AIRS FPA applied to the MIRIADS: Powerful infrared systems applications

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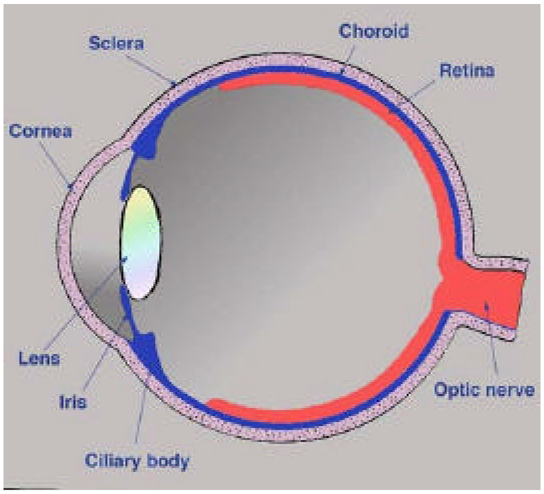
ABSTRACT

Raytheon's Infrared Operations (RIO) has invented and developed a new type of focal plane array with "Image Processing on-the-chip" named the Adaptive IR Sensor (AIRS). The AIRS FPA is based upon the human retina in that it performs signal processing near the photoreceptors. The AIRS FPA has been reduced to practice and adaptively removes detector and optic temperature drift and 1/f induced fixed pattern noise. This 3rd-generation multi-mode IRFPA, also called a Smart FPA, is a 256x256-array format capable of operation in four modes: 1) Direct Injection (DI), 2) Adaptive Non-uniformity Correction (NUC), 3) Motion/Edge Detection, and 4) Subframe Averaging. Nova Research has developed a Modular IR Application Development System (MIRIADS) which is a compact single board camera system that is highly integrated with the dewar assembly. The MIRIADS system coupled with the AIRS Smart FPA results in a very high performance wide field of view IR Sensor and processing system with integrated in one of the smallest packages to date.

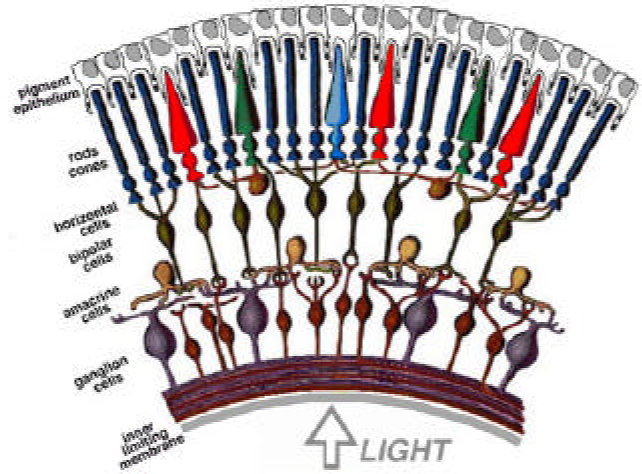
1. INTRODUCTION TO BIOLOGICALLY INSPIRED CIRCUIT ARCHITECTURES

Raytheons Infrared Operation has designed ROICs and IRFPAs that make up for the defects in IR Detectors and also continue to advance imaging technology to the point where a Sensor could be integrated onto a single chip. Scientists at RIO looked towards biological sensors for answers on how to conduct signal processing on the chip and at the same time, solve problems of pixel uniformity and operability. Figure 1 is a schematic of the Human eye with retinal photoreceptors and processing cells. Figure 2 shows a flow diagram of the visual pathway and associated processing at each level, from M.M. Gupta and G.K. Knopf[1].

Our first goal was to design circuitry with both temporal filtering (AIRS) and spatial processing (TAIP) at the pixel level in order to present a more uniform preprocessed image to the image processor. As figure 2 illustrates, performing both spatial and temporal filtering at the detector level has obvious benefits. Since the computation modules required for filtering are often simple convolutions, performing these 2-D functions on the image plane requires only neighborhood interconnections with the weights controlled synaptically. Attempting to do this in a serial digital computer is far more complex and involves large amounts of memory, memory accesses, multiplies, and adds.



1a. Side look at the components of the human eye reveals a superior adaptable WFOV vision system.



1b. The human retina has a densely packed set of rods and cones, and 4 adjacent layers of image pre-processing.

The human retina is backside illuminated like many IRFPA designs. There is a lot of processing that goes on in the human retina that is the subject of Research. The AIRS chip performs temporal processing similar to the bipolar cells, but how closely the AIRS type processing replicates the retina is the subject of future research. Suffice it to say, AIRS is a stand alone integrated image processor on a chip.

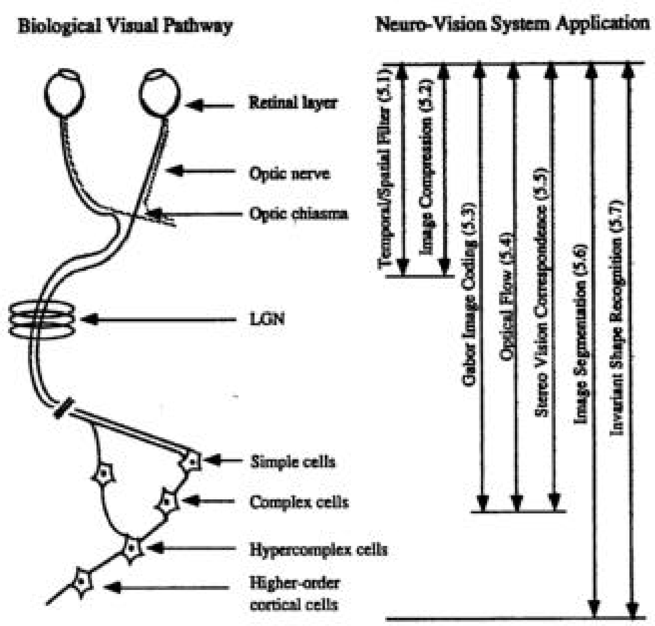


Figure 2. Biological vision research indicates that temporal and spatial processing is performed near the retina for the purposes of noise reduction and information enhancement.

In the front end of a 2-D imaging sensor using massively parallel processing elements, these convolutions can be performed in the equivalent of a single clock cycle. Thus the end goal of Smart

FPAs is to mimic biological sensors and to leverage advances in submicron ROIC designs in order to enable smaller and smarter IR detection systems.

The full up MIRIADS system is shown in figure 3. Although the MIRIADS is not approaching the optimization of the near perfect eye, it has a high level of integration with more processing functions being performed near the focal plane array than most IR or Visible sensor systems. The processing that is done on the FPA is Subframe Averaging and Temporal Filtering, while the near Focal Plane MIRIADS electronics performance timing and control signals, digitization and a set of parallel connections via the back side to connect to a custom image processing board that is currently in fabrication.

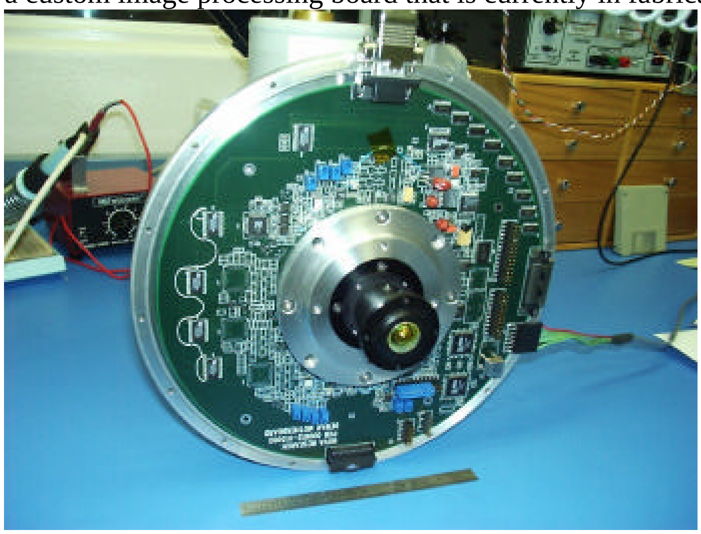


Figure 3. Photo of the MIRIADS system with the cover off. Fisheye Lens, Dewar, FPA, A/C, timing and bias generation and image processing all on one card. While the MIRIADS is not as compact or mature as the eye we are headed that direction.

2. ADAPTIVE IR SENSOR DESIGN OBJECTIVES AND PERFORMANCE RESULTS

The Adaptive Infrared Sensor (AIRS) FPA readout IC was developed with support from IRAD and NVESD. The technical objectives of this 3rd Generation design was to utilize Readout Integrated Circuit (ROIC) advancements to demonstrate biologically inspired temporal filtering at the pixel to improve the overall noise performance of focal plane array. Over the past decade both DOD and industry have made large investments into infrared improvements, and these detectors have been optimized for operation near the theoretical limits. Detector fabrication has also been systematically improved with current fabrication giving high yields and low process defects. A number of successful research, development, and production programs have advanced and sustained a high level of technical excellence involving both photovoltaic HgCdTe and InSb detectors. However even with the successes in making better IR Detectors we are asymptotically approaching an upper limit on the performance and yields of Detectors. Therefore the ROIC is deemed to be the primary FPA component capable of yielding significant improvements in performance.

The ROIC is compatible with either detective material, and serves to reduce fixed pattern noise on the FPA rather than rely on warm external electronics for this vital function. This breakthrough advancement in on-FPA processing will enable the future development of smaller, lighter, and lower power systems with ever greater operational capabilities than available in today's products. Additionally, the AIRS is the first ROIC to demonstrate an ability to adaptively "fix" bad pixels on the focal plane, thus improving the offset nonuniformity coming off the FPA. This capability also increases the useful yield and lowers cost of the detector arrays composing the focal plane. To demonstrate the ability to fix pixels, an engineering grade LWIR 30 um 256 x 256 detector array from another effort was used on the AIRS R&D lot.

Performance breakthroughs of the AIRS Smart FPA have been demonstrated in the following four modes of operation.

- **Direct Injection (DI).** The AIRS operates as a standard 2nd Generation imaging FPA.
- **Adaptive THP Scene Based Non-Uniformity Correction**. This mode allows adaptive reduction of the Low frequency noise and drift component from the scene. The fixed pattern noise (FPN) is significantly reduced in the temporal high pass filter mode(THPF). The THPF lowers the temporal noise making marginal pixels (i.e., low responsivity or high noise) perform sufficiently for use. The number of outliers (speckles) are thus effectively reduced, resulting in a dramatic improvement in operability.
- **Subframe Averaging.** This mode offers a tremendous advantage over existing designs. By averaging subframes, high photon shot noise is reduced and sensitivity is improved. Using low noise electronics and a state of the art A/D converter vastly improved sensitivity of 3 x in NEDT in the subframe accumulation mode is possible.
- **Motion Detection/Edge Enhancement:** This mode offers the ability to remove all stationary scene clutter and only detect moving targets and edges. This mode is the THP mode running at a very high update rate.

An overview of the measured performance of the Adaptive IR Sensor is shown in table 1.

Table 1. Summary of the Adaptive IR Sensor performance results.

Performance Parameter	Mode		
	Direct Injection	THPF/ Motion Detection	Subframe Averaging
Array Format	256 x 256	256 x 256	256 x 256
Pixel Pitch	30 um	30 um	30 um
Spectral Passband	LWIR	LWIR	LWIR
Flux Level @T_{bb}= 295 K, F/2	3.5 x 10^{17} Ph/cm^2-sec	3.5 x 10^{17} Ph/cm^2-sec	3.5 x 10^{17} Ph/cm^2-sec
# of Outputs	1	1	1
Frame Rate	> 100 Hz	> 100 Hz	20-100 Hz
Output Voltage Swing	> 3 Volts	> 3 Volts	3
Instantaneous Dynamic Range	> 3500	> 3500	>4800
Integration Time	47 usec	36.5 msec	36.5 msec x Nsub
Full Well Capacity	12 M e-	6 M e-	Averages 100 frames
Integrated Charge (e-)	6.5 M e-	4 M e-	Averaged 400 M e-
% of Full Well	54%	66%	54%
Mean NEDT (BLIP)	26 mK (20 mK)	< 28 mK (23 mK)	< 20 mK

Figure 4 shows the output video skyline plot of all 256 x 256 pixels in Direct Injection mode and Temporal High Pass mode. The sub-specification “C” grade detector exhibits a localized defect of about 100 pixels on the right part of the skyline that reduces the operability in the Direct Inject mode to 99.8 %. In the Temporal High Pass mode the array uniformity is reduced from 40 mv to 14 mv. Also notice the group of bad pixels (Fig 4a) have been “fixed” or brought into the mean of the distribution (Fig 4b). These are the first ever demonstrated results of actual bad pixel correction performed in the ROIC, with the FPA operability approaching 100%.

A key issue of the On-FPA Adaptive NUC is the ability to maintain low residual Fixed Pattern Noise (FPN) during normal operation. Past Smart FPA efforts have discussed the need for on FPA processing and the need for On-the-FPA NUC[2,3]. We performed a series of tests comparing the FPN of the Direct Injection Mode of AIRS with the Temporal High Pass mode.

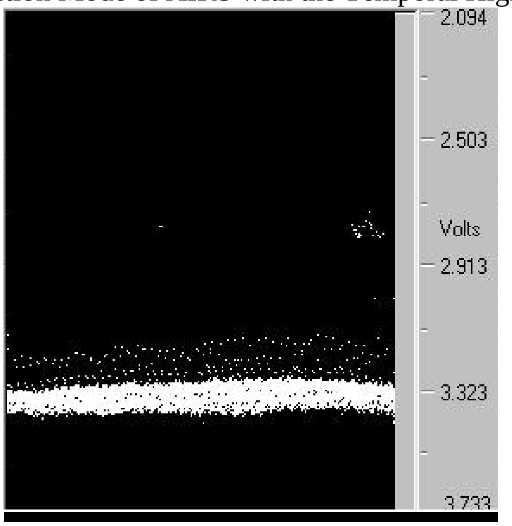


Figure 4a. Direct Injection Mode skyline plot shows good raw offset uniformity (~40 mv 1σ, σ/μ=2.5%)

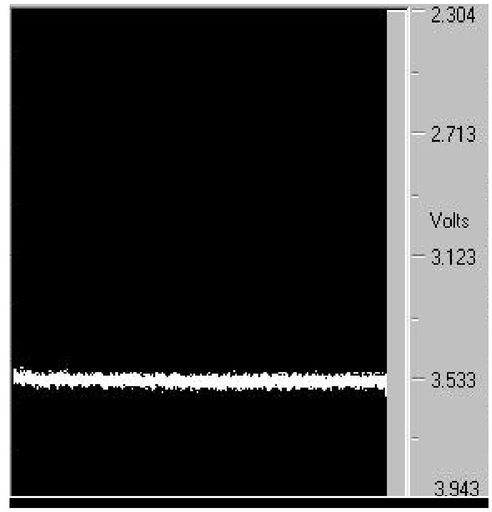


Figure 4b. Temporal High Pass skyline plot shows excellent raw Offset Uniformity (14 mV 1σ, σ/μ<1%) and Bad Pixel Substitution

In the DI mode a standard 2 Point NUC was performed in the Electronics. In the THPF mode, a 1-point Offset NUC was performed to remove the 14 mv noise that originates mainly in the column amp and unit cell buffers. Figure 5 illustrates the ability of the AIRS FPA to maintain very low residual fixed pattern noise over scene temperature excursions (Fig 5a) and time (Fig 5b).

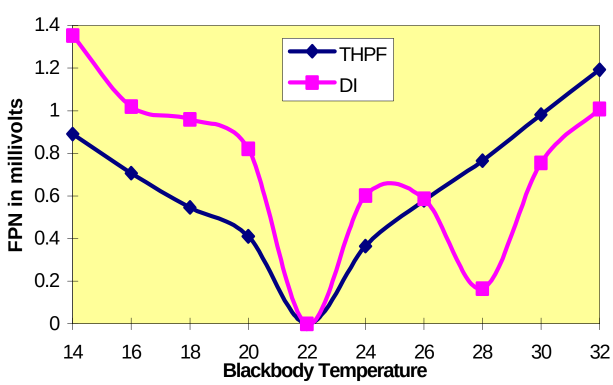


Figure 5a. Residual Spatial Noise in Temporal High Pass mode vs. Direct Injection mode shows the ability of the THPF to maintain FPN near the temporal noise floor.

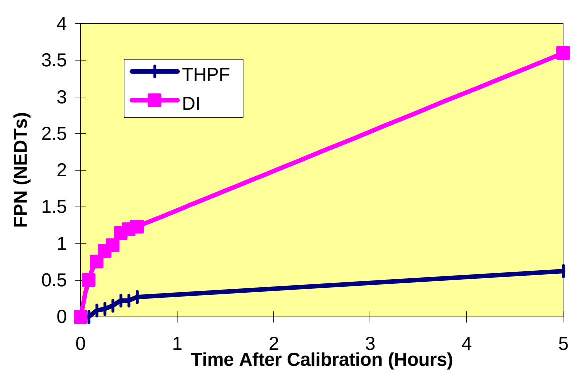


Figure 5b. Long term stability of Temporal High Pass mode vs. Direct Injection shows that the THPF maintains the fixed pattern noise near the temporal noise during a 5 hour stability test.

During performance testing, residual spatial noise of the THP mode increased only 15% over a 5 hour period. This result illustrates the robustness of the on-FPA techniques to maintain low FPN and stability over time.

Imaging tests were performed in all modes of operation. Figures 6, 7, and 8 illustrate the DI, THP, and Motion Detection mode, respectively.

Figure 6. AIRS FPA exhibits good imagery and operability in Direction Inject Mode.

Figure 7. Images from the THPF mode test. When the THPF is running a slow update rate, very few image artifacts exist.

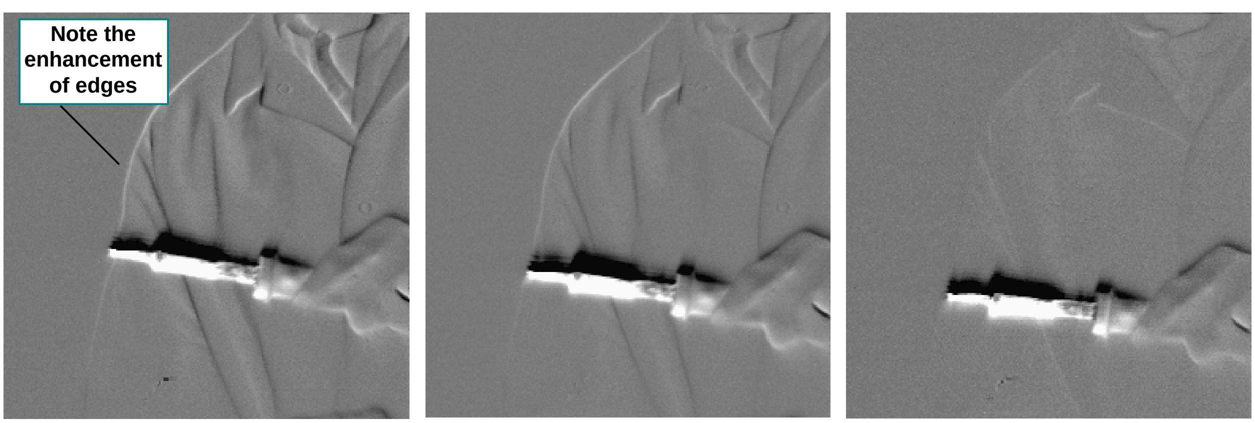


Figure 8. Sequential images taken in the Moving Target/Edge Enhancement mode. The FPA performs edge enhancement on moving targets and creates Mach bands on the hot target.

2. AIRS INTEGRATED WITH MIRIADS

Figure 9 shows an early conceptual representation of the MIRIADS camera system. A unique feature of the system is that the single circuit board (the motherboard, 9.0 inches in diameter) that is required to operate the FPA actually penetrates the vacuum space of the integral vacuum dewar and is in fact an important part of the vacuum integrity of the system. As a technology demonstration effort, this project had a goal of demonstrating that a cryogenically-cooled infrared FPA in an evacuated dewar can be mounted on the same board as the warm electronics that operates it. In this process, electrical vacuum feed-thru connections normally required of these systems are eliminated; they are replaced by internal signal layers of the multi-layer printed circuit board. Another benefit of this design is that because of the very short distance between the FPA output(s) and the associated preamplification and digitization circuitry, the signal capacitance is very low; this permits very high frequency operation for advanced imagers of the future.

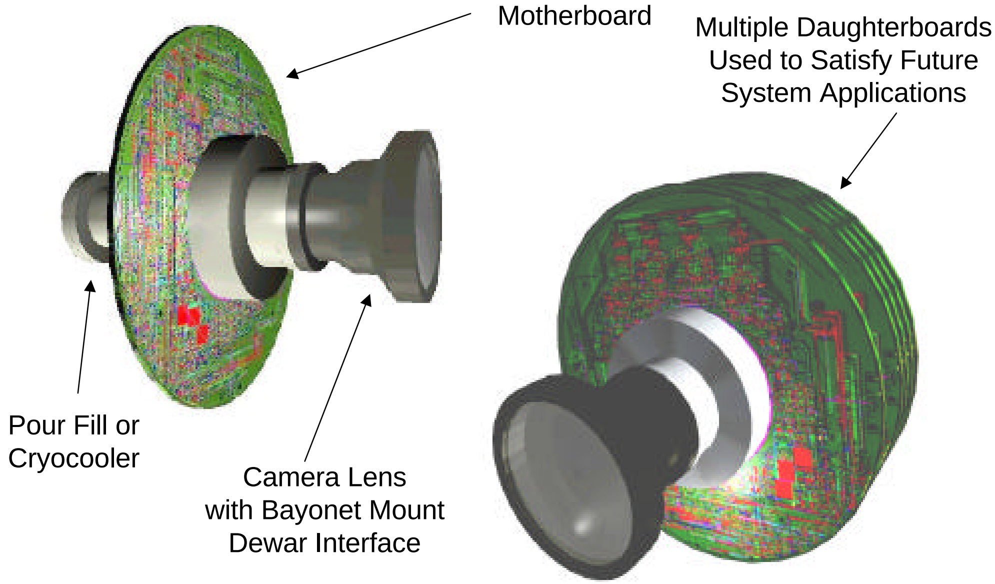


Figure 9. A single circuit board (the motherboard) is required to operate the FPA, and additional processing daughterboards may be used to post-process the real-time image data.

In addition, the MIRIADS system architecture permits a common datapath to be used to send real-time video and control data from the motherboard to a variety of processing daughterboards as shown in Figure 1. This is also indicated in Figure 10 in which numerous identical boards with different programmable logic implementations may be used to process the real-time FPA image data. A more detailed discussion of the MIRIADS is given in another paper[4].

To be as flexible as possible, the system was designed to permit cooling of the FPA with the use of liquid nitrogen (LN2) or an electric cryocooler unit through the cooling port located in the lower dewar assembly as shown on the left side of Figure 10. As will be shown later, this program also developed a large-capacity LN2 reservoir dewar subsystem that mates to the cooling port that provides many hours of cooling capacity.

A design goal was to produce a system that provided an easy interface to a commercially-available image capture and display system so as not to divert from the main goal of producing a highly modular, configurable system. For this reason, the SE-IR Corporation’s “CamIRa” display frame grabber, DSP board and software was identified and used to provide real-time display and digital data storage functions.

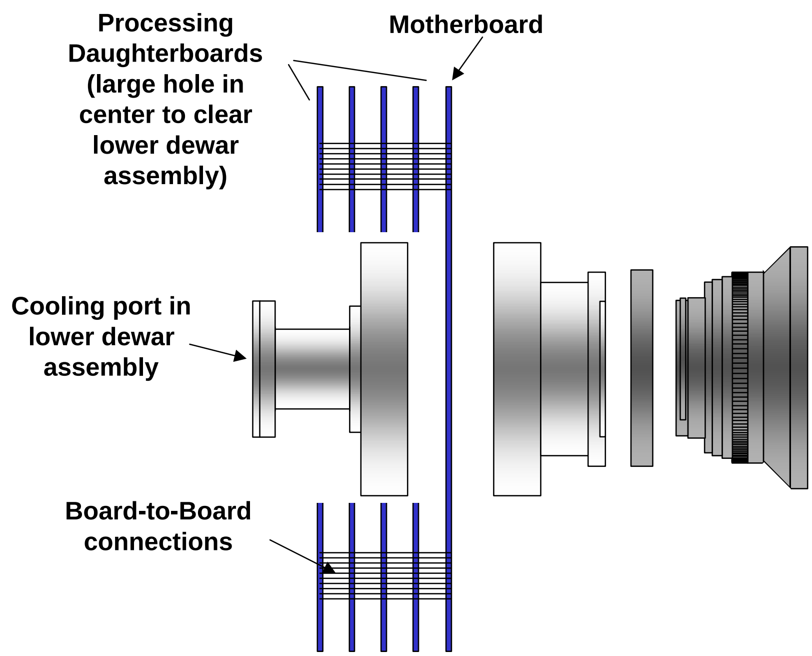


Figure 10. Schematic view of the MIRIADS camera system indicating that the motherboard is an integral part of the vacuum integrity of the cryogenic dewar.

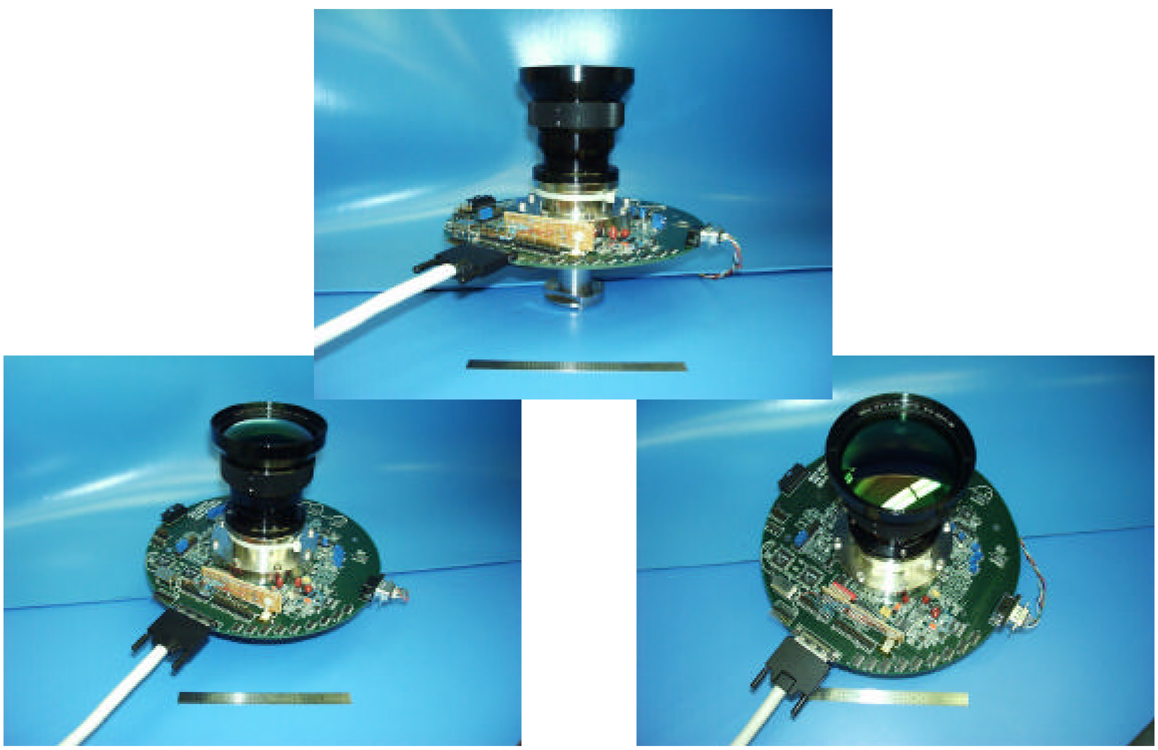


Figure 11. Three views of an existing MIRIADS system operating the Neuromorphic Infrared focal plane array showing a six-inch scale for size comparison.

Figure 11 shows the single data cable that is used to deliver the 16-bit differential data, pixel, frame and line clocks to the display system. This cable also permits software-generated camera control functions to be performed (i.e., integration time, frame rate or other camera control parameters).

It became clear through the initial operation of the MIRIADS that the small volume of LN2 that could be poured into the cooling port would only keep the detector cold for approximately ten minutes. The heat load of the system was previously measured to be approximately 1 watt at 77K, low enough for a cryo-cooler, but high enough to require multiple milliliters of LN2 if poured directly into the cooling port. The large capacity LN2 dewar shown in Figure 4 was developed to provide many hours of cooling while horizontally supporting the MIRIADS camera system to make it useful in data collection operations.

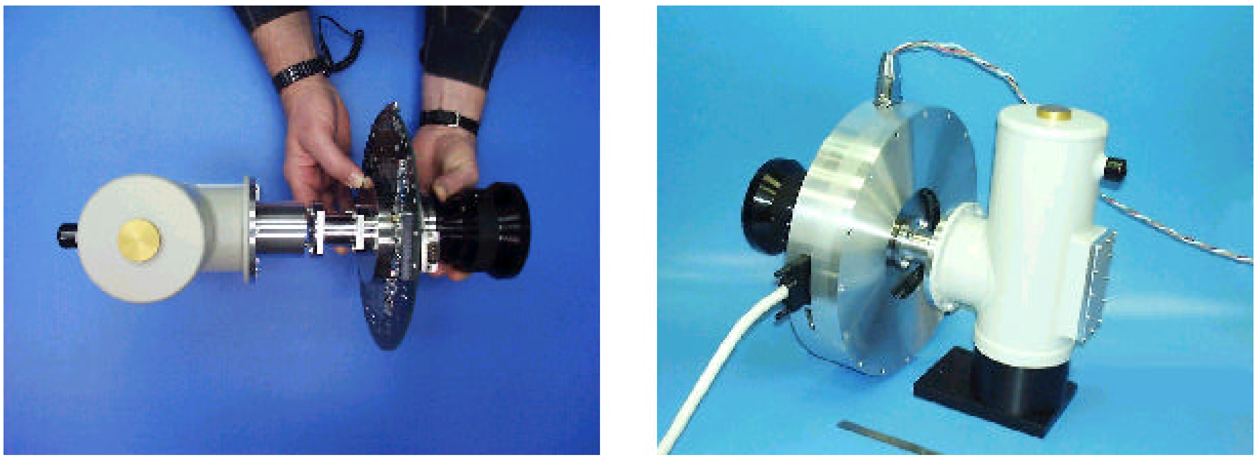


Figure 12. A high-capacity LN_2 dewar system was developed to provide long-term cooling and a horizontal mounting for the MIRIADS camera system.

The motherboard was designed with “in system programmable” (ISP) complex programmable logic devices (CPLDs) that permit the reprogramming of virtually any set of clock patterns required by the particular FPA for its operation. In addition, flexible clock level-shifting circuitry was included to supply both positive and negative clock rails. A variety of low-noise adjustable FPA bias generators are included to accommodate the power and bias requirements of virtually all FPAs that currently exist. The motherboard includes four channels of gain- and offset-adjustable preamplification circuits, four 14-bit A/D converters and on-board digital multiplexers to produce the digital data stream that is driven off the board through either RS-422 or LVDS differential drivers to provide high noise immunity in harsh EMI environments. system complete.

4. FUTURE APPLICATIONS

Figure 13 gives an example of next generation IRFPA insertion using an even more compact version of a MIRIADS like system. In order to achieve these results, we endeavor to continue to look to nature to design sensors that are biologically inspired[4-5] and modeled after the Retina as well as take advantage of recent advanced in ASIC and EPLD design.

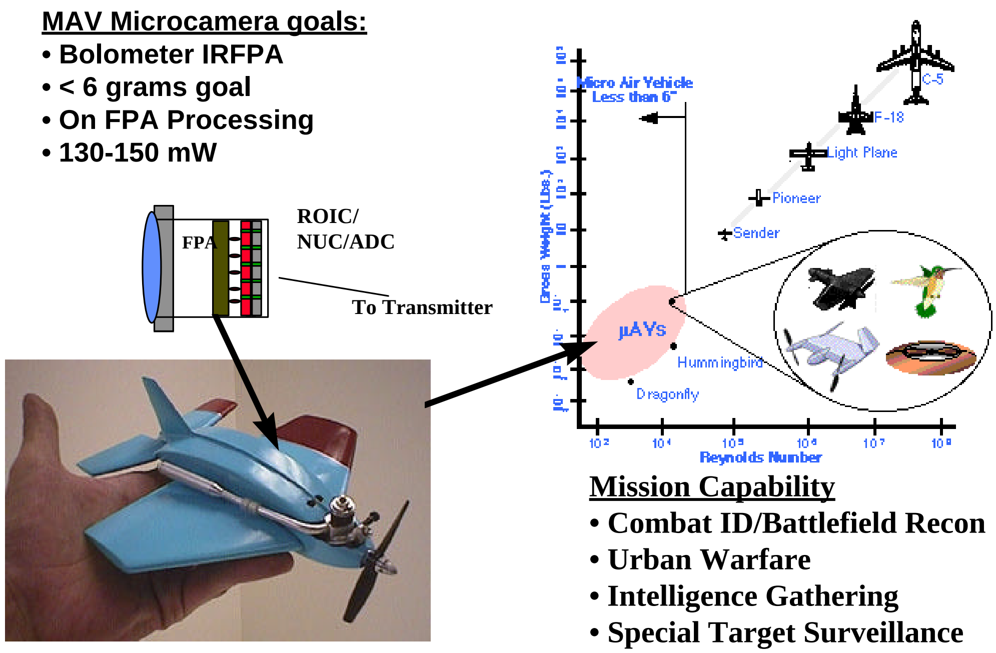


Figure 13. Example of how 3rd Generation sensor could enable high performance mission capability for Micro UAVs.

Using the biologically inspired AIRS and TAIP technology, next generation IRFPAs can provide benefits in numerous 21st century missions:

- Unattended Sensors
- Manportable Sensors
- Micro UAVs
- Ground/Wall Penetration
- Missile Warning
- Missile Seekers
- Multispectral Surveillance
- Advanced Large Area FPAs

5. SUMMARY

Raytheon has demonstrated the ability to do processing on the FPA that has previously been done in the FPA warm electronics. DOD funding has resulted in dramatic improvement in both MWIR and LWIR detectors. However, the IR detector industry is asymptotically approaching the upper limit of performance and operability. What is needed now are advanced ROICs that actually improve the performance of detectors and increase useful operability of FPAs. With the requirement for smaller, smarter, and lower power sensors, more image processing needs to be moved onto the FPA. To that end Raytheon has demonstrated biologically inspired massively parallel processing of images at the pixel level with excellent first pass success. Importantly, the AIRS FPA requires only 3 biases and 4 clocks to operate. Raytheon's Smart FPA efforts have demonstrated significant breakthroughs:

- Biologically inspired Parallel Processing at or near the pixel level
- Industry first IRFPA to "Fix" bad pixels on the FPA

- Excellent uniformity of < 1% sigma/mean with LWIR detectors
- Superior Long Term stability and image quality
- AIRS Multifunctional FPA: DI, Adaptive NUC, Subframe Averaging, and Motion Detection
- Enables a higher level of integration and sophistication of image processing on or near the FPA for a total reduction in system size while actually increasing functionality.

The excellent first results achieved with Raytheon's Adaptive IR Sensor and TAIP have proven that Multifunctional 3rd Generation FPAs with on the FPA processing are both possible to fabricate and offer more capability than existing 2nd generation IRFPAs.

ACKNOWLEDGEMENTS

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