Variable Acuity Imager with Dynamically Steerable, Programmable Superpixels

J. P. Curzan
Christopher R. Baxter
Mark A. Massie
Nova Research, Inc.
805-693-9600
jp@novaresearch.net

ABSTRACT

Nova Research, Inc. has recently developed a novel two-dimensional imaging chip whose design is based on properties exhibited by biological retinas. The “Variable Acuity” imager permits the user to program a unique spatial arrangement of “superpixels” that may be updated in real time. In effect, any spatial configuration of pixels in the imager may be realized by programming the device in a way that permits pixels to share their individually-collected photocharge with any or all of their neighbors. Single and multiple “foveal” configurations are possible, and these high spatial resolution regions may be “flown” around the FPA at the will of the controlling processor.

This device was developed through the combined requirements of (a) covering a wide total field of view while (b) retaining the highest possible spatial resolution on the targets of interest while at the same time (c) operating at the highest possible frame rate. Many thousands of frames per second are possible with the prototype imager while maintaining high spatial resolution. The prototype device operates as a visible imager, and Nova is pursuing the transition of this technology into the infrared domain. This paper will concentrate on applications of the technology and will show some imagery collected with the prototype system.

Variable acuity, superpixels, FPA, programmable, electronics, UAV

1. INTRODUCTION

Under sponsorship from the Air Force Research Laboratory Munitions Directorate, Nova Research, Inc. has successfully demonstrated the operation of a novel focal plane array (FPA) device that has the capability to be re-programmed into a limitless variety of spatial pixel configurations. The Variable Acuity Superpixel Imager (VASI) offers numerous new capabilities that will open up a variety of new applications for systems designers.

This paper presents an overview of the VASI device and provides some initial concepts for applications which may be realized through the use of this new imaging technology.

2. OVERVIEW OF VARIABLE ACUITY DEVICE

Based upon technology developments produced over the last decade, it is now possible to design a focal plane array (FPA) that incorporates a dynamic, user-defined spatial distribution of pixels. Although virtually any spatial configuration (i.e., size and location) of pixels could be defined, an important first system that has been realized has been programmed to represent the spatial configuration of the vertebrate fovea.

A “foveal FPA” as discussed here has the property of higher spatial frequency of pixel channels near the “center of attention” (COA), with a radially-symmetric spatial frequency diminishing radially out from the COA. The device as described permits the user to define any desired spatial distribution of pixels, and may change this distribution at the frame rate, if desired. In this way, the COA may be directed to move within the total field of view of the FPA in order to track objects of interest with high angular precision, without sacrificing the ability to detect other potential targets which may enter into the sensor’s periphery.

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To be demonstrated throughout the remainder of this paper, every operational advantage required of a tactical imaging sensor would be afforded through the use of this new class of imaging device:

- User-defined spatial distribution of pixels permits high accuracy “on target”, while retaining detection over the entire field-of-view (FOV). Each pixel gets programmed into a specific “superpixel” state, and it will “know” how to share its charge with neighbors such that a resulting superpixel distribution is produced.
- High frame rates are possible by programming the device into a superpixel state; pixels (whether they be “standard pixels” or “superpixels”) need to deliver only one analog data value per frame. This will minimize the total number of pixel values required to be delivered off-FPA, thus maximizing effective frame rate.

This general methodology could be applied to the use of multispectral detector arrays as well. These capabilities are now possible through the use of “READIN” commands to the FPA, used to program the characteristics of individual pixels in the array. Figure 2-1 demonstrates the concept of “FPA READIN Programmability”, resulting in a user-defined effective distribution of pixels. Also indicated in the figure is that the readout state for each pixel may be programmed individually through the use of the READIN command.

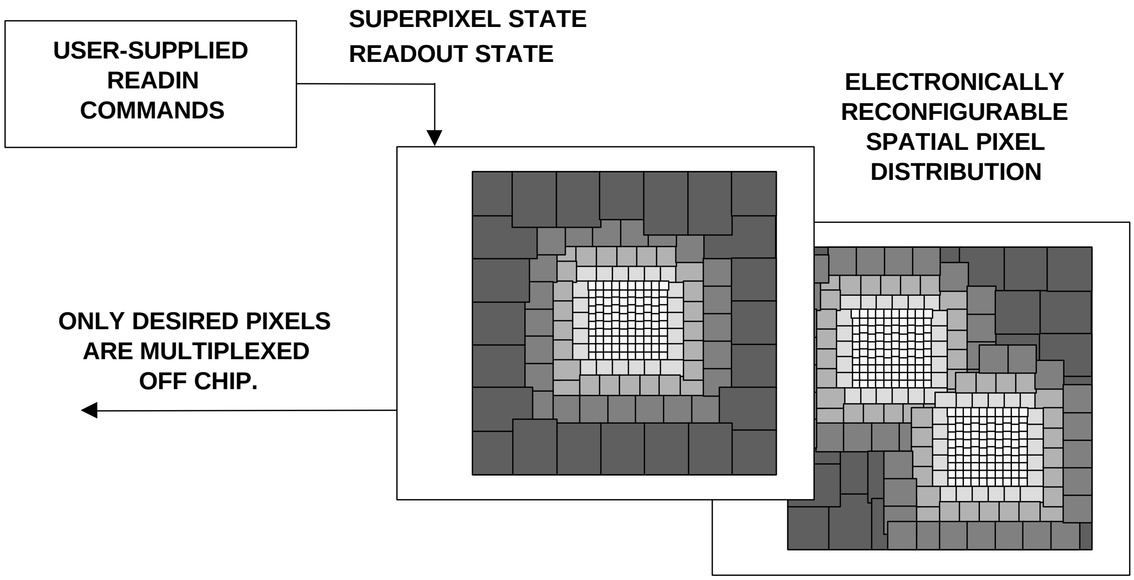


Figure 2-1 User-supplied commands are “read in” to each pixel, resulting in unique superpixel and readout state attributes.

The READIN word multiplexed into each pixel of this VASI will be used in each pixel to set it’s unique superpixel and readout state. Notice that ANY spatial configuration for the VASI would be possible; only two such configurations are shown in the figure. This capability would also permit a variety of spatial convolutions to be performed, opening up an entirely new area of advanced on-FPA image processing to the technical community.

The superpixel configuration of each pixel is used to configure switch closures in an on-chip network that interconnects neighboring pixels. In effect, the combined integration capacitance for a given superpixel will be the parallel capacitance of all connected unit cells. The combined photocharge accumulated on the effective integration capacitance produces a voltage that represents the signal on this effective superpixel.

In order to achieve a high frame rate, only one value per superpixel need be multiplexed off-chip. In addition, the device permits every standard pixel to be multiplexed out (even though it may be part of a superpixel) for diagnostic and other imaging purposes. In concept, as the row select signal ripples down a column of the device during the readout operation, only those pixels which have been previously programmed to produce their output signal will do so. Nova’s VASI design also incorporates a digital output channel that produces a “read-back” of the currently-programmed superpixel state, such that it can be recorded with the gray-level imagery produced by the device. This feature makes it possible for the reconstruction of the superpixel-based image data at a later time. A display processor with this information and the superpixel gray-level values will be able to reconstruct a display representing the appropriate spatial information in the scene.

Figures 2-2 and 2-3 illustrate the advantages of the VASI readout design over conventional on-chip data reduction techniques of pixel dilution and region-of-interest (ROI) windowing. With superpixels, only one output channel is required to obtain significant improvements in frame rate while not giving up any scene information. And having one analog output channel rather than two, four, or sometimes even 32 channels greatly simplifies off-chip A/D and re-vectoring electronics.

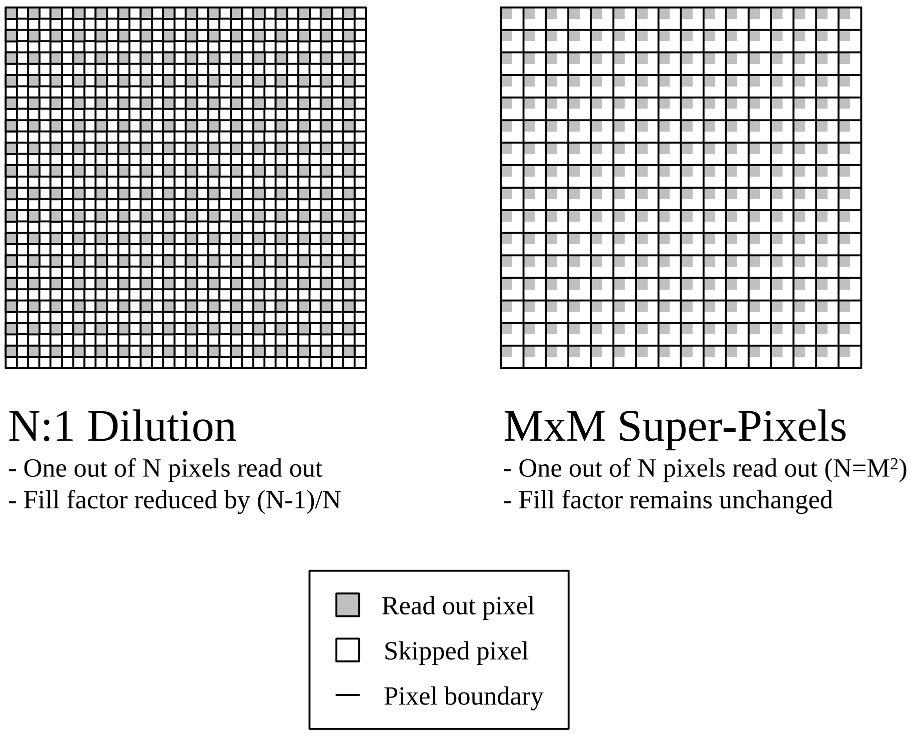


Figure 2-2 Dilution modes throw away pixel data in exchange for higher frame rates to maintain total FOV (left), while a comparable superpixel configuration maintains both FOV and fill factor since all skipped pixels share photocharge with read out neighbors.

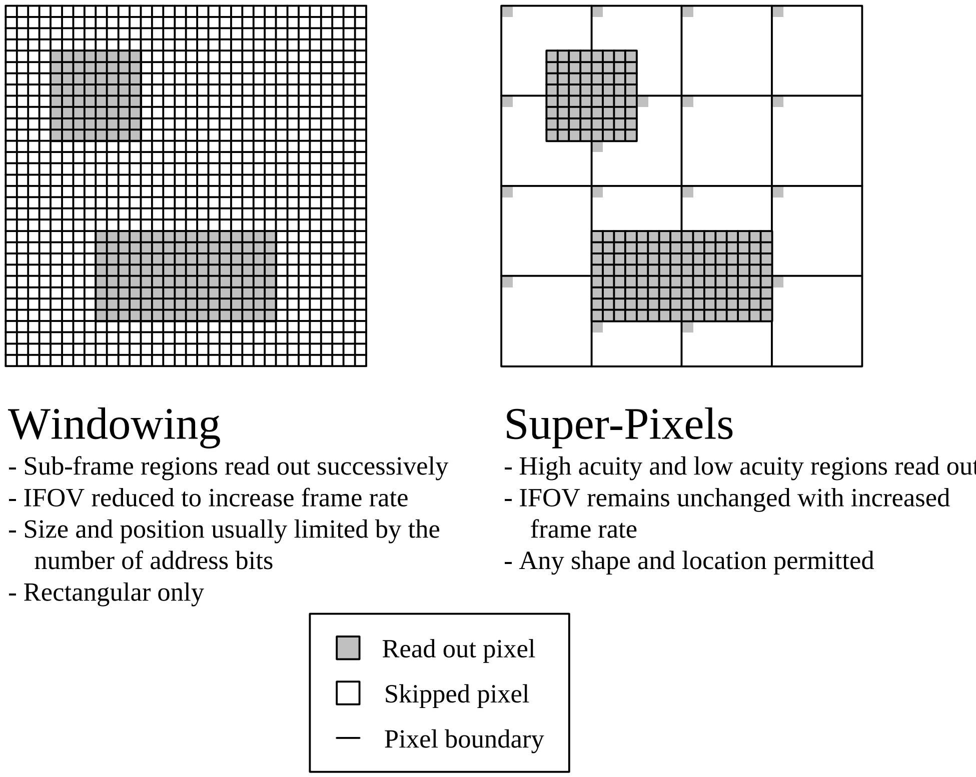


Figure 2-3 Windowing modes reduce instantaneous FOV (IFOV) while increasing frame rate (left), while a comparable superpixel configuration can read out both the high-resolution ROI as well as the low resolution peripheral pixel regions with little additional clocking overhead.

Nova has produced an operating prototype version of a VASI device operating with a monolithic visible phototransistor in each unit cell (30 micron unit cell pitch), as shown in Figure 2-4. Initial imaging and test results presented in this paper were produced from this test device. As of the writing of this paper, a larger 128 x 128 pixel device is in fabrication.

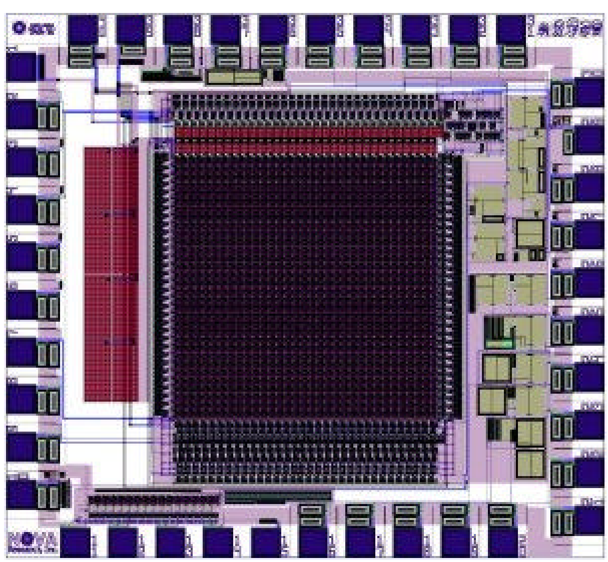
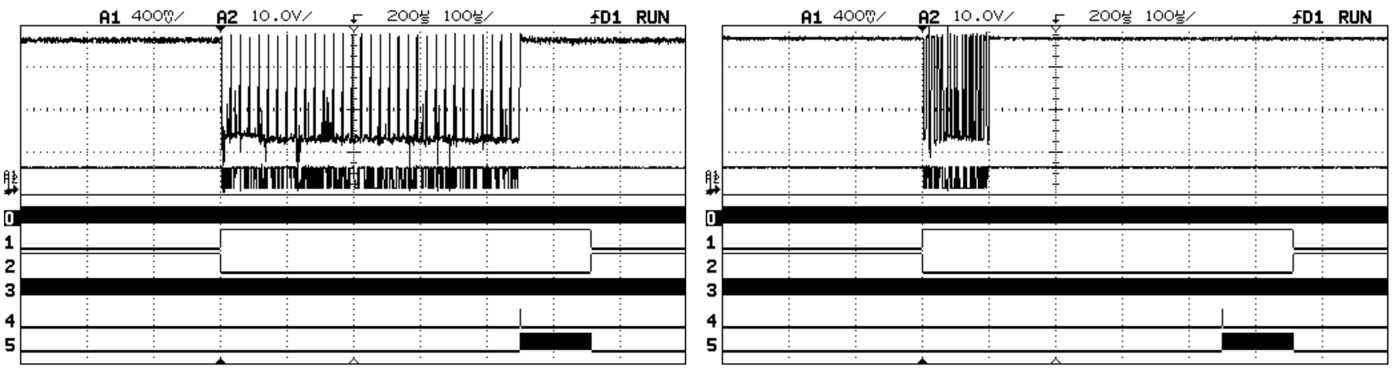


Figure 2-4 Nova's prototype 32 x 32 VASI visible imager is monolithic in construction with a phototransistor in each unit cell.

3. PRELIMINARY IMAGING AND TEST RESULTS

Prior to imaging the device, initial tests verified the correct operation of the unit cell programmability. Figure 3-1 demonstrates the results of programming a uniform 4x4 superpixel array configuration in which the behavior of the readout multiplexor is properly controlled by the superpixel state. In this case, every other column is skipped in the horizontal readout direction and every other row is skipped in the vertical readout direction, resulting in a 4-to-1 data reduction. Scope traces 0-5 in the figure represent the six input clocks required by the device. Traces 0-2 consist of master clock, integration and reset clocks for readout operation; traces 3-5 consist of superpixel programming clock, programming sync and serial programming commands. The programming clocks may operate completely asynchronously to the readout clocks—during these tests the master clock ran at 2.5 MHz while the superpixel programming clock ran at 10 MHz. This minimized frame overhead time which could be used instead for pixel integration.



(a) (b)

Figure 3-1 Oscilloscope waveforms of one readout frame in both non-superpixel configuration (a) and 4x4 superpixel configuration (b) showing analog pixel output trace (top) and digital output trace, and the input clocks (0-5). Note that in superpixel configuration only one-fourth of the pixel values are multiplexed off-chip, allowing for an increased frame rate.

As mentioned above, the readout has a superpixel disable mode in which all pixel values are read out regardless of the programmed superpixel configuration. In this mode, the chip's digital output can be used as a means of verifying each individual pixel's programmed superpixel state. This information can also be used to reconstruct the images when the readout is put back into superpixel enable mode, allowing display electronics to work autonomously with respect to command control electronics. For example, if the control system is reprogramming the superpixel state every 100 frames, then the first frame of each 100 frame sequence should be acquired while superpixel mode is disabled in order to store a complete spatial configuration profile from the digital output pad (digital output is not valid when in superpixel enable mode).

For the sake of imaging tests performed in the lab, the readout was kept in superpixel disable mode so that a consistent 32x32 array format could be acquired by the display system. Figure 3-2 shows two examples of foveated superpixel configurations realized using 1x1, 2x2 and 4x4 pixel sizes. Such configurations can be reprogrammed at the frame rate in order to "fly" the high-acuity regions within the FOV in real-time according to where the COA directs them.

Figure 3-3 shows the digital output that results from a center-foveated superpixel configuration depicted in Figure 3-2(a). The "Up" image data appears during the first half-clock of a pixel period, and the "Left" image data appears during the second half-clock. Used together, a frame of superpixel data can be fully reconstructed. "Up" and "Left" denote connectivity between an individual pixel and its upward and leftward nearest neighbor.

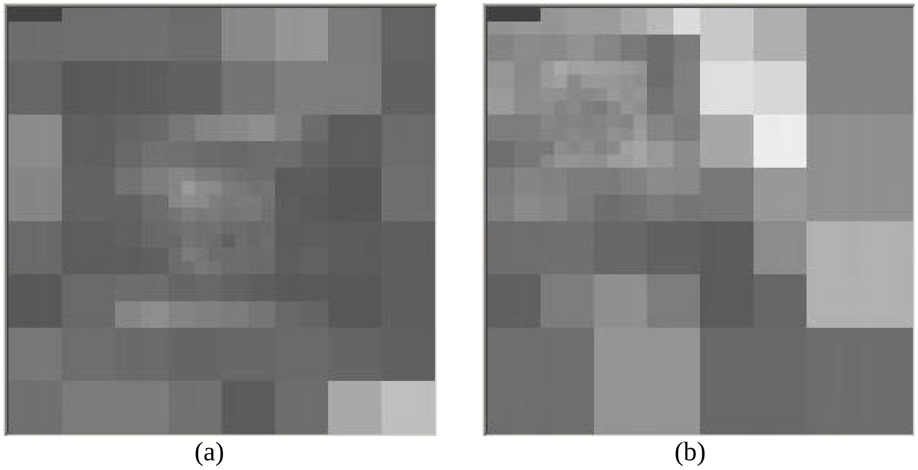


Figure 3-2 Two superpixel configurations are shown for the 32 x 32 device. Panel (a) has a central fovea, panel (b) has located the foveal region in the upper left corner.

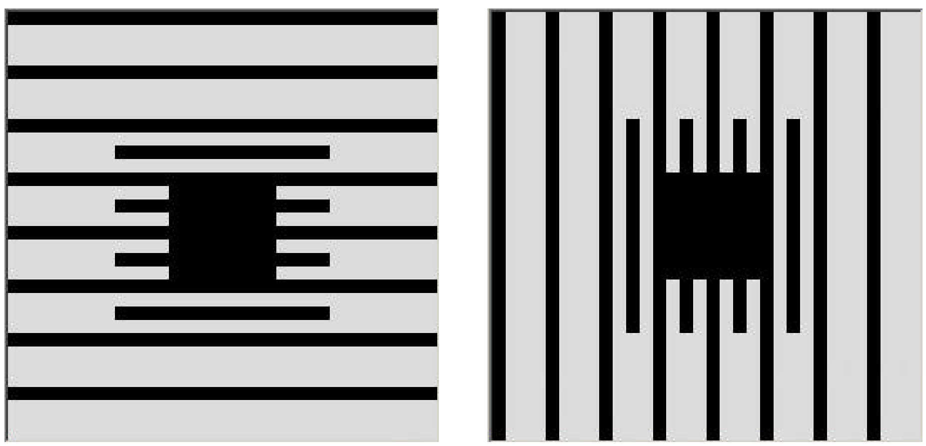
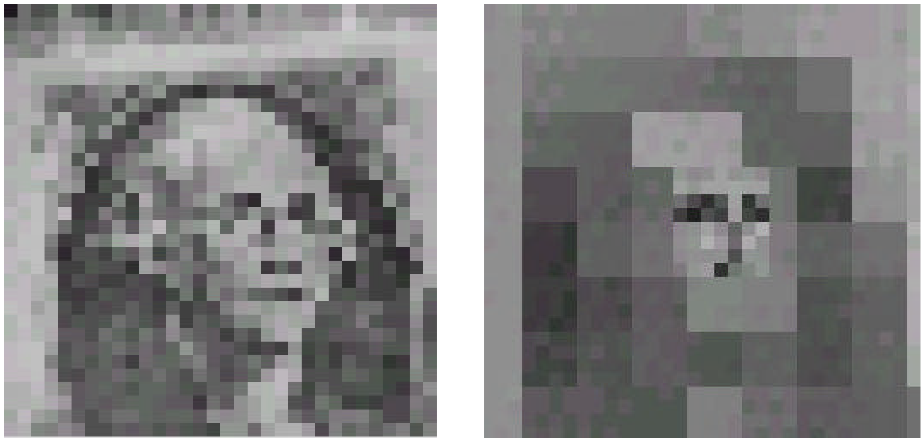


Figure 3-3 These images represent the "Up" and "Left" bits used to program the configuration shown in Figure 3-1(a). These bit values are produced from a digital output pad that the device has such that the instantaneous spatial configuration of the device may be recorded with image data.

The above images were generated using static (pre-determined) programming clock timing from the test system which did not allow for real-time COA movement. A simple single-CPLD based control system was subsequently developed that allowed a user to move an 8x8 high-acuity region within a 4x4 superpixel field by dragging the computer mouse in a console window. The mouse coordinate was transmitted as an 8-bit address across the parallel port where the CPLD used it to position the high-acuity region by shifting the superpixel programming command sequence. Figure 3-4 shows snapshots from live image sequences taken while operating in standard configuration (no superpixels) and in this superpixel configuration. Spatial noise evident in panel (b) is a result of the high contrast display setting acting on some test set output cable noise pickup.



(a) (b)

Figure 3-4 Two images from a real-time video sequence demonstrating non-superpixel configuration (a) and a programmed 8x8 high-acuity region within a field of 4x4 superpixels (b).

Six frames were extracted from a large sequence of contiguous image frames when the VASI imager was operating in its standard “non-superpixel” mode and are shown in Figure 3-5(a). A focused laser spot was imaged onto the array and the collected imagery shows the expected high resolution pixellation.

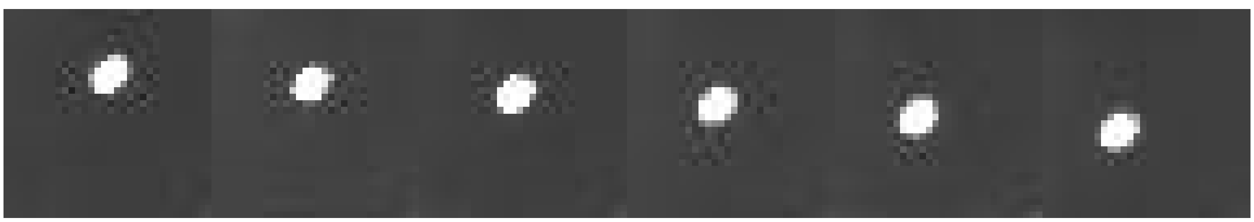


Figure 3-5(a) Six frames taken from a sequence with the variable acuity sensor operating in its high resolution mode (i.e., no super-pixellation). A focused moving laser spot is imaged onto the array.

In this mode, the 32 x 32 array may operate with a frame rate of up to approximately 1000 Hz. When the device was programmed to have a central foveal spatial characteristic as depicted in the image shown in Figure 3-2(a), a large set of contiguous frames was collected, six frames from which are shown in Figure 3-5(b). Notice how the spatial extent of the extended object is captured in a high spatial resolution mode when the object is near the center of the field of view, and how many fewer pixels are used to represent the image when the object is in the periphery of the field of view. This super-pixel mode of operation makes use of approximately 6.4 times *fewer* pixel channels than the full-resolution example above because of super-pixellation. In theory, this reduction in the number of effective pixel channels permits this imagery to be produced at a frame rate of approximately 6.4 kHz (ignoring frame overhead).

In addition, the temporal noise produced by a superpixel will be reduced as compared to “individual pixels” by virtue of the root-sum-square collection of detector currents contributed by all of the individual pixels that contribute charge to the superpixel’s effective charge well. Many future applications that require the ultimate in low-noise performance may make use of this approach to reducing effective pixel temporal noise.

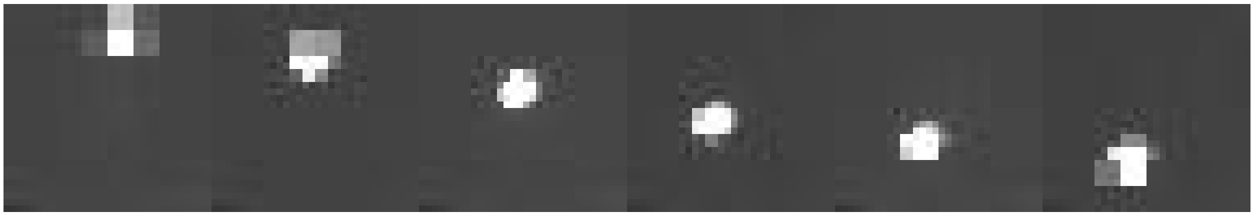


Figure 3-5(b)   Six frames taken of a focused moving laser spot with the variable acuity sensor was operating with a high spatial resolution foveal region in the center of the array.

4. BIOLOGICALLY-INSPIRED DESIGN ATTRIBUTES

Many examples in nature have demonstrated the use of multiple acuity foveal (i.e., regions of high spatial acuity) architectures, as reported by Wolpert[1]. "The human eye has one foveal region. The fovea measures approximately 400 ì in diameter and has a photoreceptor density of approximately 150,000 photoreceptors/mm^2. Some birds of prey have a density of photoreceptors of up to 1,000,000/mm^2, some 7x greater than those of humans. Greater resolution and a means to process the information without exceeding data rates and overloading the processor (brain) is a goal of almost every detector manufacturer.

"Some shore birds also have multiple foveae, one that is rectangular and oriented horizontally like some of the animals of the African savannah, conforming to the sky/water and sky/land horizon. They also have another central circular fovea, straight ahead, that is used for tracking. Optimizing the foveae for the detection process can enhance and augment detection for some applications.

"Some animals have multiple foveae like the anableps fish. This fish has an eye with two different focal lengths and two foveae. The long focal length portion of the lens focuses to one fovea for viewing in air the other, short focal length, focuses below water. Taking advantage of this technique allows lenses to be designed for multiple media applications.

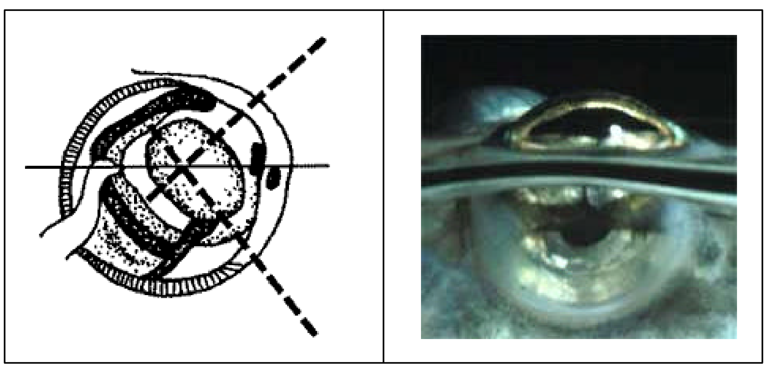


Figure 4-1 The Anableps eye has two focal lengths and two foveal regions[2]

"Most birds of prey also have two foveae. Like search & track systems that employ a short focal length optical system for acquisition, and a long focal length system for tracking, the eye is oblong and equipped with two foveae. The lens is rotated in the socket to switch between search and track modes. It is necessary to understand the "hand-off" process that is between search and track modes that allows these birds of prey to continue tracking after detection without loosing its prey. This hand-off process is critical in modern search and track systems."

Future applications of VASI technology are only limited by the imagination and inspiration of systems designers, and may be spawned by further investigations into how biological systems have evolved such systems.

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[1] Wolpert, H.D., "Bio Mimicking", private communication, 2002.
[2] http://ebiomedia.com/gall/eyes/4eye.html

5. APPLICATIONS OF VASI TECHNOLOGY

High Frame Rate Operation

Superpixel-mode operation is useful in applications requiring high effective frame rate without sacrificing total field-of-view or the spatial resolution on objects of interest within the scene. Reducing the total number of pixels per frame which must be read off of the imaging device will reduce the effective frame period, thus increasing effective frame rate. For example, the superpixel configuration as shown in Figure 3-2(a) can operate at a frame rate of approximately 6.4 times faster than that for multiplexing the entire high-resolution frame. In this mode, Nova's prototype visible VASI sensor as shown in Figure 2-4 operates at a frame rate of approximately 6.4 kHz.

Possible high frame rate applications would include high speed image motion capture/freezing, remote sensing of object closing velocities, passive depth measurement at high speed using at least two sensors and particle fragment trajectory measurements.

Tracking Systems

Motion sensing techniques may be used to direct the VASI device to "track" moving objects by placing high-resolution pixels over the moving target, leaving the rest of the image area in a low-resolution spatial condition. By comparing the center location of the "foveal" region to the center of the total field-of-view, a tracking error signal is produced that may be used to servo the sensor platform so as to reduce the pointing error. While covering a very wide total field-of-view, high resolution target imagery is maintained while keeping the target near the center of the image. Significant processing resources, if applied to the center of the field of view, would thereby retain a high degree of relevance on the target.

Vibration/Platform Stabilization

External sensors (vibrometers, accelerometers, etc.) attached to the sensor platform may be utilized to produce two-dimensional error signals which may be used to generate the requisite foveal position control to the VASI imager. Image data contained in the foveal region of the sensor, having "tracked" platform motion, would approach a "pixel stabilized" condition useful in improving a system's ability to identify objects of interest.

Nova has recently produced an updated version of the visible VASI imager that has a VASI imaging region 128 x 128 pixels in size, with proprietary optical-based "angle rate sensing" circuitry on-chip that may be used to produce the stabilization signals required for this mode of operation. A range of "Unmanned Air Vehicle" (UAV) applications exist for such a sensor configuration.

Template Matching Operations

Pre-determined object shapes may be used to program one or more "foveal" regions of the VASI imager. When the desired-shape object is imaged onto the sensor and becomes spatially aligned with these spatially-formed foveal regions, a high degree of signal correlation will exist in the output of these foveal regions. A following image processing system could evaluate this correlation condition so as to produce a "probability of match". Since the spatial configuration of the fovea may be re-programmed at the frame rate of the sensor, this would provide a convenient means for producing such two-dimensional correlations in real time.

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