Biologically inspired obstacle avoidance – a technology independent paradigm

D. Abbott *(Keynote Speaker)* A. Yakovleff *, A. Moini, X.T. Nguyen, A. Blanksby, R. Beare, A. Beaumont-Smith, G. Kim †, A. Bouzerdoum, R.E. Bogner, K. Eshraghian ‡

Centre for GaAs VLSI Technology and Dept. of Electrical & Electronic Eng.
The University of Adelaide, SA 5005, Australia
email: dabbott@eleceng.adelaide.edu.au

ABSTRACT

With regard to obstacle avoidance, a paradigm shift from technology centered solutions to technology independent solutions is taking place. This trend also gives rise to a shift from function specific solutions to multifunctional solutions. A number of existing approaches will be reviewed and a case study of a biologically inspired insect vision model will be used to illustrate the new paradigm. The insect vision model leads to the realization of a sensor that is low in complexity, high in compactness, multifunctional and technology independent. Technology independence means that any front end technology, resulting in either optical, infrared or mm wave detection, for example, can be used with the model. Each technology option can be used separately or together with simple data fusion. Multifunctionality implies that the same system can detect obstacles, perform tracking, estimate time-to-impact, estimate bearing etc. and is thus non-function specific. Progress with the latest VLSI realization of the insect vision sensor is reviewed and gallium arsenide is proposed as the future medium that will support a multifunctional & multitechnology fusion of optical, infrared, millimeter wave etc. approaches. Applications are far reaching and include autonomous robot guidance, automobile anti-collision warning, IVHS, driver alertness warning, aids for the blind, continuous process monitoring/web inspection and automated welding, for example.

Keywords: Photodetectors, smart sensors, insect vision, collision avoidance, biologically inspired engineering, GaAs, VLSI

1 INTRODUCTION

In the mobile robots and IVHS/AVCS arena, electronic vision systems for navigation and obstacle avoidance have traditionally been developed from the bottom-up approach – ie. beginning with a favored front end detector

*Also with the Defence Science and Technology Organisation (DSTO), Information Technology Division, Salisbury, SA 5108, Australia

†With Seoul National University, Kwanak-gu, Shinlim-dong, 151-742, South Korea

‡Also with Edith Cowan University, Joondalup, WA 6027, Australia

0-8194-1955-9/95/$6.00

technology, the system is put together around this starting point. This is the syndrome of finding solutions based around a single 'pet' technology, such as millimeter wave or infrared, and for example has been prevalent in the area of obstacle detection & analysis. From experience this has led to systems that are function specific or limited in functions, such as velocity estimation, size estimation, bearing, range etc.

There is now a gradually changing attitude favoring a top-down deployment, where the systems engineering approach starts with a definition of the task, hence identifies the required functions and leads, if necessary, to a multitechnology solution. There is a window of opportunity to be captured by early systems deployment with multitechnology solutions, rather than waiting for the 'perfect' single solution. As human and infrastructural needs are constantly changing, a 'pet' technology solution, once developed, may no longer have a valid application. A top-down approach therefore is inherently more flexible and is not stifled by the limitations of a particular front-end technology.

Another syndrome is 'the sledge hammer to crack a nut' approach using full resolution imaging and intensive computation, with great precision, to carry out visual tasks that do not require great accuracy nor full image data. 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 unecessary, simple motion detection of object boundaries offers an efficient solution. A world-first single-chip device, based on insect vision principles, has been developed[1–5] that 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.

We use this biologically inspired system solution as a case study of a smart sensor that is both multifunctional and is independent of the front-end detector technology. This technology independence means that the same system concept can operate in the optical, infrared, millimeter wave etc. bands. Futhermore due to the simplicity of the output parameters, data fusion for a multitechnology solution is relatively straight forward.

In this paper, we briefly describe the insect vision chip and we review the progress and future plans. Gallium arsenide is proposed as the ideal base medium for realising a system that can support multitechnology front-end solutions. We also review some of the developments of other workers in the area of smart sensors.

2 OVERVIEW OF INSECT VISION

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 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, range, and speed of objects in the visual environment.

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 front-end detectors.

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, for automotive applications, are function specific and usually perform only one task.

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.[6,7] The system exploits this concept to produce a compact real-time motion & proximity detector.

Insects, compared to humans, possess a relatively simple visual system, yet are capable of performing complex visual tasks. 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.

Conventional robotics systems often utilize 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.[8] For instance, the response observed in a number of insect species is generally in a different direction from that of the detected pattern motion,[9,10] while guard bees seem to control a stable "hovering" position by responding to the small positional changes of a fixated pattern.[11] Moreover, psychophysical evidence suggests that primates may extract heading direction and depth information simultaneously.[12]

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.[13,14]) 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 utilized 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.[15]

3 REALIZATION OF INSECT VISION CHIP

The IC realization is an array of photodetectors with parallel analog differentiators to detect changes in contrast. 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, which is simply glued to the surface of the chip. Photocurrent from each detector is transformed into a voltage using a subthreshold circuit technique, thus providing a logarithmic response. This built-in form of automatic gain control (AGC) 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 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 as in Fig. 1 – where the template states $\uparrow, \downarrow$ and $-$ indicate increasing contrast, decreasing contrast and no change respectively.

Interpretation of the template is then found by a lookup table. The template codes themselves provide

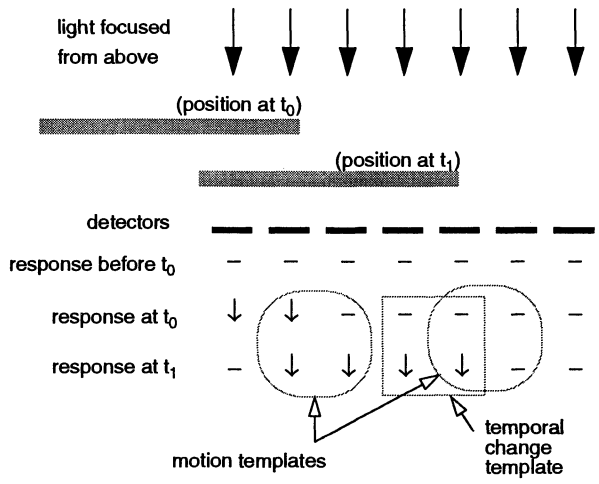

Figure 1: Coding of Templates

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, Fig. 2, and angular direction can be inferred from the fact that each horizontal location corresponds to 1° of visual angle. Range can be calculated from these two parameters, by simple geometrical argumentsa, provided the velocity of the observer is known.[4,5] If only the relative velocity between the observer and obstacle is known then time-to-impact can be found instead.

Looming objects can be detected by exploiting the fact that moving edges are of identical polarity. For instance, if the object is dark with respect to the background, the motion templates detected to the left and right would indicate bright-to-dark changes in contrast. Fig. 3 shows an example of a looming picture – the angular velocity of the edge on the right hand side is, on average, slower than the edge on the right.

The detection of looming illustrates one example of interpreting velocity measurements by taking into account the polarity information conveyed by the templates. In general, if an object's contrast with respect to the background is reasonably constant, and if the object is wide enough or close enough to the sensor, relative motion should elicit the detection of at least two edges.

The simple cases shown in Fig. 4 differ only in terms of polarity (ie. changes in contrast) and directions. Therefore, detecting such conditions consists of associating pairs of track on the basis of the absolute velocities being similar, and on identifying the combinations of changes in contrast.

It should be pointed out, however, that associated tracks do not necessarily correspond to edges belonging to the same object, particularly in the case where the sensor is rotated about its central axis ('panning' motion), and all the objects in the environment are static.

4 COMPARISON WITH OTHER APPROACHES

The single-chip insect vision IC, for detecting motion, via realization of the Horridge template model,[6,7] is a world-first.[1–3] 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

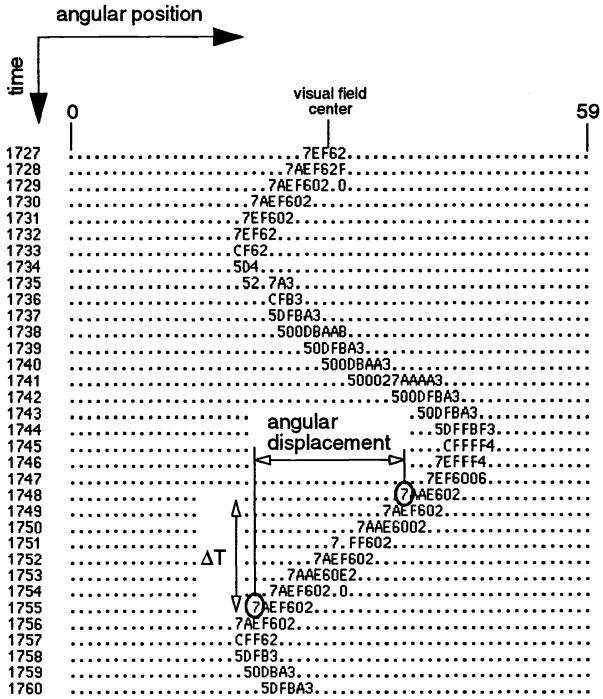

Figure 2: Example template output pattern.

Figure 3: Looming pattern.

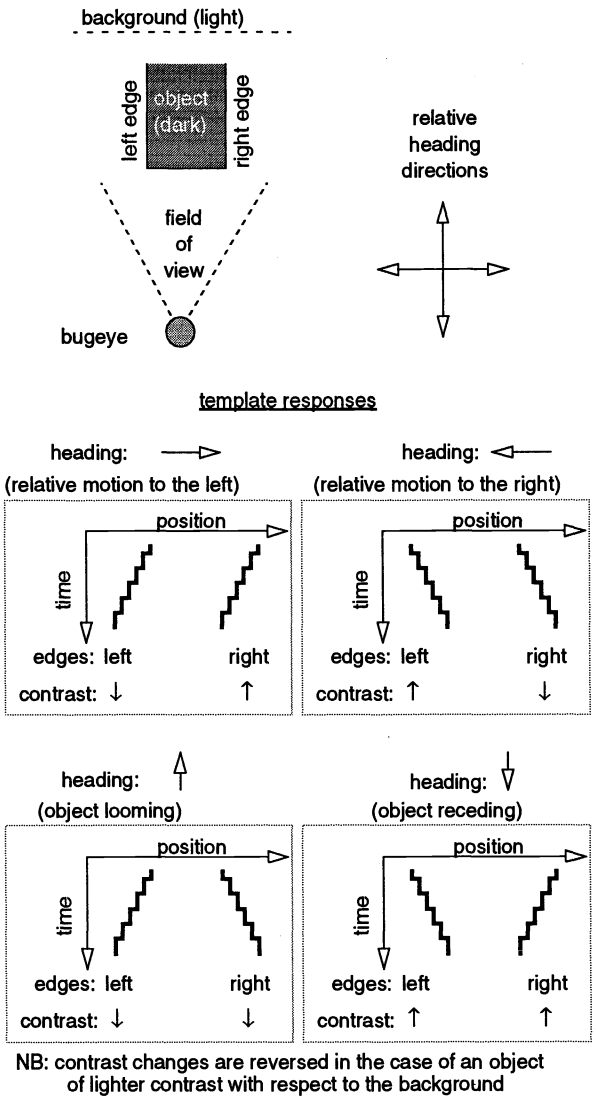

Figure 4: Response to different heading directions.

lateral inhibition,[25] but these do not pertain to motion.

The work of John Tanner and Carver Mead at Caltech on the *correlating optical motion detector*[26] 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[27,28] and the Marr and Hildreth zero-crossing detector,[29] 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[30] to discrete infrared detectors.[31,32] 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, 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,[33] 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.

5 STATUS AND FUTURE DIRECTIONS OF THIS WORK

Table 1 indicates the chronological development and future vision for our insect vision chip dubbed the 'bugeye.' Bugeye I of 1992 vintage 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 produced a chip with improved dynamic range and contained a multiplicative noise cancellation circuit (MNC).[34] The digital sections of the chip were discarded in favor of an external microcontroller. 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 50Hz or 60Hz 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

Version	Size	Technology	Year
Bugeye I	64 by 12	2μm CMOS	1992
Bugeye II	64 by 2	1.2μm CMOS	1994
Bugeye III	64 by 32	0.8μm CMOS	1996
Bugeye IV	64 by 64	BiCMOS	1997
Bugeye V	64 by 64	GaAs or CGaAs	1998

Table 1: Evolution of 'Bugeye' Insect Vision Chip

the edges.

The latest Bugeye III design contains a truly 2 dimensional array of detectors. AGC occurs at every node by virtue of logarithmic compression due to subthreshold detector circuits, however contrast change detection is carried out by only one row of differentiators. This is achieved by clocking signal out of the device as in conventional 2D arrays.

Bugeye IV will be an array of a larger size and perhaps exploit the qualities BiCMOS, being an analog device. Bugeye V will be a proof-of-concept in GaAs. This can be in a conventional E/D MESFET process or in the newly emerging complimentary CGaAs process.

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') is better controlled in GaAs.
- The surface structure of GaAs is more suited for lattice matching with a Cadmium Mercury Telluride (CMT), an important infrared sensitive material. This will enable insect eyes to see in the dark.
- We discovered for the first time that GaAs transistors are 20-30 times more sensitive to light at the edges.[23] 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.[24] 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.

6 CONCLUSION

A world-first VLSI 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. A second generation of this device contains 60 by 2 detectors and multiplicative noise cancellation (MNC) to reduce the effects of hum from AC lighting, produce edge enhancement and carry out a form data compression. Current work is extending the present concept to a 2-D array and future work will exploit the many advantages of a gallium arsenide implementation.

7 ACKNOWLEDGEMENTS

This work has been generously funded by the Australian Research Council (ARC), the Department of Employment Education and Training (DEET) and Britax-Rainsfords P/L. A special thanks is due to Emeritus Professor G. A. Horridge for his inspiration.

8 REFERENCES

[1] A. Moini, A. Bouzerdoum, A. Yakovleff, D. Abbott, O. Kim, K. Eshraghian, and R. E. Bogner, "An analog implementation of early visual processing in insects," *International Symposium on VLSI Technology, Systems, and Applications,* Taipei, pp. 283-287, May 12-14, 1993.

[2] A. Yakovleff, A. Moini, A. Bouzerdoum, X. T. Nguyen, R. E. Bogner & K. Eshraghian, "A micro-sensor based on insect vision," *Conference on Computer Architectures for Machine Perception (CAMP'93),* New Orleans, USA, pp. 137-146, 15–17 Dec. 1993.

[3] A. Bouzerdoum, R. E. Bogner, K. Eshraghian, A. Moini, A. Yakovleff & X. T. Nguyen, "A VLSI front-end visual processor based on insect vision," *Sensory Stratagems: From Living Eyes to Seeing Machines,* Canberra, 7–11 Feb. 1993.

[4] D. Abbott, A. Moini, A. Yakovleff, X.T. Nguyen, A. Blanksby, G. Kim, A. Bouzerdoum, R.E. Bogner & K. Eshraghian, "A new VLSI smart sensor for collision avoidance inspired by insect vision," *Proc. SPIE,* Boston, **Vol. 2344**, pp. 105-115, Nov. 2-4, 1994.

[5] A. Yakovleff, D. Abbott, X.T. Nguyen & K. Eshraghian, "Obstacle avoidance and motion-induced navigation," *Proc. Comp. Arch. for Machine Perception (CAMP'95),* Como, Italy, pp. 384-393, 18-20 Sep. 1995.

[6] G. A. Horridge, "The compromise between seeing spatial layout and making visual discriminations," *Current Science,* **Vol. 60,** No. 12, pp. 686-693, June 1991.

[7] G. A. Horridge, "Ratios of template responses as the basis of semivision," *Phil. Trans. Roy. Soc. London B,* **Vol. 331,** pp. 189-197, 1991.

[8] W. Reichardt "Autocorrelation, a Principle for the Evaluation of Sensory Information by the Central Nervous System," in *Sensory Communication,* Walter A. Rosenblith Ed., MIT Press and John Wiley & Sons (New York, London), pp. 303-317, 1961.

[9] C. Lazzari and D. Varju "Visual lateral fixation and tracking in the haematophagous bug *Triatoma Infestans,*" *Journal of Comparative Physiology A*, **Vol. 167**, pp. 527-531, 1990.

[10] A. Borst, M. Egelhaaf and H.S. Seung "Two-dimensional Motion Perception in Flies," *Neural Computation,* **Vol. 5**, pp. 856-868, 1993.

[11] A. Kelber and J. Zeil "A robust procedure for visual stabilisation of hovering flight position in guard bees of *Trigona (Tetragonisca) angustala* (Apidae, Meliponinae)," *Journal of Comparative Physiology A,* **Vol. 167**, pp. 569-577, 1993.

[12] J.A. Perrone and L.S. Stone, "A Model of Self-Motion Estimation Within Primate Extrastriate Visual Cortex," *Vision Research,* **Vol. 34**, No. 21, pp. 2917-2938, 1994.

[13] D. Regan and K.I. Beverley, "Looming Detectors in the Human Visual Pathway," *Vision Research,* **Vol. 18**, No. 4, pp. 415-421, 1978.

[14] D. Regan and S.J. Hamstra "Dissociation of Discrimination Thresholds for Time to Contact and for Rate of Angular Expansion," *Vision Research,* **Vol. 33,** No. 4, pp. 447-462, 1993.

[15] R.M. Robertson and A.G. Johnson "Collision Avoidance of Flying Locusts: Steering Torques and Behaviour," *Journal of Experimental Biology, Vol. 183,* pp 35-60, 1993.

[16] A. Yakovleff, X. T. Nguyen, A. Bouzerdoum, A. Moini, R. E. Bogner, K. Eshraghian, "Dual-purpose interpretation of sensory information," *Proc. IEEE Int. Conf. Robotics and Automation,* San Diego, **Vol. 2,** pp. 1635-1640, 8–13 May, 1994.

[17] X. T. Nguyen, A. Yakovleff, A. Moini, K. Eshraghian, A. Bouzerdoum, R. E. Bogner, "VLSI architecture of a low computational load processor for a visual system based on insect vision," *European design & test conf.,* pp. 85-89, 1994.

[18] X. T. Nguyen, A. Bouzerdoum, R.E. Bogner, K. Eshraghian, D. Abbott, A. Moini, "The stair-step tracking algorithm for velocity estimation," *ANZIIS-93,* Perth, pp. 412-416, 1–3 Dec., 1994.

[19] X. T. Nguyen, A. Bouzerdoum, A. Yakovleff, A. Moini, R. E. Bogner, K. Eshraghian, "VLSI robotic microsensor: range-finder from self motion," *IEEE Proc. mechatronics and machine vision in practice,* Toowoomba, pp. 78-83, 13–15 Sep., 1994.

[20] A. Bouzerdoum, A. Moini, A. Yakovleff, X. T. Nguyen, R. E. Bogner, K. Eshraghian, "A smart visual micro-sensor," *Proc. IEEE Int. Conf. on Systems, Man and Cybernetics,* 2–5 Oct. 1994.

[21] X. T. Nguyen, K. Eshraghian, A. Moini, A. Bouzerdoum, A. Yakovleff, D. Abbott, R. E. Bogner, "An implementation of a smart visual micro-sensor based upon insect vision," *12th Australian Microelectronics Conference,* Queensland, pp. 129–134, 5–8 Oct., 1993.

[22] D. Abbott & K. Eshraghian, "Gallium arsenide MESFET imager," *World Intellectual Property Organisation, International Bureau,* Geneva, **Patent WO 93/07643**, 15 Apr. 1993.

[23] D. Abbott, S. Cui, K. Eshraghian & E. McCabe, "Photovoltaic gate biasing edge effect in GaAs MESFETs," *Electronics Letters,* **Vol. 27**, No. 21, pp. 1900-1902, Oct. 1991.

[24] A. J. Parfitt, D. W. Griffin, P. H. Cole, "On the modelling of metal strip antennas contiguous with the edge of electrically thick finite size dielectric substrates," *IEEE Trans. Antennas and Propagation,* **Vol. 40**, No. 2, Feb. 1992.

[25] R. B. Darling and W. T. Dietze, "Implementation of multiplicative lateral inhibition in a GaAs sensory neural-network photodetector array," *IEEE J. Quantum Elec.,* **Vol. 29,** No. 2, pp. 645-654, Feb. 1993.

[26] J. Tanner and C. Mead, "A correlating optical motion detector," *Proc. Conference on Advanced Research in VLSI,* M.I.T., pp. 57-64, 1984.

[27] J. Tanner and C. Mead, "An integrated analog optical motion sensor," In: *VLSI Signal Processing II,* pp. 59-76, IEEE Press, 1986.

[28] A. Moore and C. Koch, "A multiplication based analog motion detection chip," *Visual Information Processing: From Neurons to Chips,* Proc. SPIE, **Vol. 1473**, pp. 66-75, 1991.

[29] W. Bair and C. Koch, "Real-time motion detection using an analog VLSI zero-crossing chip," *Proc. SPIE Visual Information Processing: From Neurons to Chips*, **Vol. 1473,** pp. 59-65, 1991.

[30] "Mitsubishi HSR III," *Mitsubishi Motors Corporation*, (company brochure), Tokyo, Japan.

[31] B. E. Stuckman *et al*, "A solid state infrared device for detecting the presence of car in a driver's blind spot," *Proc. 32nd Midwest Symposium on Circuits and Systems,* Part 2, pp. 1185-1188, 1989.

[32] W. Hyland, "Sideminder: advanced blind spot monitoring," *Auto-Sense*, (company brochure), Denver, Colorado, USA.

[33] W. Lam *et al*, "Millimeter-wave imaging using preamplified diode detector," *IEEE Microwave Guided Wave Lett.,* **Vol. 2,** No. 7, pp. 276-277, Jul. 1992.

[34] A. Moini, *et al*, "Multiplicative Noise Cancellation (MNC) in Analog VLSI Vision Sensors," *IEEE Proc. Elec. Tech. Directions to the Year 2000,* Adelaide, Australia, pp. 253-257, May 23-25, 1995.