

## **Recent developments in biologically inspired seeker technology**

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### **ABSTRACT**

As electro-optic sensors increase in size and frame rate, the data transfer and digital processing resource requirements also increase. In many missions, the spatial area of interest is but a small fraction of the available field of view. Choosing the right region of interest, however, is a challenge and still requires an enormous amount of downstream digital processing resources. In order to filter this ever-increasing amount of data, we look at how nature solves the problem. The Advanced Guidance Division of the Munitions Directorate, Air Force Research Laboratory (AFRL/MNG) at Eglin AFB, Florida, has been pursuing research in the area of advanced sensor and image processing concepts based on biologically inspired sensory information processing. A summary of some vertebrate and invertebrate inspired “neuromorphic” processing efforts will be presented along with a seeker system concept utilizing this innovative technology. Concepts and requirements for future such efforts will also be discussed.

**Keywords:** Neuromorphic, biomimetic, smart FPA, on-FPA processing

### **1. INTRODUCTION**

Electro-optic systems of the future will include very large sensors feeding an enormous amount of data to the digital mission processing subsystem. Infrared focal plane arrays (FPA) of 128 x 128 detector elements are now readily available and 256 x 256 and 512 x 512 arrays have been recently demonstrated in both single and dual color formats. 1024 x 1024 detector element FPAs will be probably be available in the near future. As these imaging arrays grow in detector number for higher resolution, so will the computing requirements for the embedded digital image processing system. Very high computational bandwidths will also be required to detect and identify objects of interest in imagery provided by future high frame rate, million detector FPAs. The required processing throughput should be readily available with the advances in digital VLSI CMOS technology. However, the data transfer rate of FPA image data into the digital processor is limited by the bandwidth of the cryo-cooler analog interface and analog to digital converter (A/D) placed between the sensor and processor resources. Today's sensors provide many orders of magnitude of dynamic range, only to have the data bandlimited by the readout chip's multiplexing circuitry and A/D. One approach to solve this processing bottleneck problem could be to incorporate a certain amount of pixel-level processing within the detector unit cell, similar to the technique implemented in biological sensory information processing systems. Figure 1 shows a functional signal flow diagram of the human visual information processing system. As seen in Figure 1, visual information is preprocessed by the retinal neural layers before being furnished to the visual cortex via the lateral

geniculate nuclei (LGN). Biological systems perform processing directly at the sensory sub-system. The vertebrate retina is one such system that is essentially a three-dimensional massively parallel neural processor<sup>1, 2</sup>.

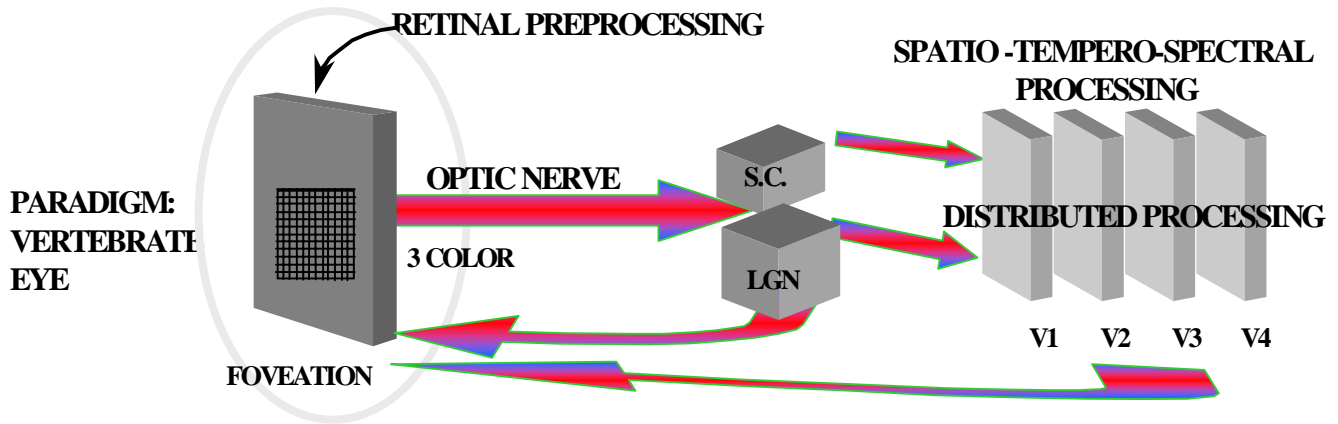


Figure 1. The Vertebrate Visual System.

Figure 2 shows the image processing functions performed by the neural layers of the retina. Details on the processing flow in the retina have previously been published<sup>1, 3</sup>. One important feature to point out here is the output of the horizontal-bipolar cell layer (sometimes referred to as the outer plexiform layer). The horizontal cell performs a spatial “Gaussian” smoothing on the input. The bipolar cell acts as a difference amplifier, accepting inputs from both the photodetector and the horizontal cell layer. This bipolar cell difference is commonly referred to as the Difference of Gaussian<sup>4</sup>, or DoG filter. This DoG filter is an essential spatio-temporal filter in image processing terminology. It is useful for both edge and contrast enhancement.

The insect visual system is of course a much smaller physical unit than the vertebrate visual system. Yet, for its survival, the insect’s visual performs the same basic image processing functions, i.e. spatial and temporal filtering. Figure 3 shows the neural processing layers of the insect. It is believed that the “...neural mechanisms acting in the lamina were concluded to take a kind of spatio-temporal average of the photoreceptor signals, which is subtracted from the receptor input.”<sup>5</sup> I.e., the output of the lamina synaptic layer is essentially a DoG filtered representation of the input. The information processing wiring of the insect visual architecture is well understood<sup>6</sup>, and many research organizations are pursuing mapping processing models of various insects to silicon demonstrations.

<sup>1</sup> Werblin, F. and J. Teeters, (1991), "Real Time Simulation of the Retina Allowing Visualization of Each Processing Stage", Proceedings of the SPIE Vol 1472.

<sup>2</sup> Dowling, John , (1987), *The Retina: An Approachable Part of the Brain*, Harvard University Press, Cambridge, Massachusetts.

<sup>3</sup> McCarley, P., R. Wehling, and M. Massie, (1995), "Continuing Developments in Biologically-Inspired Smart Focal Plane Concepts," Proc. SPIE, Vol. 2474.

<sup>4</sup> Marr, David, Vision, (1982) *A Computational Investigation Into the Human Representation and Processing of Visual Information*, W.H. Freeman.

<sup>5</sup> Egelhaaf, M. & A. Borst, (1993) "Movement detection in arthropods," In F.A. Miles & J. Wallman (Eds.): *Visual Motion & its Role in the Stabilization of Gaze*. New York: Elsevier Science Publishers, p 63.

<sup>6</sup> Douglas, J. & N. Strausfeld, (1998), "Functionally & Anatomically Segregated Visual Pathways in the Lobula Complex of a Calliphorid Fly," in Journal of Comparative Neurology 396:84-104.

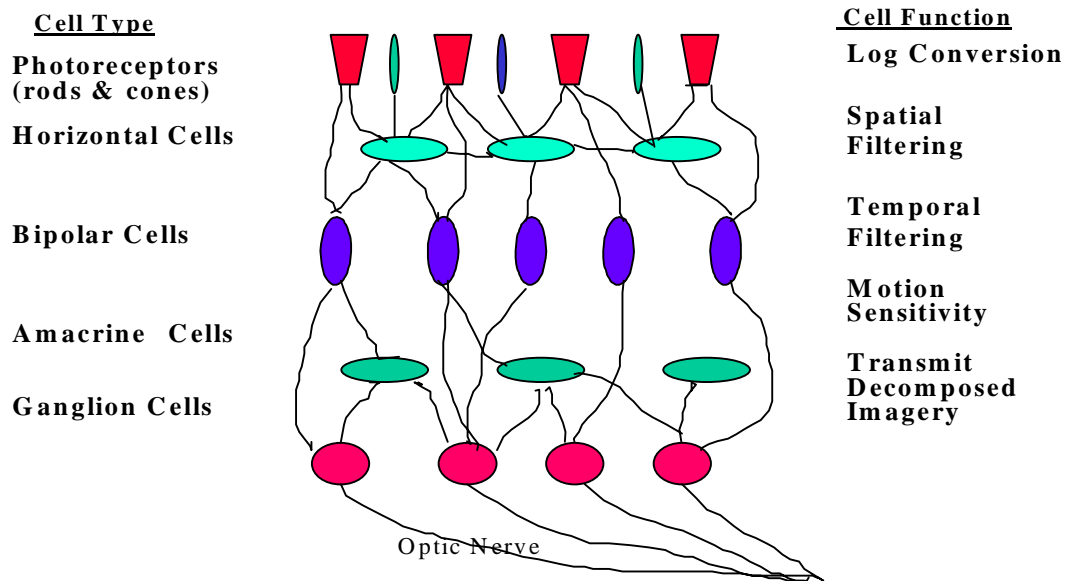


Figure 2. A model of the vertebrate retina, showing the neural processing layers and image processing functions performed.

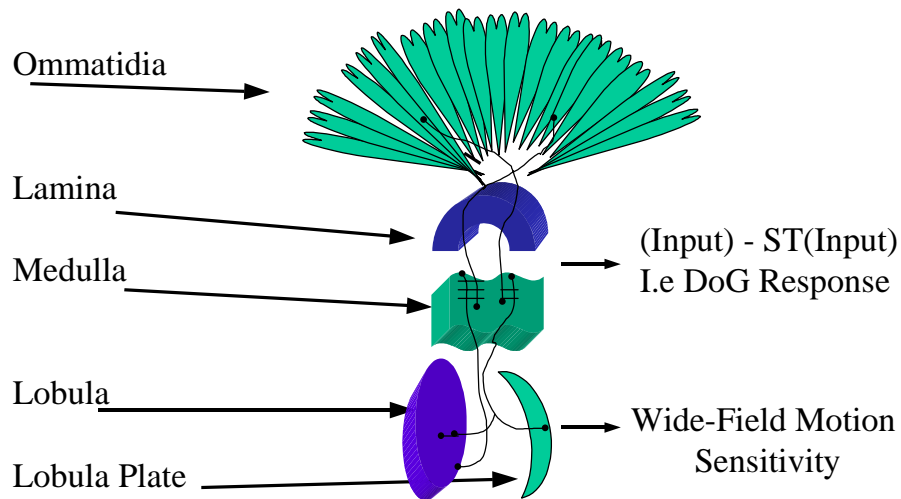
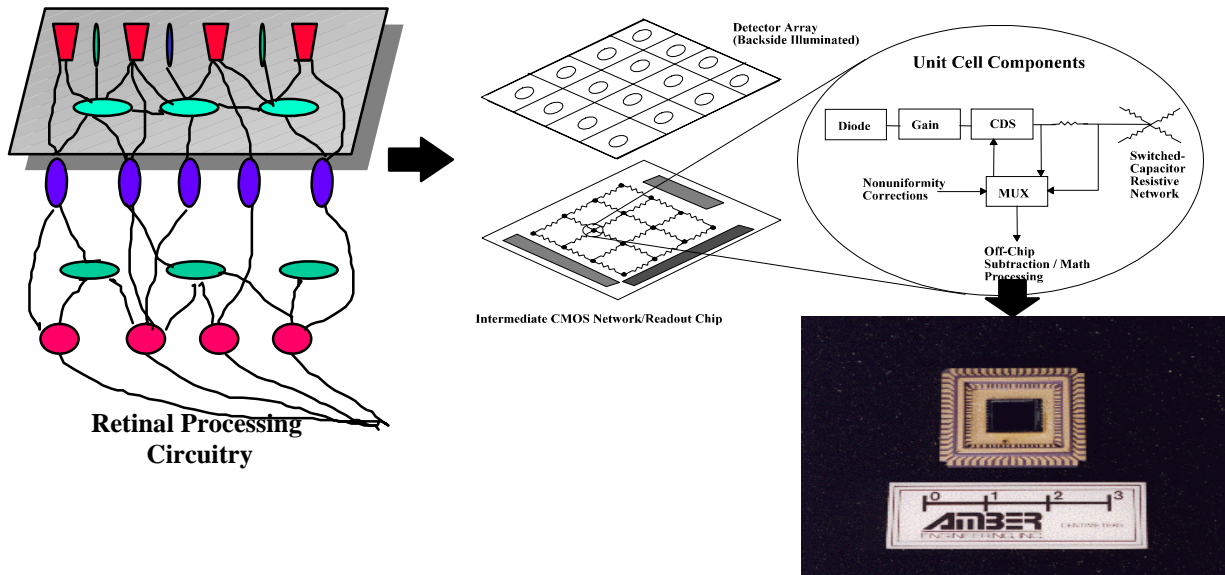


Figure 3. A Model of the Invertebrate Retina. Adapted from K. Hausen, (1989), "The Decoding of retinal image flow in insects" in F.A. Miles and J. Wallman, (Eds.): *Visual Motion & its Role in the Stabilization of Gaze*, New York: Elsevier Science Publishers, p 203-229.

## 2. SOME EXAMPLES OF NEUROMORPHIC ON-FPA PROCESSING

The world's first "smart FPA" was developed by Amber Engineering, Inc., Goleta, CA (now part of Raytheon Infrared Operations) for AFRL/MNG in 1992. This Smart Neuromorphic IR FPA (SNIF) sensor opened an entirely new avenue of possible applications for imaging focal plane array based systems. The SNIF system performs a DoG filtering function, similar to what occurs in the horizontal-bipolar cell layers of the primate retinal system. This function typically requires a very computationally intensive spatial-temporal filter operation when implemented in digital. However, the SNIF chip executes this function on the focal plane, at the seeker frame rate, and with very low power dissipation. Figure 4 shows that the SNIF is just another imaging IRFPA, only with built-in spatiotemporal filtering circuitry. Implementation details have been previously reported<sup>7, 8</sup>.

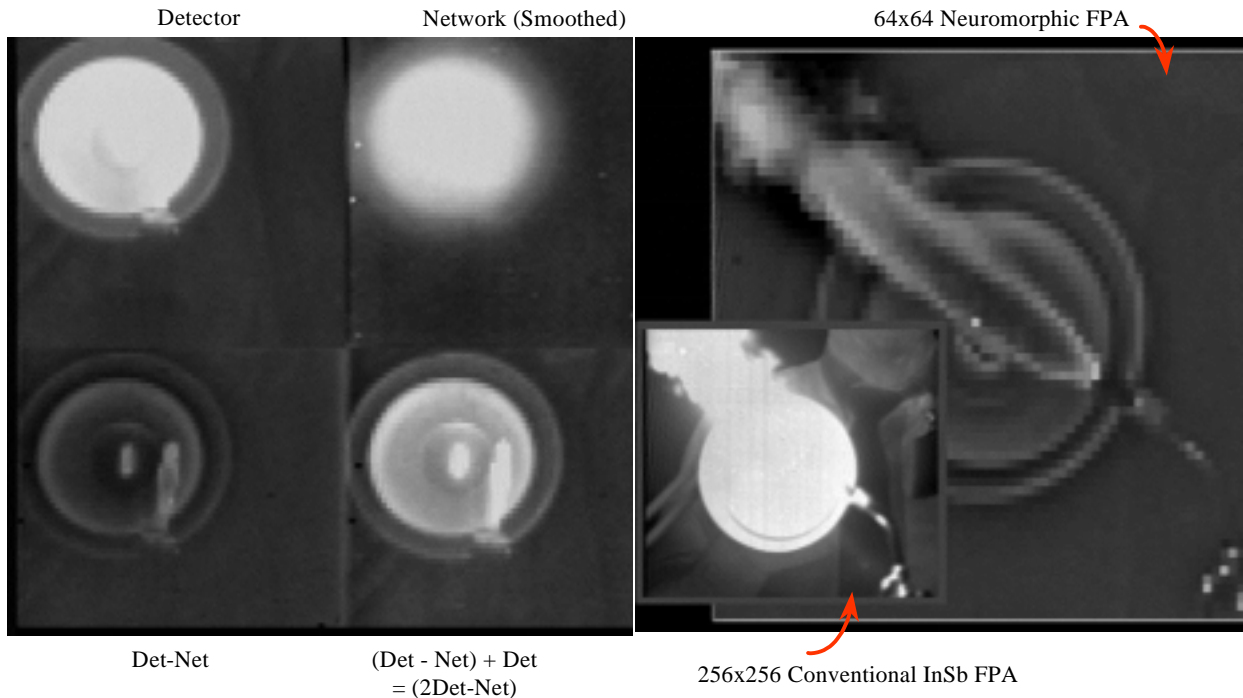


**Figure 4. The SNIF sensor assembly is a hybrid structure which uses a 64 x 64 InSb detector array indium bump-bonded to a CMOS Readout & Processing Integrated Circuit.**

Sample imagery of the detector output, network (Gaussian smoothed), and detector minus network, or DoG process, is shown in the left side of Figure 5. When compared to a conventional imager, the SNIF device performs a real time local contrast enhancement, which does not allow it to "saturate" when a high flux input is presented. An example of this capability is shown in the right side of Figure 5.

<sup>7</sup> Massie, M., P. McCarley, and J.P. Curzan, (1993), "Neuromorphic Infrared Focal Plane Performs Sensor Fusion, On-Plane Local Contrast Enhancement, Spatial and Temporal Filtering", Proc. SPIE, Vol. 1961, pp-17, Orlando.

<sup>8</sup> Massie, Mark et. al., (1994), Neuromorphic Seeker Infrared Demonstration Sensor, Final Report, DTIC, WL-TR-94-7034.



**Figure 5: SNIF Imagery. Left: Clockwise from upper left: Logarithmic Detector Response, Smoothing Network Response, Net - Det, (Net-Det)+Det. Right: Conventional 256x256 InSb FPA imagery inset in 64x64 SNIF Imagery**

During the same time period that AFRL/MNG sponsored the development of this “first generation” smart FPA, we were also sponsoring advancements in multi-band quantum well infrared photodetectors (QWIP)<sup>9</sup>. A “second generation smart FPA” was developed which married the dual-band QWIP technology with novel implementations of neuromorphic filtering. Dubbed “NeuroSeek”, this device combines a spatially and temporally registered Midwave Infrared/Longwave Infrared (MWIR/LWIR) detector structure with a “smart” neuromorphic analog image processing into an advanced IRFPA. A Readout and Processing Integrated Circuit (ROPIC) VLSI chip was developed by Pacific Advanced Technology<sup>10</sup>, and a dual color detector array was developed by Lockheed Martin (Sanders group). These two components will be hybridized to produce the NeuroSeek FPA.

The NeuroSeek device may be operated as a conventional dual color 256 x 256 imager, or a variety of “Region of Interest” (ROI) modes may be commanded to perform DoG processing (which increases the effective signal to noise of the detected image). Binarized video data is available in all modes of operation. The NeuroSeek device was developed so as to provide EITHER the full-frame 256 x 256 dual color mode of operation OR the ROI reduced frame size mode of operation. A primary reason for the ROI mode is to increase the effective frame rate. Figure 6 shows the image processing flow through the chip. NeuroSeek performs signal processing that has been traditionally relegated to off-FPA digital processors. It will perform this processing in the analog domain directly on the focal plane at faster effective speeds with reduced power requirements as compared with the more traditional Digital Signal Processor (DSP) approaches. The effective *digital* throughput which would be required

<sup>9</sup> Faska, T. et al, (1994), “MultiSpectral Quantum Well Staring Focal Plane Arrays and Systems,” Proc. 3rd Annual AIAA/BMDO Interceptor Technology Conference.

<sup>10</sup> McCarley, P., M. Massie, C. Baxter, B. Huynh, (1998), “NeuroSeek Dual Color Image Processing IRFPA,” Proc. SPIE, Vol. 3360-02.

to perform the same level of processing was shown to be on the order of billion operations per second (GOP)<sup>11</sup>. This coupled with power dissipation in the milliwatts provides an effective TeraOPS/Watt benchmark!

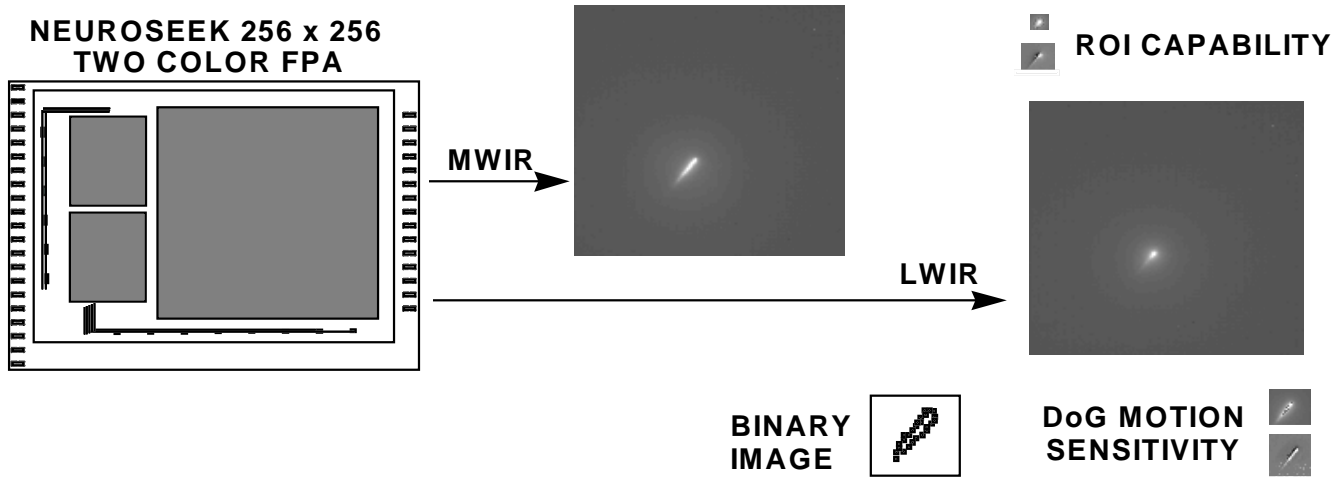


Figure 6. NeuroSeek produces simultaneous 2-color MWIR/LWIR imagery as well as processed ROI image data.

Figure 7 shows a representation of the result of two on-chip processing operations in which both the MWIR and LWIR data have been edge enhanced using the DoG processing capability, followed by binary edge extraction using an on-chip pixel intensity two-level thresholder. This process is sometimes referred to as a “Marr” filter.

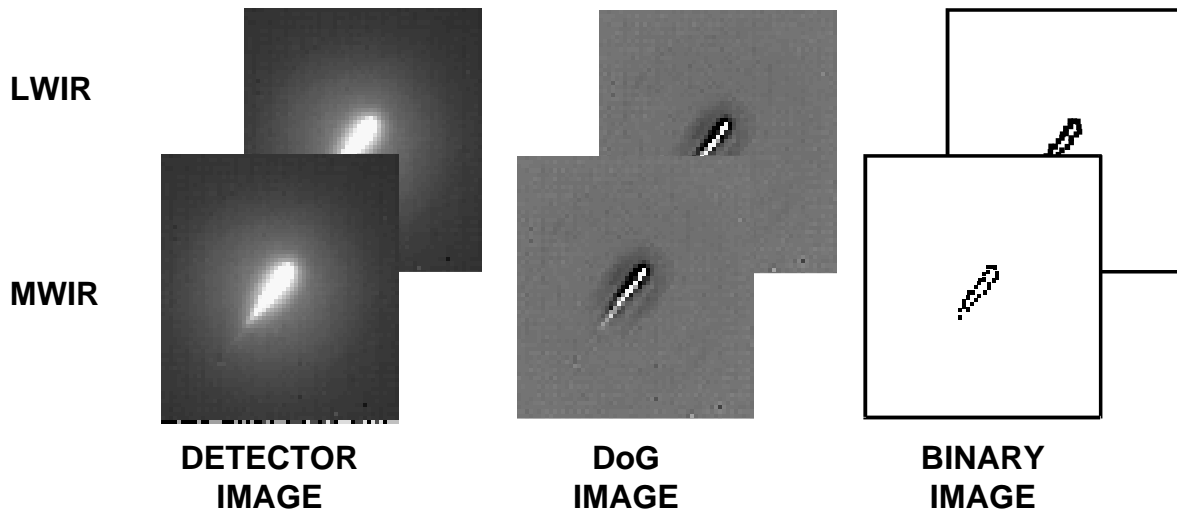
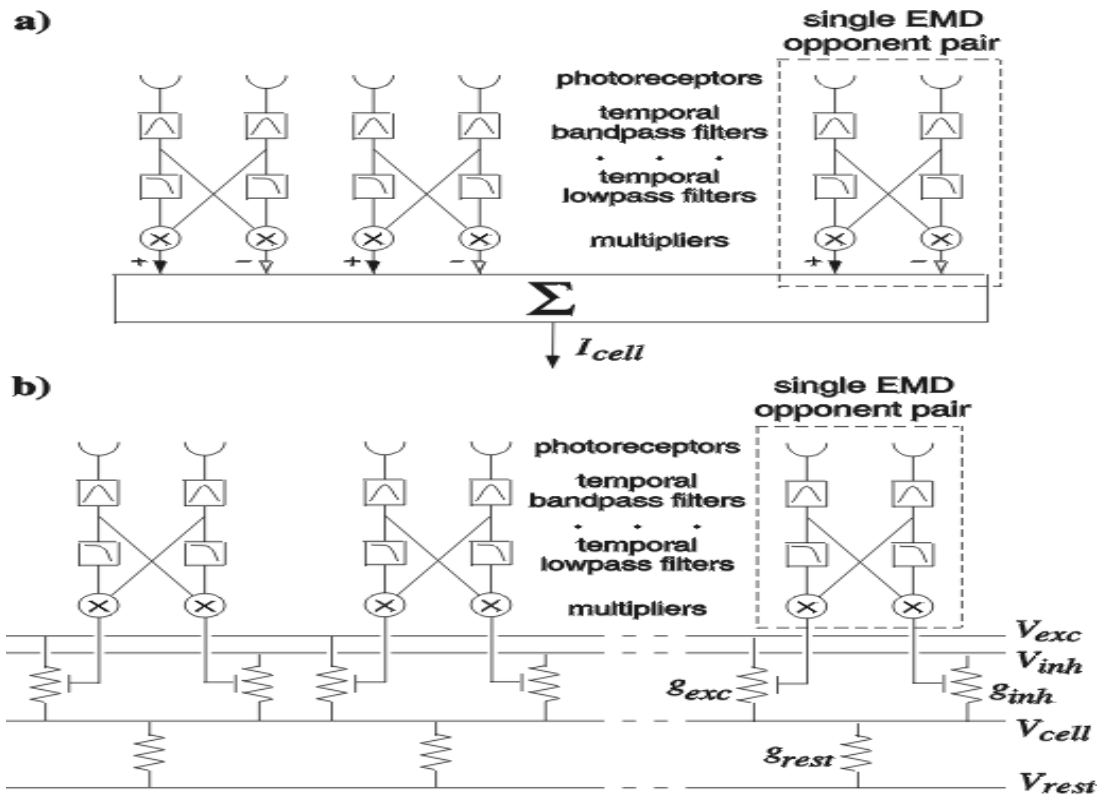


Figure 7. Region of interest processing modes enhance detection contrast and perform preprocessing functions at high frame rates.

<sup>11</sup> McCarley, P., M. Massie, and B. Huynh, (1996), “The NeuroSeek Infrared Focal Plane Array: A High Density Two Color On-Chip Neuromorphic Processing Focal Plane Array for Motion Sensing Applications,” Proceedings of the IRIS Specialty Group on Passive Sensors.

Dr. Christof Koch of the California Institute of Technology and Dr. Hua Li of Texas Tech University have published a collection of papers regarding the design and implementation of biologically-inspired vision chips in which a large variety of techniques developed over the last decade are compiled<sup>12</sup>. This book brings together into one source the widest collection of work performed as of the publication date (1995) and will serve as an important reference for future efforts.

Dr. Reid Harrison, having been a graduate student at Cal Tech and associated with Koch and Mead, wrote his doctoral thesis on the subject of the “Elementary Motion Detector” (EMD)<sup>13</sup>, a biological structure that has been found to exist in the visual systems of many invertebrates (and in similar forms in vertebrate animals). We believe this to be the latest academic effort with regard to the design and development of neuromorphic vision-based imaging and/or sensing chips. In his research, Harrison, “built VLSI systems incorporating light sensors and information processing circuits side by side on the same chip. These continuous-time analog CMOS circuits operate in the weak inversion (subthreshold) regime to match biological time constants and achieve sub-milliwatt power dissipation. Detailed characterization showed our sensor to be an accurate implementation of the Hassenstein-Reichardt motion detector model originally developed to describe insect visual response.”<sup>13</sup> Harrison’s models of wide-field motion sensitive neurons of the fly’s visual system are shown in Figure 8.



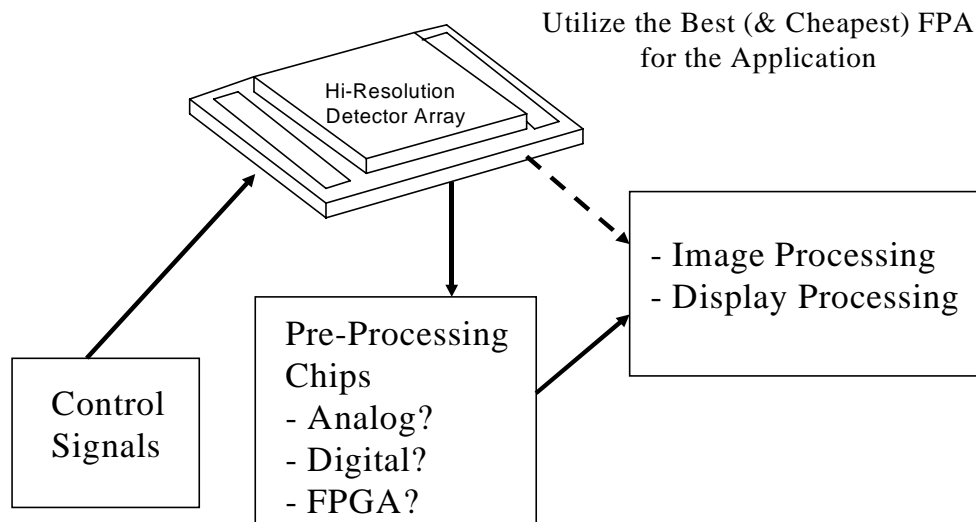
**Figure 8. a) Linear spatial integration. Arrays of EMD opponent pairs are subtracted locally to achieve strong direction selectivity, with the spatially distributed outputs being summed together. b) Nonlinear spatial integration. EMD opponent pairs modulate excitatory and inhibitory synaptic conductances of the wide-field neuron. The EMD activity can pull the neuron away from its resting potential  $V_{rest}$ . (Reprinted with permission from Harrison<sup>13</sup>)**

<sup>12</sup> Koch, C. and Hua Li, Editors (1995), *Vision Chips Implementing Vision Algorithms with Analog VLSI Circuits*, IEEE Computer Society Press.

<sup>13</sup> Harrison, Reid R., (2000), “An Analog VLSI Motion Sensor Based on the Fly Visual System, PhD thesis,” California Institute of Technology.

## 2. WHERE ARE WE GOING FROM HERE?

Advances in electronics will of course drive the architectures of future imaging systems. We have seen CMOS VLSI feature size dramatically decrease within the last decade – going from 1.25  $\mu\text{m}$  and larger down to .35 $\mu$  for analog processes and .08 $\mu$  for digital processes. Field programmable gate arrays (FPGA) allow the design of reconfigurable computing architectures. FPGAs coupled with low cost digital signal processors (DSP) can make for very powerful digital computers, albeit power hungry. Portable consumer electronic applications will drive the development of very low power high performance digital devices. With the advances in multi-chip modules (MCM), it is only a matter of time when both analog and low power digital devices will be integrated into a single small module. Integration of these technologies will be the basis for future generation imaging systems. Although we demonstrated two IRFPAs with built-in processing (other groups have demonstrated similar devices), these tended to be very complex chip designs. We are now able to integrate the best hi-resolution sensor array for the application at hand with near FPA processing chips (analog and/or low power digital). Figure 9 shows one such concept from a functional point of view.



**Figure 9. Functional flow of a Next Generation “Smart” Imaging System?**

Using the technologies discussed, it may be possible to map the processing of biological visual systems into a modular architecture. Figure 10 shows a conceptual mapping of the various levels of the vertebrate visual system into corresponding electronic modules. There are of course issues with each layer that needs to be dealt with during the engineering of the imaging system.

Figure 11 shows a multi-layer processing approach of this concept, and Figure 12 shows an implementation of such multi-layer processing in a sensor electronics system developed by Nova Research, Inc. under AFRL/MNG sponsorship called the “Modular InfraRed Imaging Applications Development System”, MIRIADS. Actual hardware is shown in Figure 13, a system that operates the SNIF device as previously described and shown in Figure 5.

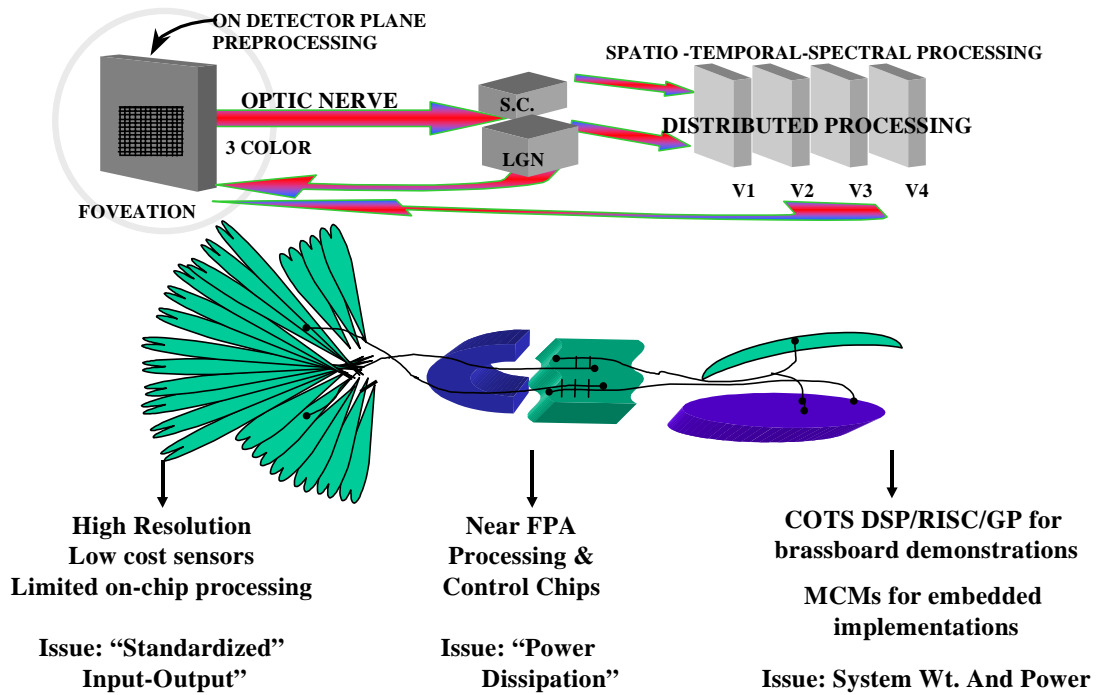


Figure 10. From Biology to Hardware - A Modular Approach

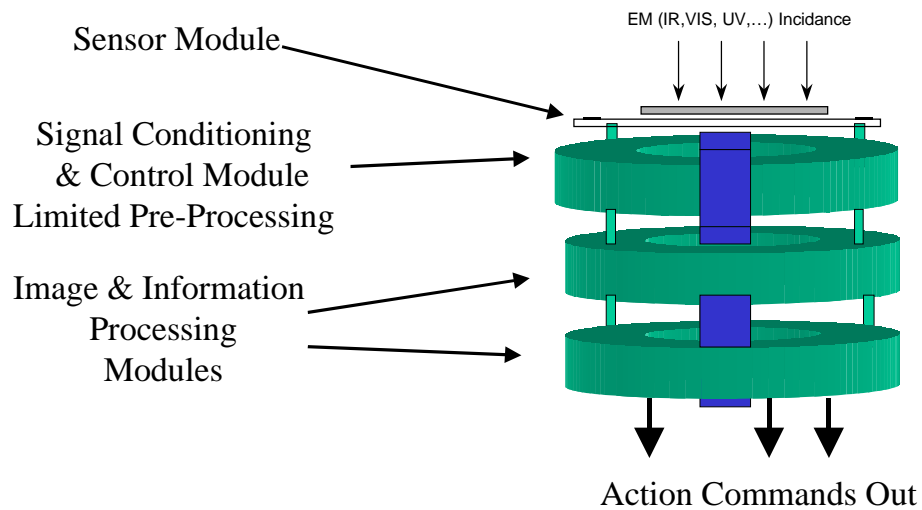
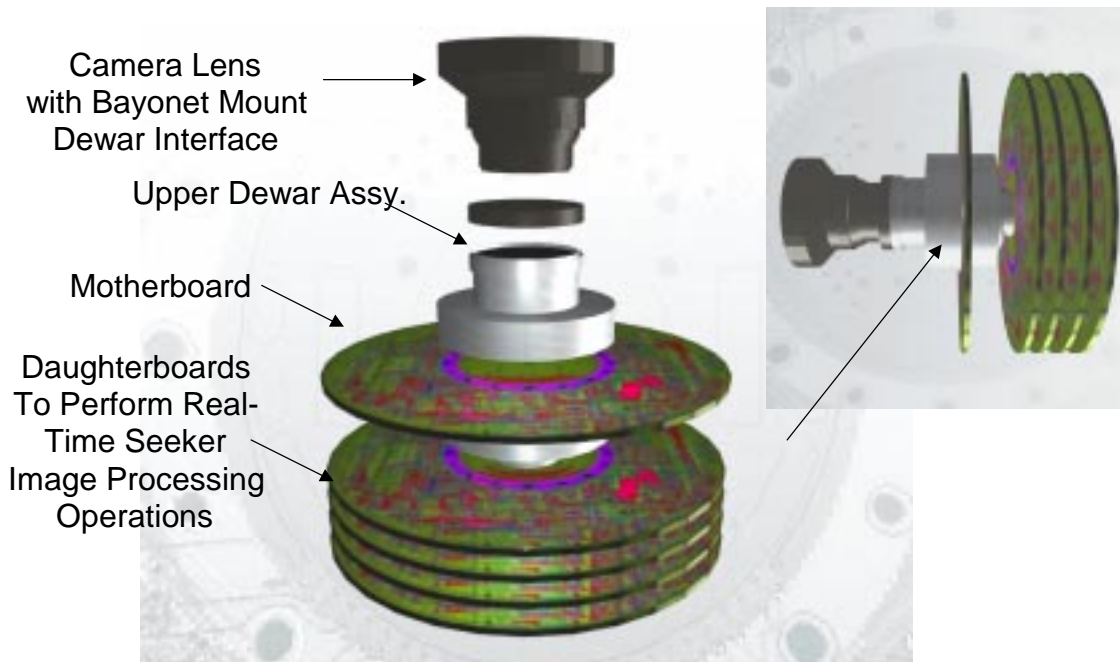
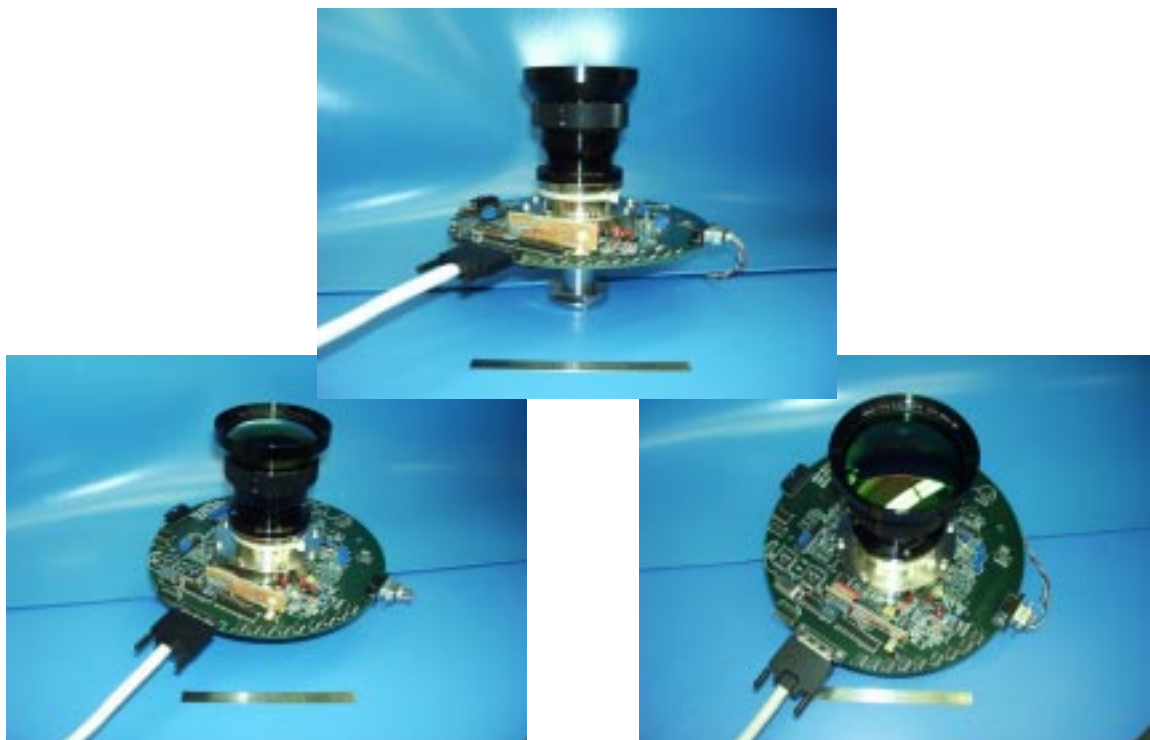


Figure 11. One Concept of Implementing an Imaging System



**Figure 12. Nova's Modular InfraRed Imaging Applications Development System (MIRIADS) provides a modular architecture for operating virtually any existing focal plane array device and allows for a vertical flow of processed information for a variety of system applications.**



**Figure 13. Three views of an existing MIRIADS system operating the SNIF focal plane array showing a six-inch scale for size comparison.**

Having just speculated that modularity should be the key driver for (near) future system, what is in store for the far term? The continuous decrease in CMOS feature size may possibly slow down in the near future using conventional lithography approaches. Instead of fighting with the quantum effect problem of very small electronic components, we should use this as an electronic transport media to fabricate future very dense devices. This was a subject of research by the author and others<sup>14</sup>. Quantum electronic devices not much larger than angstroms can be used as the building block for quantum logic gates, which in turn can be combined and locally interconnected by the trillions to produce quantum ICs. These quantum ICs can then be the building blocks to completely new modular, yet very dense computing kernels. Figure 14 shows one such concept of a quantum based image processor. By utilizing very low power quantum device technology, each sensor element can have its own *dedicated* ADC/DSP/Memory. It may indeed be possible to one day integrate a high performance 3-D massively parallel processor monolithically coupled with a high resolution multi-band detector array, and functionally implement the neural inspired processing architecture shown in Figure 15. This may just be a pipe-dream, however, as research engineers we need to have a “vision” of innovative technologies and potential applications to shoot for.

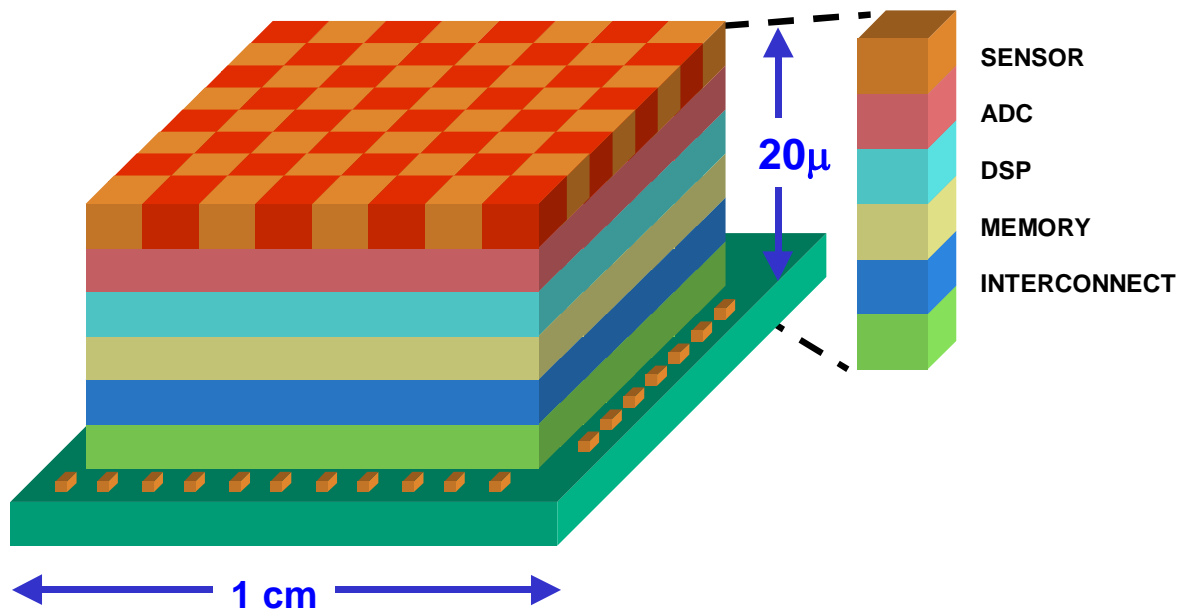
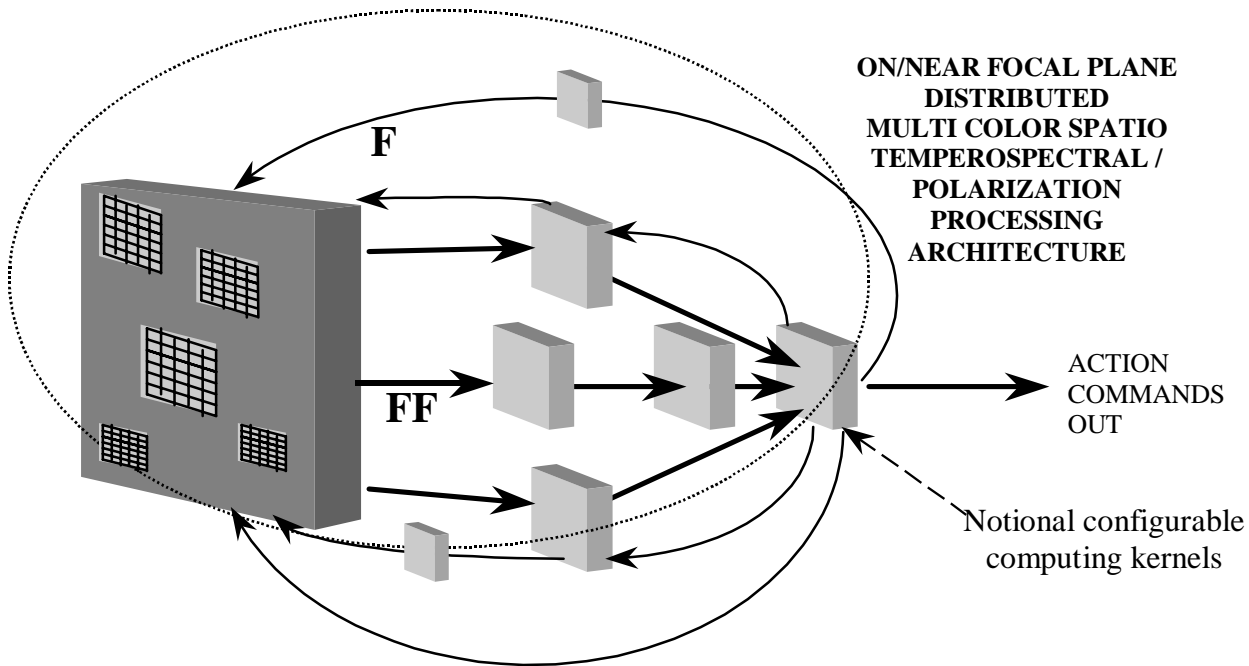


Figure 14. Quantum Imager and Processor

<sup>14</sup> McCarley, P. & G. Frazier, (1993), “Quantum Imager & Processor for Guided Interceptors,” Proc. SPIE Vol. 1957 (1957-30).



**Figure 15. Functional Composition of a Quantum Imager and Processor**

### 3. CONCLUSION

This paper describes some recent biologically inspired “neuromorphic” FPA developments. Although quite capable, these chips were very complex. In the near term, “smart” imaging systems should take advantage of commercially available high-resolution sensors, and integrate them with near FPA processing chips in a modular fashion. However, ten years from now system designers may have “quantum” based imager and processor components. This would lead to extremely high performance imaging systems no larger than today’s pentium class chips. This capability will provide tremendous payoff in a multitude of applications not yet imagined. This has been by no means an exhaustive review of biologically inspired sensory processing, For example, we did not have time or space to discuss the research in “foveal” or multi-resolution<sup>15,12</sup> sensors and its potential applications and payoff.

### 4. ACKNOWLEDGEMENTS

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<sup>15</sup> Stack, D. J., et.al. (2000) “Target acquisition and tracking system based on a real-time reconfigurable multi-window CMOS image sensor,” Proc. SPIE Vol. 4025 (4025-22).