A new VLSI smart sensor for collision avoidance inspired by insect vision

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ABSTRACT

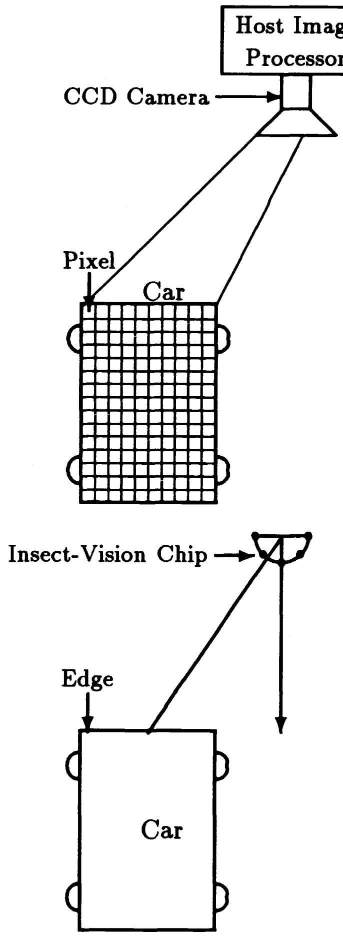
An analog VLSI implementation of a smart microsensor that mimics the early visual processing stage in insects is described with an emphasis on the overall concept and the front-end detection. The system employs the 'smart sensor' paradigm in that the detectors and processing circuitry are integrated on the one chip. The integrated circuit is composed of sixty channels of photodetectors and parallel processing elements. The photodetection circuitry includes p-well junction diodes on a 2μm CMOS process and a logarithmic compression to increase the dynamic range of the system. The future possibility of gallium arsenide implementation is discussed. The processing elements behind each photodetector contain a low frequency differentiator where subthreshold design methods have been used. The completed IC is ideal for motion detection, particularly collision avoidance tasks, as it essentially detects distance, speed & bearing of an object. The Horridge Template 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 the areas of automobile anti-collision, IVHS, autonomous robot guidance, aids for the blind, continuous process monitoring/web inspection and automated welding, for example.

Keywords: Photodetectors, smart sensors, insect vision, GaAs, VLSI

1 INTRODUCTION

The Intelligent Vehicle Highway System (IVHS) is essentially a marriage between an electronic highway management system and cars with smart sensors, instrumentation & communication devices, to reduce traffic congestion and increase safety. In a number of countries, IVHS programs have built up considerable momentum and there are now a number of Australian initiatives.[1] The social benefits of this vision are well documented [2] and include reduced traffic congestion, fuel consumption, road accidents and more efficient travel.

The developed insect vision sensor has a number of possible automotive applications, as shown in Table 1, and can either be used stand-alone or can be integrated as part of a future IVHS system. The sensor is essentially a smart motion detector, based on optical flow, and in an IVHS environment would be expected to feedback hazard



CCD System

- Complex image processing on a separate host computer.
- All picture elements (pixels) are processed.
- Bulky and expensive.
- Uses conventional camera lens.

Insect-Vision System

- Measures range, bearing, and speed of objects.
- Simple on-chip processing integrated with detectors.
- Tracks edges of objects only.
- Compact and cheap (10–20% cost of CCD system)
- Detectors have logarithmic response, so no iris needed.
- Cylindrical gradient index lens used – no focussing needed.

Figure 1: Insect vision concept compared to conventional CCD camera.

information such a frequency of blind-spot hits, white line crossing hits, poor braking distance hits etc., to the central control hub, for indentification of high-risk zones.

Conventional imaging devices and associated image processing have yielded only limited success in mobile real-time applications, due to the vast amounts of visual data and bulk of required processing hardware.

For collision avoidance tasks, where full imaging is uneccessary, simple motion detection of object boundaries offers an efficient solution. A world-first single-chip 4.5mm × 4.6mm device, based on insect vision principles, has been developed[3–5] in a 2 μm p-well CMOS process, that simply outputs the range, 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 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, range, and speed of objects in the visual environment.

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 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 automotive applications.

The concept and advantage of the system, in comparison to a conventional CCD camera is illustrated in Fig. 1, the compactness of insect vision being because it:

- Detects movement by optical flow
- Does not 'see' full image, just moving edges – hence small & compact
- No variable focusing needed
- No iris action needed.

The 'intelligence' part of the insect vision is independent of the technology used. So it can never be displaced or become obsolete as new technologies are discovered – in fact it can be used with any technology:

- Optical (with silicon or gallium arsenide)
- Infrared (for night vision)
- Millimetre wave (excellent for poor weather conditions)
- Direct output from an electrical instrument (eg. ECG, echocardiogram, etc.).

Finally, a major advantage is that insect vision is multifunctional. In other words, on a car for instance, the very same chip design can do all the functions of braking distance, lane tracking, blind spot detection etc. Other competing non-insect detectors are function specific and perform only one task.

2 COMPARISON WITH OTHER APPROACHES

The single-chip insect vision IC, for detecting motion, via realization of the Horridge template model,[16] is a world-first.[3–5] The use of insect vision principles enables a compact *smart-sensor* with the processing on the same chip as the detector array. Other workers have implemented other insect vision processing tasks, such as lateral inhibition,[17] but these do not pertain to motion.

The work of John Tanner and Carver Mead at Caltech on the *correlating optical motion detector*[18] in 1984, was inspirational and has led to several VLSI implementations of other motion detection algorithms. Unfortunately, most implementations were based on the gradient scheme[19,20] and the Marr and Hildreth zero-crossing detector,[21] which are computationally intensive and inherently noise sensitive; both models are concerned with an accurate estimation of the velocity, which in turn requires an accurate estimate of the spatial and temporal derivatives of the intensity function. The result is that all the implementations were sensitive to light intensity; as the light intensity dropped the estimate of the velocity deteriorated quickly.

In regard to detectors on automobiles, other workers have gone from the solution of multiple CCD cameras[22] to discrete infrared detectors.[23,24] The CCD camera approach is complex in that it extracts too much information for relatively simple tasks, such as lane sensing, which then has to be interpreted by extensive image recognition post-processing. On the other hand, the complexity problem is solved by the move towards simple discrete infrared detectors, for blind spot detection. However, as the principle is to coarsely detect hot car engines, this technology cannot be used for, say, white line sensing. Furthermore, high risk blind spot hazards of non-engine-hot objects such as pedal bikes must be identified from background clutter.

Our proposed insect vision motion detector is balanced between these two extreme ends. It is much more compact than the CCD approach and yet more visually discriminating than the discrete infrared approach,

Area	Application	Description
Automotive	Blind spot detector	Sensor detects presence and *direction* of objects in blind-spot using *optical flow* techniques
	Braking distance warning	Time to impact is actually calculated using Hoyle's formula for looming objects
	White line tracking	Achieves lane tracking, for smart cruise control or swerving monitor under manual control
	Driver's head monitor	Monitors natural frequencies of of driver's head to detect alertness
	Automatic parking	In the future, a driver's key chain tag will remotely activate central locking, theft alarm system and auto parking sequence – sensors will guide against collision
	Auto road sign reading	If road signs are encoded with a coarse 'bar code,' this may become a viable low-cost technique
	IVHS sensors	Blind spot hits, critical braking distance hits etc. are sent to IVHS control hub – hit histograms will then identify hazardous zones
Physically handicapped	Blindness aid	Detector on walking stick gives supplementary feedback
	Wheelchair aid	Anticollision warning device
Domestic	Auto vacuum cleaner	Compact detectors allow vacuum cleaner to run autonomously
	Smart iron	As movement is detected, iron gives warning if it is motionless for too long, to prevent burning
	Security	Movement detectors for domestic security
	Electronic pet	Roams autonomously and can search & destroy unwanted pests – no mess, no chemicals and solar powered
Industrial	Autonomous robot	For hazardous areas or harsh environments
	Automated welding	Insect vision is ideal due to melting edges in continuous movement
	Process control	Continuous process monitoring/web inspection
Medical	Vital function monitor	Monitors waveforms through optical flow techniques
	Hospital robot	Autonomous slave

Table 1: Some possible insect vision technology application areas

therefore represents the ideal automotive solution. For instance, as the insect vision chip is based on *optical flow* it can distinguish between the false alarm case of a parked car or a car passing in the opposite direction from the genuine case of a car approaching from the rear into the blind spot region. It also has the potential to perform multiple tasks such as lane sensing, blind spot detection and braking distance warning. For future research programs an infrared version of insect vision will be the next logical step, for poor driver visibility due to harsh weather conditions.

Microwave blind spot detectors are active systems requiring both transmitter and receiver, whereas insect vision is purely passive and therefore saves the need for a transmitter device. Millimetre wave passive detectors have been demonstrated,[25] and the antennae are small enough to integrate on a GaAs insect vision chip. The drawback is the requirement for expensive 90GHz technology and therefore is not an immediate commercial possibility. However, this option and realization of this device is a logical step for a future research phase to improve harsh weather performance.

3 THE CHIP

The developed chip contains a 1-D linear array of 60 photodetectors. Upon this foundation, the next stage will be to build a 2-D array chip. Several 2-D array chips can then be assembled to form a 180° or 360° near-omnidirectional sensor, for example. A possible scenario would be six chips in a hexagonal ring.

The design is a "smart" micro-sensor which accepts a time-varying pattern of stimuli and indicates the bearing, range, and speed of objects in the visual environment, ie. a sensor which identifies the 3-D arrangement of objects in space from motion rather than 3-D forms of the objects themselves from shading (which requires coding of relative intensities). Specifically the system is based on the use of *optical flow* to detect and locate obstacles. The optical flow information is derived via simple special purpose parallel processing combined with codified templates.[16] The system exploits this concept to produce a compact real-time motion & proximity detector.

Insects, compared to humans, possess a relatively simple visual sys, 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 and contains a large number of identical parallel channels

The photoreceptors in the retina sample the visual field and 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.

The IC realization is a linear array of 60 photodetectors with 60 channels of parallel analog differentiators. Processing at each node mimics the parallel structure of the insect visual system and provides improved edge discrimination in varying light conditions.

The light is focused onto the surface by a gradient index (GRIN) lens, with a visual angle of 72°. The lens has a 1.8 mm diameter and has been chosen due to it's flat surface that can be simply glued to the chip. The spacing between each of the 60 photodetectors has been designed so that each channel corresponds to a 1° angle, thus giving a total visual angle of 60°.

Photocurrent from the each detector is transformed into a voltage using a subthreshold circuit technique, thus providing a logarithmic response. This form of automatic gain control provides a wide dynamic range, as insects do not use a bulky iris mechanism.

The signal voltage is then buffered, time differentiated and thresholded to digitally 2-bit encode the detected

T1 / To	– –	↓ –	↓ ↓	↓ ↑	– ↑	↑ ↑	↑ –	↑ ↓	– ↓
– –		←			→		←		→
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Figure 2: Template table.

light variations. These detected contrast changes are then multiplexed in pairs, from adjacent channels, together with the previous sample time states of the same pair, to form a Horridge template.

Interpretation of the template is then found by a lookup table, see Table 2, stored in RAM and the outputs are then stored in an intermediate RAM. The template codes themselves provide information on object direction, whereas the orientation of a group of templates on a spatio-temporal plane provides information on angular velocity and bearing. Angular velocity is given by the inverse of the gradient of the output template pattern, Figure 3 and angular direction can be inferred from the fact that each horizontal location corresponds to 1° of visual angle.

4 GALLIUM ARSENIDE

The excellent progress and maturity of the Gallium Arsenide technology has lead to the development of high-speed systems, with as many as 1.44 million GaAs transistors per chip, suitable for working in harsh environments. Therefore, one of the next goals is to create a significant advance in the area of solid-state vision systems via the research of a high-speed Gallium Arsenide (GaAs) version of the chip. We propose a GaAs sensor, to be fabricated in a standard or near-standard GaAs digital IC process. The superior speed-power performance of GaAs over silicon and the excellent ongoing progress in GaAs fabrication maturity make GaAs a favorable choice.[3,17] The short absorption lengths and short carrier diffusion lengths in GaAs enable high sensitivity whilst maintaining low detector crosstalk and improved performance during optical overload (blooming).

Presently, the chosen 2μm CMOS process contains p-wells on an n-epi layer. The p-well/n-epi junction was chosen for the photodetection, rather than the n^+/p-well junction, because of greater quantum efficiency (QE)

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...........................7.AAEFFFF60002..5......
.......................7AEFFFFF602......73........
..................7AAAAEFFF6F002........C4..4.....
...........7.AAAAA000000000020........7AE4..4.....
.......7AAAEAF60002...................CFF4..4.....
....7AAEFF60F02......................7EF62..2.....
.7AEFFF602..2.......................CFF62.........
.C600002...........................7EFF4..........
.52...............................7EFF62..........
.................................7EFF62...........
................................7EF602............
.......7AAAAA..................7EF62..............
.......50DFFBAA3...............CF62...............
.........500DFFBAAA3..........7EF4................
............5000DFFBAAA3.....7EF62................
.................500DFFFBAAAAEFF4.................
......................50DFFFFFF62.................
........................500D0FFBAAAA3.............
..........................7E.00000002.7AAAAAAAA3..
.........................CF4............50DFFFFFF4
........................7E62E.............50.DFFF4
.......................7EF4..................50022
......................7EF4........................
.....................7EF62..2..............7.F4...
.....................CF62...............7AAEFF4...
...................7A002...........7AAAA0000002...
...................C62.........7AEFFF602..........
..................702......7AAAEF60002............
.................7E4...7AAAEA00002................
.................CFBAAAB60000.....................
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Figure 3: Example template output pattern.

due to the greater depth of epi over well. The choice of a n-substrate process, over a p-substrate, was not critical for photodetection as the minority carrier diffusion lengths are much greater than the epi depth, in each case. The choice of epi over bulk is essential due to improved modulation transfer function (MTF), which implies a greater ability to detect higher spatial frequency detail. This is illustrated in Figure 4, where although the diffusion curve for 550nm in bulk is acceptable, the MTF for 800nm is severely degraded in bulk compared to epi. Although the diffusion curves are obtained from the well known function of quantum efficiency, the expression for QE in epi[14] can be readily generalized for QE in a finite slab. The geometrical-only curve is obtained from the usual sinc function expression and represents the ideal case in absence of diffusion effects – we speculate that this could be achieved in GaAs where the unipolar n^+/SI junction collects majority carriers, hence any diffusion terms vanish. Using the usual Planck's Law curve formulation we estimate the responsivity of our p-well/n-epi junction to be 53mA/W, whereas for the GaAs case we obtain 71mA/W. Therefore, in practice, for a scene illumination in the range 10^{-3} to 10^2 W/m^2, we expect a signal current from hundreds of femtoamps to tens of nanoamps, for our silicon element and slightly higher results for GaAs. For future work, GaAs may be promising for cases where demands are made on increasing the processing speed, whilst maintaining low power for mobile applications – as a by-product we would expect an improved MTF and responsivity.

The advantages of using gallium arsenide include:

- GaAs has high speed for low power dissipation and is the choice technology for mobile communications, mobile global positioning systems (GPS) etc. – hence a GaAs insect vision chip will integrate well with this technology.
- GaAs high speed is also useful for digital circuitry that may be useful to integrate on the same chip, such as a high-speed customized Hough transform engine.
- GaAs chips actually have fewer manufacturing steps (about half) than silicon CMOS chips – hence at full maturity will be more reliable, have better yield and may even be cheaper.
- In GaAs, light is absorbed ten times closer to the surface, than in silicon. Therefore, light is more efficiently detected. Also if there is too much light overload (called 'blooming') this is better controlled in GaAs.
- The surface structure of GaAs is more suited for sandwiching together with an important infrared sensitive material called Cadmium Mercury Telluride (CMT). This will enable insect eyes to see in the dark.

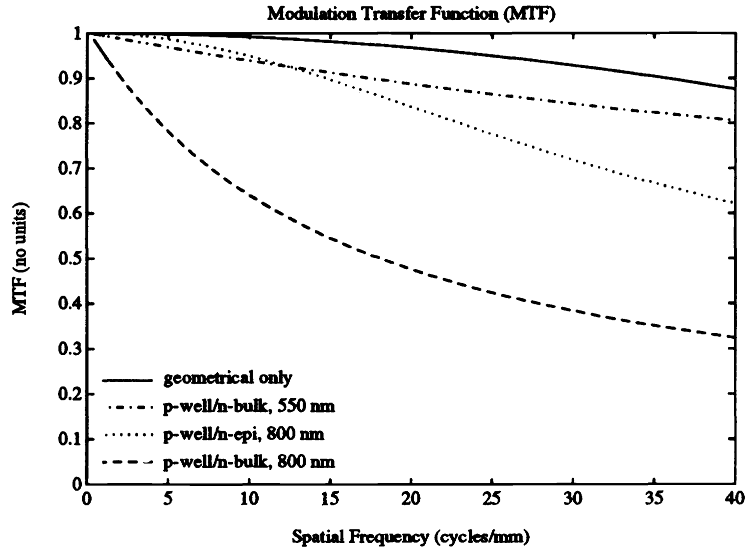

Figure 4: Theoretical MTF versus spatial frequency. Diffusion-only curves are for specific optical wavelengths. Geometrical-only curve is for the actual 7/20 aperture to pitch ratio used.

- We discovered for the first time that GaAs transistors are 20-30 times more sensitive to light at the edges.[14] This is called the photovoltaic self-biasing edge-effect. This will enable insect eyes that work in very poor light conditions.
- GaAs is the choice material for the integration of millimeter wave microantenna structures.[15] This has two exciting possibilities: (1) mm wave antennas can replace the photodetectors to produce excellent performance in poor weather, (2) for an automobile, or any system, that uses multiple insect vision chips, wireless interchip communication can take place.

5 RANGE

From Figure 5, it can be seen that $\theta \approx \phi$ and $R\frac{d\theta}{dx} = \sin\theta$, where R is the range. As the detectors are moving at a velocity V, the angular velocity is given by,

$$\dot{\theta} = \frac{d\theta}{dt} = \frac{d\theta}{dx}\frac{dx}{dt} = \frac{V\sin\theta}{R}$$

this formula was first considered in the context of aircraft navigation by Whiteside and Samuel.[26]

In the context of in-lane traffic, however, the range of a looming object is the relevant quantity for braking distance warning. In this case the range is given by,

$$R = \frac{V}{\dot{\theta}}\sin\theta\cos\theta = \frac{V}{\dot{\theta}}\frac{\sin 2\theta}{2}$$

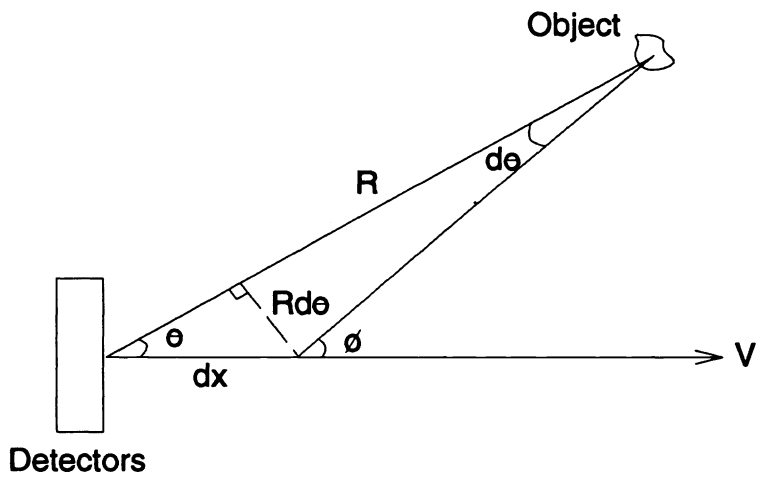

Figure 5: Calculation for range

where V is the velocity of the detectors, θ is half the angle subtended by the car in front and $\dot{\theta}$ is the apparent angular velocity of it's rear wing tip. This formula assumes that the car ahead is stationary – if it is moving, it's velocity must also be known to calculate the range. This must be calculated by some other means or alternatively if *relative* velocity is considered, then 'time-to-impact' t can be calculated instead which is also a useful quantity,

$$t = \frac{\sin 2\theta}{2\dot{\theta}}$$

$\dot{\theta}$ is simply given by the inverse of the slope of the template pattern. As each template corresponds to a visual angle of 1°, then θ is simply half the number of template channels subtended by the object. Notice for small θ, the formula reduces to $t = \theta/\dot{\theta}$ which is the more usual form of Hoyle's formula used in the context of looming astronomical bodies.[27]

6 CONCLUSION

A world-first VLSI 4.5mm × 4.6mm CMOS integrated circuit has been developed that mimics the compact and yet powerful visual capabilities of an insect. The chip contains a linear array of 60 photodetectors. Future work will be to extend the present concept to a 2-D array and to also exploit the many advantages of a gallium arsenide implementation. The entomologist Thomas Eisner[28] said "Bugs are not going to inherit the earth – they own it now. So we might as well make our peace with the landlord." To this we can add that there is still much to be learned from the landlord.

7 ACKNOWLEDGEMENTS

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