

# On-Chip Signal Processing Configurations for Focal Plane Arrays

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## ABSTRACT

Third generation Focal Plane Arrays (FPAs) are being designed to incorporate numerous sophisticated “smart” functions, useful in the preprocessing and filtering of real-time image data. Designers at Nova Research, Inc. have developed ROIC designs which have increased the capabilities of these devices in the area of signal and image processing. These new FPAs are more versatile than their predecessors through the implementation of a variety of programmable modes of operation. This paper will discuss a variety of such processing functions and modes.

Design configurations for such FPAs will be discussed with regard to the incorporation of general and specific signal processing functions. Such functions will include but not be limited to: edge enhancement and edge extraction, accommodating high and low signal flux environments, high speed windowing and foveated pixel arrangements.

Keywords: infrared, on-FPA processing, ROIC, smart sensors, filtering

## INTRODUCTION

The importance of incorporating signal and image processing functions either directly on the Focal Plane Array (FPA) or very near to it lies in the requirement to perform these functions in a very small volume, for a very low investment of electrical power. Systems concepts are being developed in which infrared camera systems must be designed to fit into the small head of an airborne platform while simultaneously processing the image data such that it is useful for a variety of other related functions. These functions may include target identification and efficient target identification.

This paper discusses some of the functions incorporated into on- or near-FPA electronics and provides some insight as to how the technology may be extended into future applications. Following sections will discuss some specific design implementations that have been reported in the open literature.

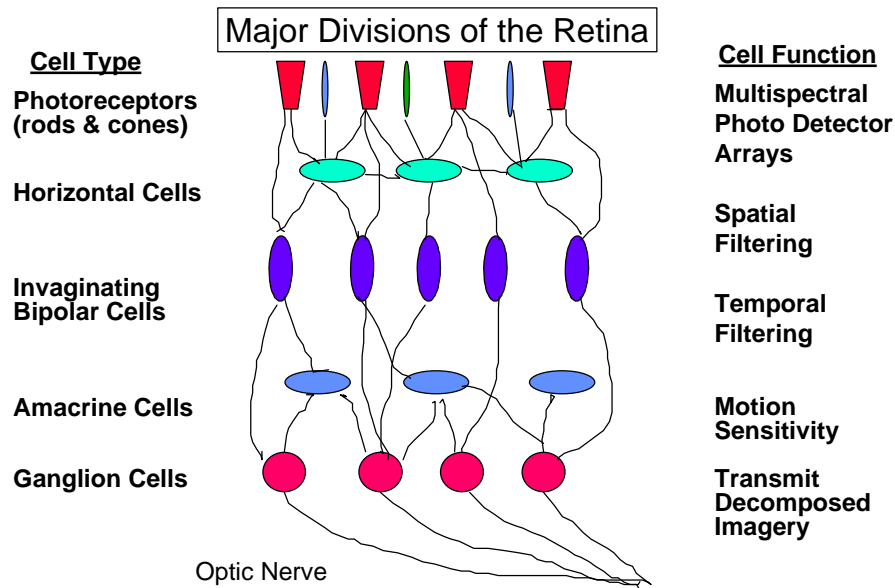
Mead has reported that it is possible to mimic the form and function of biological sensors using silicon design practices<sup>1</sup>. In their pioneering work to develop an operational “Silicon Retina”, Mead and Mahowald helped develop the basic circuit designs required to produce an operational light-sensitive imaging array that had “built-in” operational responses very similar to that of the retina possessed by all vertebrate animals<sup>2</sup>.

Figure 1 shows a schematic diagram of the cellular construction of a vertebrate retina, and identifies the particular function for each cellular layer. If one were to design a silicon implementation of these functions, circuit element would be included to perform the functions of multispectral photo-detection, spatial and temporal filtering, motion detection and subsequent transmission of a reduced image dataset to following processing stages. A challenge to the designer is to successfully design this circuitry to reside in the very small unit cell areas available in a Focal Plane Array (FPA) unit cell, or to incorporate this circuitry in the unit cell of a “co-processing” integrated circuit that is physically separated by a small distance from the FPA.

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<sup>1</sup> C. Mead, “Neuromorphic Electronic Systems”, Proc. IEEE, Vol. 78, No. 10, 1990, pp. 1629-1636.

<sup>2</sup> C. A. Mead and M. A. Mahowald, “A Silicon Model of Early Visual Processing”, Neural Networks, Vol. 1, 1988, pp. 91-97.



**Figure 1. Silicon-based sensors are being designed based upon the cellular construction of biological retinas<sup>3</sup>.**

## 1.0 EDGE ENHANCEMENT TECHNIQUES

Nature has the great advantage of being able to wire its circuits in three dimensions, each circuit bathed in a protective electrolytic substance that aids in the conduction of electrical signals from transmitter to receiver. It also has the ability to repair damaged circuitry on its own. In effect, nature “distributes” the tasks of operation and maintenance of its designs to the lowest possible level.

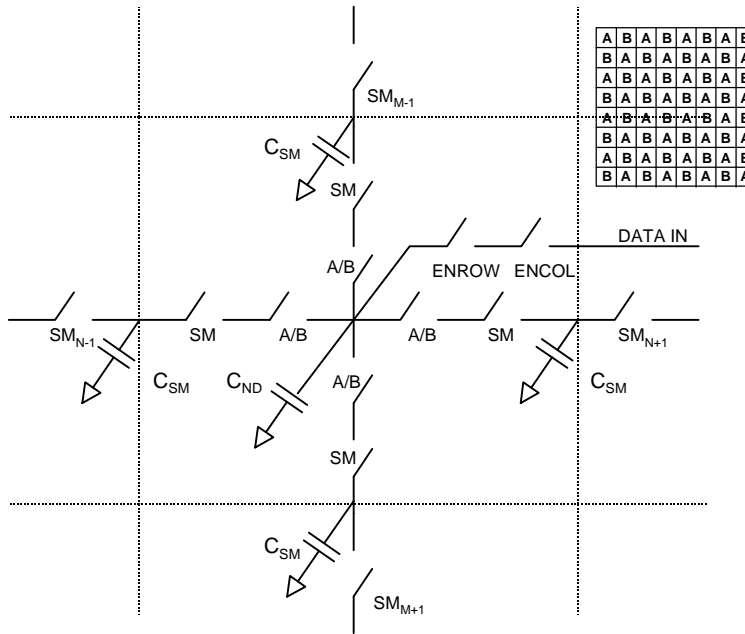
In a similar way, we are designing sensor arrays such that individual pixels have the ability to communicate with neighboring pixels, sharing information and making decisions appropriate to the task at hand. We must make use of our present technology which permits two-dimensional circuit elements to be utilized, with limited use of the third dimension. As silicon processing advances, opportunities to implement advanced image processing algorithms in silicon are now being realized.

Figure 2 shows a two-dimensional array of capacitors connected by means of a switched-capacitor network. Used by Massie<sup>4</sup>, et. al, Umminger<sup>5</sup> and others in their previous work, switched capacitors are convenient because they consume minimal space and are digitally addressed. By controlling the switch phasing to the network, charge initially stored on a node capacitance is exponentially distributed radially outward from the node capacitance. The radial migration of charge depends upon the number of switching cycles executed, and the ratio of capacitances between the node capacitor and the transfer capacitances in the switched capacitor network. Figure 3 represents the timing relationships required for such charge migration to occur. The resulting image representation is that of an image which is electronically blurred – a useful form of the image for finding sharp edges in the scene.

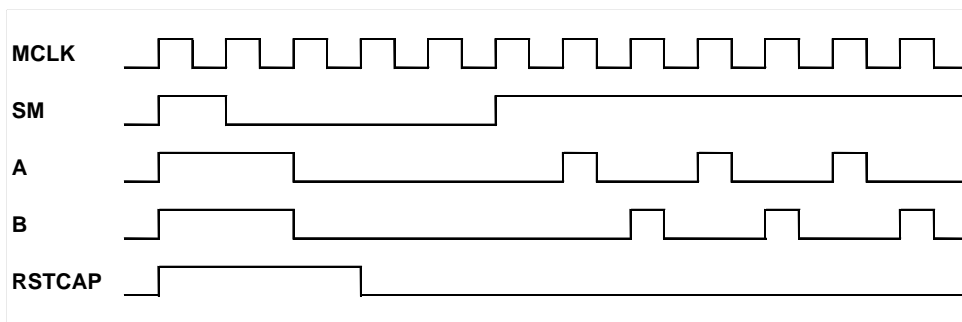
<sup>3</sup> Massie, M. A., C. R. Baxter, B. L. Huynh, P. L. McCarley, “NeuroSeek Dual-Color Image Processing Infrared Focal Plane Array”, SPIE AeroSense 1998, Focal Plane Array Electronics IV, Orlando, 1998.

<sup>4</sup> Massie, M. A., J. T. Woolaway, B. L. Huynh, G. A. Johnson, R. F. Cannata, W. J. Parrish, “Neuromorphic Infrared Focal Plane Performs On-Plane Local Contrast Enhancement, Spatial and Temporal Filtering”, Proc. of IRIS, Passive Sensors, January, 1992.

<sup>5</sup> Umminger, C. B. and C. G. Sodini, “Switched Capacitor Networks for Focal Plane Image Processing Systems”, IEEE Trans. Circuits & Systems for Video Technology, Vol. 2, No. 4, 1992, pp. 392-400.



**Figure 2. Sophisticated biological image processing functions may be mimicked in silicon by using conventional switched capacitor networks.**



**Figure 3. Externally-applied control signals presented to the switched-capacitor network of the previous figure produce a charge sharing response which intentionally blurs the image.**

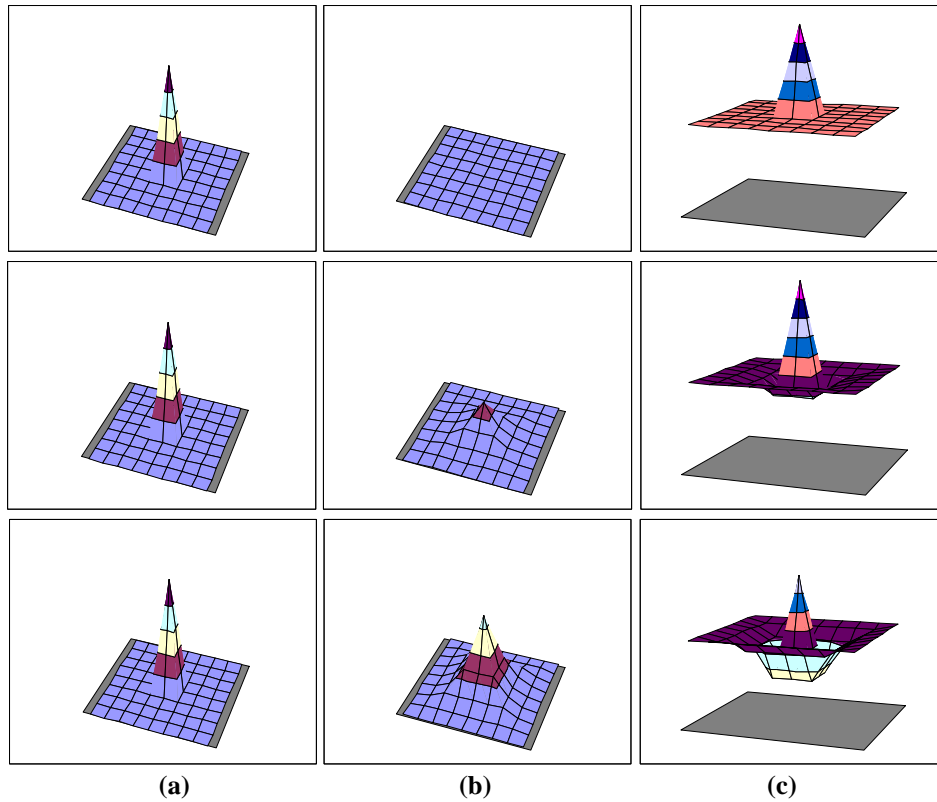
With an emphasis on supporting the use of real-time electronics to model the essential features of biological retinas, Poggio was one of the first researchers to apply mathematical theory to the description of how the vision process is computed<sup>6</sup>. Poggio's work was in part the result of previous efforts to describe the vision process by Marr<sup>7</sup>. They realized that an intermediate blurred representation of the visual field was required such that a difference taken between the unblurred and blurred representations of the visual field produced an image with enhanced edge features.

To demonstrate this, Figure 4 presents a sequence of images that produce such an edge-enhanced result. The (a) set of images represent the "input image" to the sequence. In this case, it represents the photoresponse of a small FPA in which a single pixel is illuminated with light. The upper set of images occur first, followed in time by the middle set, and finished with the lower set of three images. The (b) group of vertical images show the image as it is contained in time on the node capacitances of Figure 2, as signal charge becomes distributed away from respective image sites. The (c) group shows the mathematical difference that is taken between the (a) and (b) sets of images. Notice that, as time proceeds, the bright center of the image has the effect of inhibiting the response of neighboring pixels. Mead's "Silicon Retina" and Massie's "Neuromorphic

<sup>6</sup> Poggio, T., V. Torre and C. Koch, "Computational Vision and Regularization Theory", Nature, Vol. 317, No. 6035, 1985, pp. 314-319.

<sup>7</sup> Marr, David, Vision: A Computational Investigation Into the Human Representation and Processing of Visual Information, W.H. Freeman, 1982

Infrared Focal Plane” produce imagery consistent with this diagram. Referred to as the “Difference of Gaussians” or DoG, this process has been shown to be implemented in the retinas of vertebrate animals.

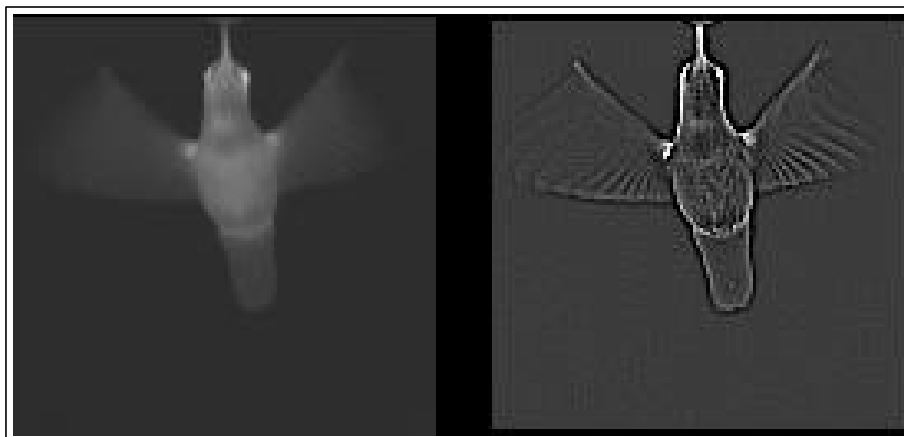


**Figure 4. (a) An input “scene” is represented by a single-pixel response.**

**(b) A Gaussian blurring of the input scene produces an intermediate response which proceeds from top to bottom.**

**(c) The mathematical difference between the input scene and the blurred scene produces the DoG response.**

A visual representation of the DoG function is shown in Figure 5. A frame of infrared imagery of a hummingbird in flight was processed using the DoG technique as described above to indicate that low-contrast image variations present in the original image are clearly visible in the DoG-processed image. Not only are the bright (hot) portions of the image retained



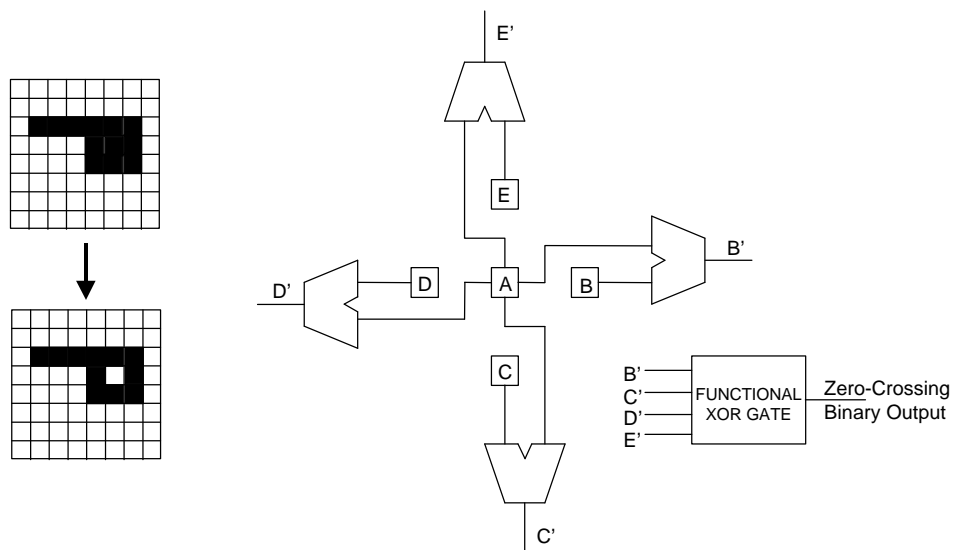
**Figure 5. The DoG response of a hummingbird shows enhanced edge contrast. (Infrared imagery courtesy of the SE-IR Corporation, Goleta, CA)**

near the deltoid musculature and near the eyes, but the lower-contrast variations are enhanced to show individual feathers and texture present in the body of the hummingbird. Radiometric accuracy is lost through this image transformation, but the essential information represented by texture variations and heat centers are preserved. The “NeuroSeek” Infrared Focal Plane Array, designed and produced by Pacific Advanced Technology of Santa Ynez, CA, incorporates the features as described above, as well as hosting a variety of other on-chip functions<sup>8</sup>.

A variety of researchers have identified the capability of biological systems to detect when a particular sensor-produced signal crosses from the “positive” to the “negative” (or vice-versa) signal domain. Such a “zero-crossing” may be detected and used to identify the precise edge of an object within the field of view. The zero-crossing operation is naturally applied after a DoG, because the DoG produces zero-mean image data (i.e., approximately half of the DoG image distribution is in the positive domain, half is in the negative domain).

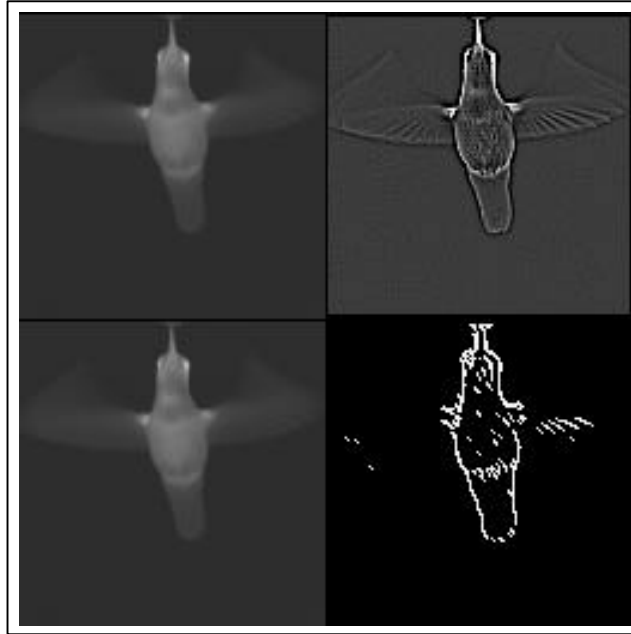
A conceptual “zero-crossing” detection architecture for an FPA that could be realized in a silicon device is shown in Figure 6. Each element of the two-dimensional imaging array is compared with its nearest neighbors in the X- and Y- directions. When “A” is compared with each of its neighbors, a determination is made as to whether its value is above or below the value of its neighbor. A “functional” XOR operation is performed on the result of each of four comparator operations, which in turn produces the zero-crossing response as shown by the “P” in Figure 6.

This operation has the potential to be performed on a frame-by-frame basis for real-time zero-crossing image processing. A significant advantage to performing this operation is that the essential spatial edge information contained in the image is preserved, while dramatically reducing the quantity of digital data required to represent the salient aspects of the image. For example, a 1024 x 1024 pixel FPA image contains 1,048,576 discrete element values. Storing the entire frame of image data using a 12-bit grey level depth per pixel results in a frame that is 1.57 megabytes in size. If on the other hand, the 1-bit zero-crossing representation were stored, its size would be only 131 Kbytes. Smaller frame size equates directly to higher data throughput rates; in this case, throughput could be as much as 12 times faster for the reduced-size zero-crossing data set.



**Figure 6. A hardware implementation of a zero-crossing operation may be realized by utilizing analog comparators and a functional XOR operation.**

<sup>8</sup> Massie, M. A., C. R. Baxter, B. L. Huynh, P. L. McCarley, “NeuroSeek Dual-Color Image Processing Infrared Focal Plane Array”, SPIE AeroSense 1998, Focal Plane Array Electronics IV, Orlando, 1998.



**Figure 7. The zero-crossing image as shown in the lower-right image preserves the essential geometries in the scene, but conveys the information in a 1-bit representation.  
(Infrared imagery courtesy of the SE-IR Corporation, Goleta, CA)**

To demonstrate how the zero-crossing image preserves the spatial integrity of the image, Figure 7 compares the original input scene (left-most images) with the DoG image (upper right) and the zero-crossing image (lower right). Many algorithms that follow depend upon the reduced size of the zero-crossing image dataset. In his chapter on “Zero-Crossings and the Primal Sketch”, Marr lays the foundation for a description of how zero-crossings are used in biological vision systems<sup>9</sup>. Following this, his chapter on “Directional Selectivity” makes use of such zero-crossings in order to perform “directional selectivity” in order to separate surfaces which are moving independently of one another.

Marr makes use of the concept that if a zero-crossing is produced, and if the vision system producing the zero-crossing representation has the ability to store at least one previous frame of information, then the system has the ability to infer the direction of motion of the zero-crossing edge. “Selectivity” may be utilized such that the imaging system simply does not report edges which are moving in certain user-selected directions. This may be shown to be a very powerful technique if, for example, detections due to background motion in the scene must be eliminated. If the direction of the background motion relative to the stationary sensor is known, such a technique could completely eliminate the background’s motion from the resulting imagery.

In another application, Marr points out that simultaneous zero-crossing detections from two eyes separated by a fixed angular displacement may be used effectively. If, for example, one eye detects zero-crossings for an object that are moving to the left, while the other eye detects zero-crossings for the object that are moving to the right, the brain determines that the object is moving in the depth direction. In his words, such “looming” sensing is made possible through the analysis of zero-crossings which are moving in incompatible directions. Applied to at least two simultaneous zero-crossing detectors as shown in Figure 6 and combined with some simple logic, a system could be used in this case for passive ranging applications.

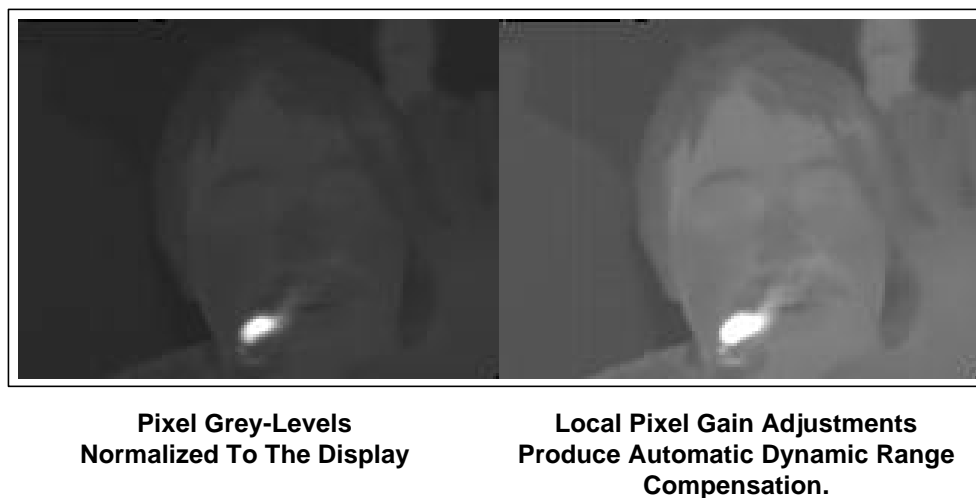
<sup>9</sup> Marr, Vision, A Computational Investigation into the Human Representation and Processing of Visual Information, “Directional Selectivity”, W. H. Freeman and Company, New York, 1982, pp. 159-182.

## 2.0 AUTOMATIC SENSOR-BASED GAIN ACCOMMODATION

Matching the dynamic range of detected signals to the dynamic range of display devices or following analysis systems is a universal challenge for systems designers. If the sensor itself had the ability to “self-adjust” its output so as to more nearly match the signal range for following display devices or analysis systems, powerful sensing systems could be made to be smaller, less expensive and more functional.

Figure 8 shows the application of a pixel-based technique to the task of effectively displaying 12-bit infrared camera data to the 8-bits (or less) display capability of a computer display (or laser printer). In most “Automatic Gain Control” (AGC) systems, it is necessary to compute some statistics on the image data. For example, the mean and standard deviation of imagery is typically required such that the pixel grey-levels residing within a preset number of standard deviations from the mean are linearly spread across the display range of the system. While radiometrically scalable, this technique requires a large computational overhead and would be difficult for the sensor itself to compute.

The image on the left side of Figure 8 was normalized such that the hottest pixel response was set to the maximum white value, and the coldest pixel response was set to the minimum black value. Since most of the information is contained in the dark portion of the histogram when properly representing all pixel levels linearly from black to white, the display is not very useful for a human observer. The right image of Figure 8 shows the image after a simple pixel-based operation is applied to the data. In effect, this example simulates how an FPA or near-FPA co-processing circuit could be designed so as to automatically adjust the integration time of the sensor such that the resulting data is always represented in an acceptable fashion for a human observer.



**Figure 8. On- or Near-FPA operations may be used to automatically adjust the sensitivity of the pixel so as to accommodate wide dynamic range image data.  
(Uncooled IR imagery courtesy of Indigo Systems, Inc., Santa Barbara, CA)**

Each pixel in Figure 9 essentially compares its value to a user-defined preset value. If its value is below the preset reference value, the pixel decides to increase its integration time, thus effectively increasing its responsivity. The amount of integration time change is very small with any individual frame. Likewise, if the pixel's value is above the preset reference value, the integration time is reduced, thus reducing the effective sensitivity of the imager. Fortunately, in most imaging applications, the imagery is always moving; if it were not, the imager's output would fade away since the contrast variations present in the input scene would be reduced.

It is interesting to note that the micro-cicadic motion exhibited by the human eye is probably required to maintain such a pixel-based gain compensation in a condition such that the viewer always retains high contrast in widely-varying illumination conditions. The temporal characteristics of the motion detection and gain accommodation features of the human eye are based upon the detection requirements of the eye-brain system. For example, if the primary use of the eye-brain combination were to hunt prey or evade attack from a predator, the size and weight of the person who must move at the required speed would define how fast the visual system must operate.

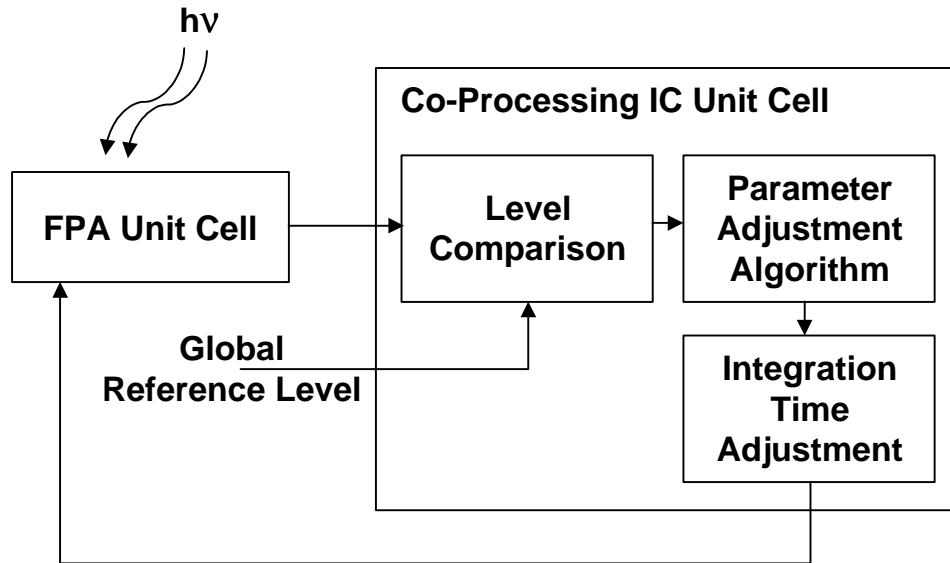


Figure 9. A simple feedback technique is offered as an example for producing pixel-based gain accommodation.

### 3.0 OTHER RELATED ON- OR NEAR-FPA FUNCTIONS

As applications for infrared sensors grow, the sophistication of these devices must grow as well. Numerous applications exist which require that the infrared camera system operate at a high effective frame rate. How would it be possible to permit the device to run faster? A common approach is to design the device to incorporate numerous parallel output data channels. In essence, a device with two output channels running at full speed would produce twice as much data per unit time as that of a FPA with a single output channel running at full speed. On the other hand, the more output channels contained on a device, the more power will be dissipated by the FPA; this is undesirable, especially for devices which must be cooled to operate at cryogenic temperatures.

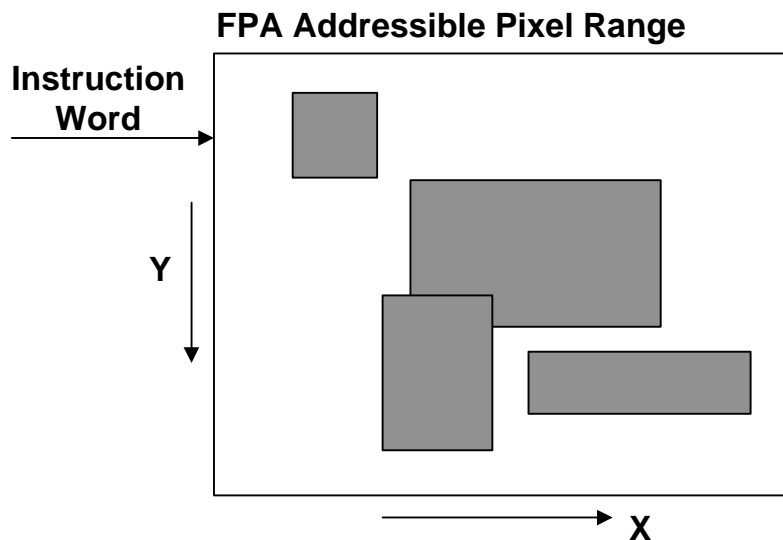
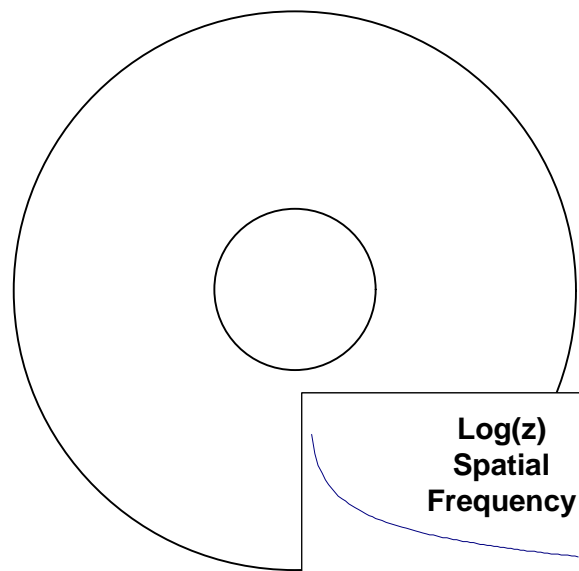


Figure 10. High-frame-rate sensors may be designed utilizing randomly-addressable “Region of Interest” readout multiplexer designs.

Figure 10 depicts a type of FPA which contains a digital chip-controller that generates the clocking required to multiplex only certain user-specified regions of image data out at the frame rate. First developed in 1991 at Amber Engineering, this “Region of Interest” (ROI) processing readout multiplexer permits the user to specify rectangular portions of the FPA for which image data is desired<sup>10</sup>. The FPA itself may be viewed as an analog memory device, in that the pixel response for the previous frame is held as a voltage on an in-cell capacitor. The multiplexer makes use of a source-follower device within the unit cell to represent a scaled version of the pixel’s value. The pixel’s value may be read many times without degrading its value because the source follower represents a high-impedance connection to the outside world. Such a “non-destructive read” operation may be very useful for cases in which overlapping ROIs must be sampled so as to obtain a good representation of the overall scene without taking the time to multiplex out every pixel value on the FPA.

Such an operation requires information to be supplied from the user or the controlling processor. In the case of ROI and other types of on-chip control, many designers have made use of a serial control word that is uploaded to the FPA on a regular basis. This serial control word instructs the FPA to be placed into a variety of operational modes, including those which define the size and location of the ROI. In the case of the 512 x 512 pixel FPA developed at Amber as reported in the referenced paper, a 30-bit control word was required to specify the parameters of the ROI, and this control word was supplied to the FPA with each successive frame. The size and location of the ROI could be adjusted at the frame rate, an obvious advantage for systems which must operate at high frame rates and follow objects of interest. This device could operate at effective frame rates of approximately 60 frames/second for the full 512 x 512 image size, and at approximately 20,000 frames/second for ROI sizes of 16 x 16 pixels.

And finally, Figure 11 presents the concept of a new generation of FPA devices designed specifically to enhance the tracking ability of the infrared system. Such a “foveated” sensor has a central region of pixels that are at a significantly higher spatial density than those near the periphery of the device. If modeled after vertebrate retinas, the spatial frequency of pixels as a function of radial position would be described by a  $\text{Log}(z)$  distribution, where  $z$  identifies the radial direction. It makes sense that most of the processing resources invested in a tracking system would be located near the center of the field-of-view. The foveal sensor satisfies this requirement, and adds some other interesting features.



**Figure 11. Novel new sensors make use of spatial aggregations of pixel channels with varying spatial density and responsivity.**

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<sup>10</sup> Huynh, B., C. Fletcher, M. Massie, "The Flexible Random-Access Multiplexer Engine (FRAME) Readout Architecture", Proceedings of the IRIS Specialty Group on Passive Sensing, February 1991.

The radiometric sensitivity of such sensors is typically lower in the central region than it is near the edge of the sensor. In many systems, this is because the object being tracked is very bright (or hot), and it produces a very strong signal. In order not to saturate the detector's response, the central region would require a lower sensitivity. On the other hand, the system would be very interested to know of the presence of new objects which may enter into the field-of-view. For this reason, peripheral pixels, even though having a low spatial frequency, would be highly responsive. A significant contribution to the development of this technology area was invested by Van der Spiegel, and reported in the literature describing the development of CCD imagers utilizing foveal sensor design concepts<sup>11</sup>.

#### **4.0 SUMMARY**

A variety of researchers have "reduced to practice" the modeling of biological imaging sensors into silicon-based implementations. This paper has provided an overview of some of these important contributions, and has offered an association with the integrated circuit designs and technology required to realize these functions. Most of these designs make use of simple silicon integrated circuit architectures to perform well-defined operations inspired by biologically-based sensors.

As integrated circuits become more dense, a higher level of functional integration will be realized. It is up to systems designers to be creative, and to effectively use nature's examples to their advantage. In many cases, it is believed that the migration of sophisticated preprocessing functions either at- or near to the FPA will result in improved overall performance of sensor systems with respect to size, weight, electrical power and cost.

#### **5.0 ACKNOWLEDGEMENTS**

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<sup>11</sup> J. Van der Spiegel, et al., "A Foveated Retina-Like Sensor Using CCD Technology", Analog VLSI Implementations of Neural Systems, 1989, pp. 189-212.