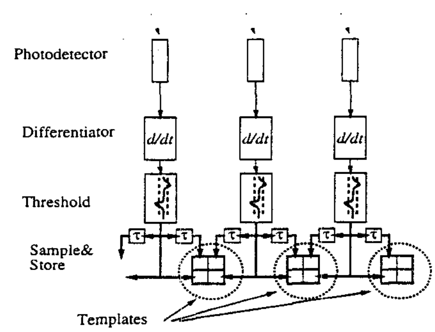

Figure 1. Template model functional blocks

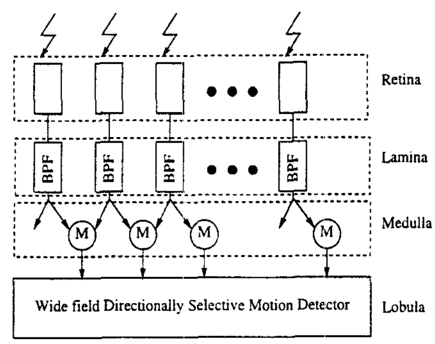

Figure 2. Simplified model of the insect visual system

with no iris action or focusing adjustment required – this is also a feature of the developed sensor – leading to a truly solid-state vision system. Such simplicity is an important factor for high-volume robotic/automotive applications.

The chip accepts a real-time optical image and indicates the motion of edges in the visual field. ¿From the outputs of the chip, we can infer the bearing, time-to-impact, and speed of objects in the visual environment.

Fig. 1 shows the concept of the Template Model. Light is detected by photoreceptors, a temporal differentiation of the signal takes place, the signal is thresholded and then two samples (separated in time by τ) are combined with those of an adjacent channel to form a 2 by 2 spatio-temporal template.

On the other hand, Fig. 2 shows a schematic representation of the biological architecture of insect vision. The photodetection layer is called the retina and the individual segments of the compound eye are called ommatidia. The next layer is called the lamina and this performs a band pass filter (BPF) function to select higher frequencies or alternatively it can more simply be a high pass filter (HPF). This function can be thought of as a coarse temporal differentiation – when a signal is differentiated it is the high frequency edges that are passed through. Hence, in the Horridge model this is represented as a differentiator. The purpose of this stage is to detect temporal changes in contrast (motion). The next layer, called the medulla, detects changes between adjacent ommatidia – hence local motion is detected. The Horridge model does the same, however, makes a departure from biology, at this point, by considering digitally thresholded data. The final lobula layer represents the 'intelligence' and this analyses the local contrast changes and decides more globally whether motion has taken place over a wider field. This section is not dealt with in the template model. The template model only goes as far as the medulla.

In our physical VLSI implementation, the receptors are simply p-well/n-epi junction photodetectors. Light is focussed by means of a GRIN lens and the photocurrent is converted to a voltage by a subthreshold circuit technique that guarantees a logarithmic photoresponse. The logarithmic response to light intensity allows us to dispense with the need for an iris, which is not present in insect vision and is not specifically addressed by the template model. This function can be regarded as an auto gain control (AGC) mechanism.

Temporal differentiation is physically achieved by an operational transconductance amplifier (OTA) based differentiator. The time constants required to mimic insect vision are in the order of 10 ms. Thus to avoid the problem of a large capacitance area for the differentiator, it turns out that a feedback resistance in the order of 1 Giga-Ohm is required! This creates quite a design challenge and a number of active resistor configurations have been tried, including one based on the channel length modulation effect.

The next stage is template formation where the signal is simply thresholded, sampled and stored, and hence a template consists of the current and and stored outputs of adjacent channels. The chosen sampling rate is in the order of a 100 Hz, which is adequate for analog VLSI, and also comparable with the fastest time constant of insect motion detection neurons [17].

After the templates are formed, they are simply matched (hence the name 'template') against a look up table to interpret the direction of motion locally to the receptors that generated that template.

The next stage is to perform the function of the lobula and interpret the local motion information to select an overall motion over a wider field. Here the Horridge model stops and does not deal with this issue. The way we physically extract overall motion information from clusters of templates is basically via software control of an external microcontroller. The insect vision chip loads template information into an external memory and an off-the-shelf microcontroller performs various 'template tracking' algorithms to extract the bearing, speed and time-to-impact of an approaching object [18, 19, 20, 21].

The comparison between the biological insect eye architecture, the template model and our physical IC implementation, in terms of required function is summarised in Table. 1.

4. Status and future directions

Table 2 indicates the chronological development and future vision for our insect vision chip dubbed the 'bugeye.' Bugeye I of 1992 vintage [1, 23, 24] was the first design for proof-of-concept and it contained both analog and digital circuitry. The signal was differentiated for detecting changes in contrast. It successfully operated with bearing, velocity and time-to-impact being successfully extracted from the template output. However, the drawback was that it only worked under DC light sources.

The Bugeye II redesign [22] produced a chip with improved dynamic range and contained a multiplicative noise cancellation circuit (MNC) [25]. The digital sections of the chip were discarded in favour of an external microcontroller. The analog differentiator circuitry and thresholding circuitry were implemented. The MNC circuit allowed the chip to successfully operate under AC lighting conditions. The principle of MNC is to simply divide the signal in each channel by the spatial average over a number of channels. The circuit is designed so the averages over 3, 5 or 7 channels can be externally selected. As the detected signal luminance L is simply a function of the reflectance of an object ρ *times* the illuminance of the incident light E, division by the spatial average cancels the E terms (containing the unwanted AC noise component), resulting in a simple ratio of reflectances or *contrast ratio*. This has three benefits: (1) reduction in the effect of the 50 Hz or 60 Hz hum from AC light sources, (2) a data compression due a simple contrast ratio figure producing numbers close to unity and (3) and edge enhancement due to a reduction in spatial average near the edges.

The Bugeye III, designed in 1995, contained a truly 2 dimensional array of detectors. AGC occurred at every node by virtue of logarithmic compression due to subthreshold photodetector circuits at every node, however differentiation was carried out sequentially. This was achieved by clocking the signal out of the device as in conventional 2D arrays. An on-chip 8-bit A/D converter enabled differentiation to occur off-chip in the digital domain. The move towards digital processing was to address the limitations

Function	Biological Model	Template Model	Physical/VLSI Implementation
Photodetection	Retina (ommatidia)	Receptor	• pn junction photodiode • GRIN lens • Subthreshold I-V converter (logarithmic AGC)
Temporal Contrast Change Detection	Lamina (BPF)	Temporal differentiator	OTA differentiator
Local Motion Detection	Medula	Template formation	Thresholding, sample and store circuitry
Wide Field Motion Detection	Lobula	N/A	Template tracking – software control via microcontroller

Table 1. Comparison of IC implementation with biological and template models.

imposed by analog circuitry – particularly susceptibility to noise.

Bugeye IV [26], designed in 1996, is a 64 by 4 array with analog differentiators, thresholding and digital storage. The differentiator design was selected as the best from a test chip containing 17 different designs. Results showed that the injection of digital noise into the analog sections of the chip, is an area needing further attention.

The 1996 MNCSI (Multiplicative Noise Cancellation and Shunting Inhibition) chip was essentially a test chip containing a number of MNC and SI circuit variations. However, it also contained a plain 64 by 6 pixel test array without any on-chip processing. Template patterns were successfully produced via off-chip digitisation. The move back to 2 μm CMOS saved costs and was found to be adequate for our application.

Bugeye V (1997) contains a 64 by 4 array with MNC and a 64 by 8 array without MNC. Both arrays incorporate full differentiation, thresholding and template formation. Differentiation is switchable between analog or 8-bit digitised modes. This will enable us to carefully compare the analog versus digital approach. In addition the motion templates are formed on chip and displayed with image. Thus, the output of the chip is an image of the scene and a second image displaying motion information. Each pixel in the motion image indicates the presence or absence of motion in that particular pixel and the direction of motion (leftward or rightward).

Future directions will be to explore an array of a larger size and perhaps exploit the qualities BiCMOS, if an analog approach is deemed superior. A proof-of-concept chip in GaAs, in a conventional E/D MESFET process or newly emerging complimentary GaAs process will enable us to exploit the superior photocollection efficiency in GaAs and provide better analog/digital isolation via the semi-insulating substrate. The use of GaAs HIGFET gates may

Version	Pixels	Technology	Year
Bugeye I	64 by 1	2μm CMOS	1992
Bugeye II	64 by 2	1.2μm CMOS	1994
Bugeye III	64 by 32	0.8μm CMOS	1995
Bugeye IV	64 by 4	0.8μm CMOS	1996
MNCSI	64 by 6	2μm CMOS	1996
Bugeye V	64 by 8/4	2μm CMOS	1997

Table 2. Evolution of 'bugeye' insect vision chip

provide a convenient high resistance for analog differentiation.

In order to minimise design risks, it was deemed preferable at the start to employ a 'stable' and well-behaved technology, and so far each IC has been fabricated in CMOS. However recent developments indicate that GaAs may eventually become a viable alternative to CMOS [6].

In addition to developing better circuits, the optical interface should not be neglected. The GRIN lens that was used earlier imposes certain restrictions on the design. This lens has been replaced by another small lens which is held by a mechanical apparatus in front of the chip. However, better performance may be obtained using a relatively new technology, called 'binary optics,'; this technology is beginning to be successfully employed in other domains. The technology consists of integrating tiny microlenses on the surface of the IC.

Further developments include extension of the insect vision chip concept to the IR band and even the mm-wave band to improve poor weather performance. This requires essentially a change of the front-end technology, but the processing principles remain essentially the same. With mm-techniques, low-cost is the main issue – consequently passive antenna arrays on alumina, with simple Schottky diode detector circuits, will be initially investigated at 37 GHz, with eventual extension to 94 GHz.

5. Conclusion

We have reviewed our physical IC implementation of a motion detector, based on the template model, and have carefully outlined each function with reference to the biological architecture of insect vision.

The first chip contained a linear array of 60 photodetectors. A second generation of this device contained 60 by 2 detectors and multiplicative noise cancellation (MNC) to reduce the effects of hum from AC lighting, producing edge enhancement and carrying out a form data compression. Future work will extend the present concept to a full 2-D array and will exploit the many advantages of a gallium arsenide implementation, binary optics. Investigation of a front-end for IR or mm-wave detection also looks promising for enhancing poor weather performance.

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