

MIRIADS – Miniature Infrared Imaging Applications Development System Description and Operation

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ABSTRACT

A cooperative effort between the U.S. Air Force Research Laboratory, Nova Research, Inc., the Raytheon Infrared Operations (RIO) and Optics 1, Inc. has successfully produced a miniature infrared camera system that offers significant real-time signal and image processing capabilities by virtue of its modular design. This paper will present an operational overview of the system as well as results from initial testing of the “Modular Infrared Imaging Applications Development System” (MIRIADS) configured as a missile early-warning detection system.

The MIRIADS device can operate virtually any infrared focal plane array (FPA) that currently exists. Programmable on-board logic applies user-defined processing functions to the real-time digital image data for a variety of functions. Daughterboards may be plugged onto the system to expand the digital and analog processing capabilities of the system.

A unique full hemispherical infrared fisheye optical system designed and produced by Optics 1, Inc. is utilized by the MIRIADS in a missile warning application to demonstrate the flexibility of the overall system to be applied to a variety of current and future AFRL missions.

FPA, electronics, dewar packaging, fisheye optics, sensor processing

1. INTRODUCTION

Under sponsorship from the Air Force Research Laboratory Munitions Directorate, Nova Research, Inc. has successfully completed the development of the MIRIADS system. MIRIADS is an infrared camera system that has the capability to operate virtually every existing infrared focal plane arrays, with the additional capability to perform powerful real-time signal and image processing on the resulting image data. The great flexibility of the system architecture will speed the time required for existing FPA resources to be used in imaging tests, and the programmable nature of the signal processing system will permit a variety of mission-specific algorithms to be applied to the real-time digital data.

This paper presents an overview of the system and provides some initial imaging and performance data for two systems that have been configured to operate two focal plane arrays (FPAs) that have much different operational requirements and image formats.

2. OVERVIEW OF MIRIADS DESIGN AND FUNCTIONALITY

Figure 1 shows a 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, one of the program's goals was to demonstrate that a cryogenically-cooled infrared FPA in an evacuated dewar could be mounted on the same board as the warm electronics that operate it. Using this approach, electrical vacuum feed-through connections normally required of these systems are eliminated. The feed-through connections are replaced by internal signal layers of the multi-layer printed circuit board, thus reducing single point failure mechanisms that can lead to a breach in the vacuum seal. Another benefit of this design is the inherently short conductor lengths between the FPA output(s) and the associated pre-amplification and digitization circuitry. As a result, the signal capacitance is very low. This permits very high frequency operation for advanced imagers today and into the future.

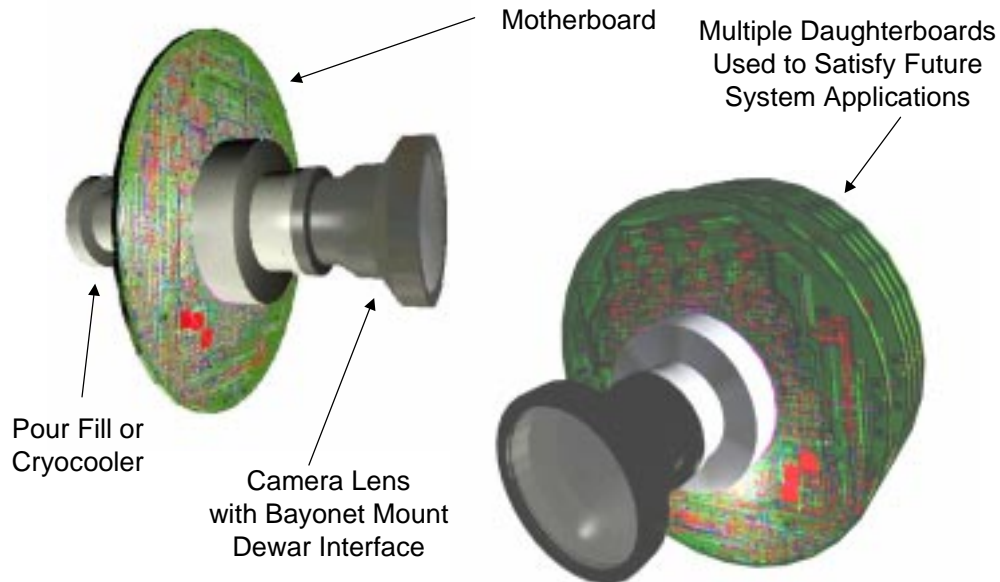


Figure 1. A single circuit board (motherboard) is required to operate the FPA. Additional processing circuit boards (daughterboards) may be used to post-process real-time image data.

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 illustrated in Figure 2 in which numerous identical daughterboards can be stacked and programmed to perform unique data or image processing functions either on the FPA image data or the processed data from any of the daughterboards in the stack. Processing can be performed in a serial and/or parallel manner based on the processing required. Using in-system programmable logic, processing functions can be changed quickly and easily based on mission requirements without disassembling the system to change hardware configuration settings or swapping-out hardware.

Flexibility in the system architecture permits cooling of the FPA using either a large-capacity liquid nitrogen (LN2) reservoir dewar subsystem or an electric cryocooler unit that can be attached to the cooling port located in the lower dewar assembly as shown on the left side of Figure 2.

The MIRIADS system was designed to provide an easy interface to a commercially-available image capture and display system. In support of this goal, SE-IR Corporation's "CamIRa" display frame grabber, DSP board and software was used to provide real-time display and digital data storage functions.

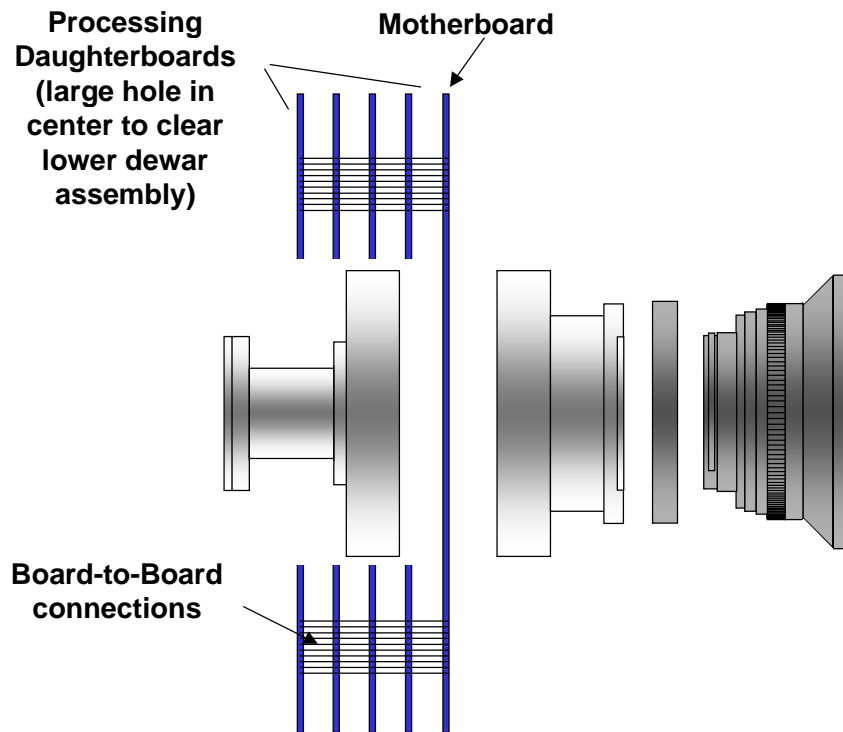


Figure 2. Illustration of the MIRIADS camera system components that include a lens with bayonet mount, dewar with integrated motherboard and a multi-daughterboard stack.

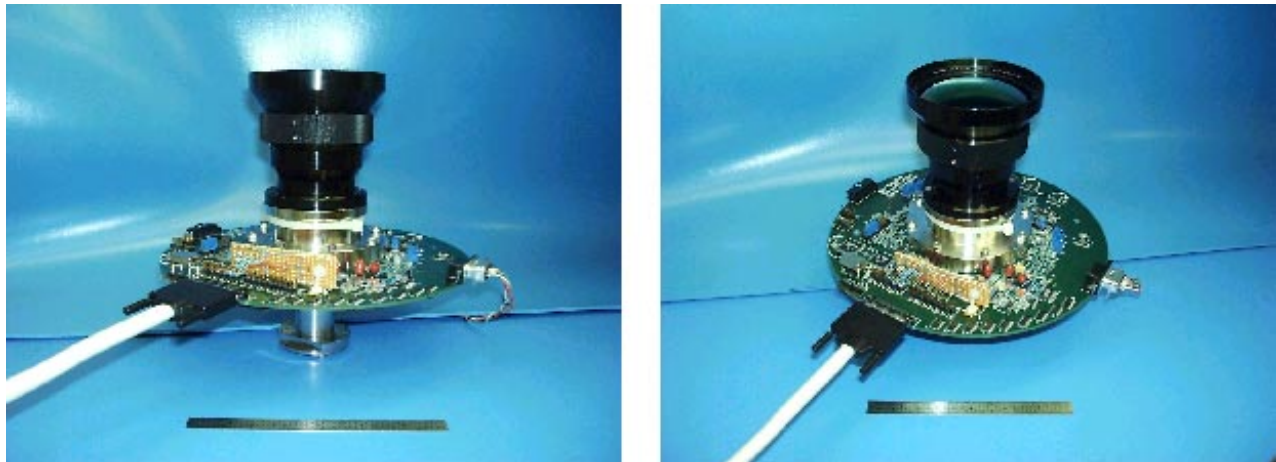


Figure 3. Two views of an existing MIRIADS system operating the Neuromorphic Infrared focal plane array showing a six-inch scale for size comparison.

Two cables are required to operate the MIRIADS system. Figure 3 shows a 68-pin SCSI-3 type data connector and a DB-9 power connector. The data cable delivers 16-bit differential data, pixel, frame and line clock signals to the display system. This cable is also the interface between the camera system and peripheral DSP that provides software-generated camera control functions such as integration time, frame rate or other camera control parameters. The power forms required of the camera system are +5 volts and +/-12 volts.

While operating the Neuromorphic focal plane, the heat load of the system was measured to be approximately 1 watt at 77K. This is low enough for a cryo-cooler, but high enough to require multiple milliliters of LN₂ if using a pour fill method of

cooling. 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.

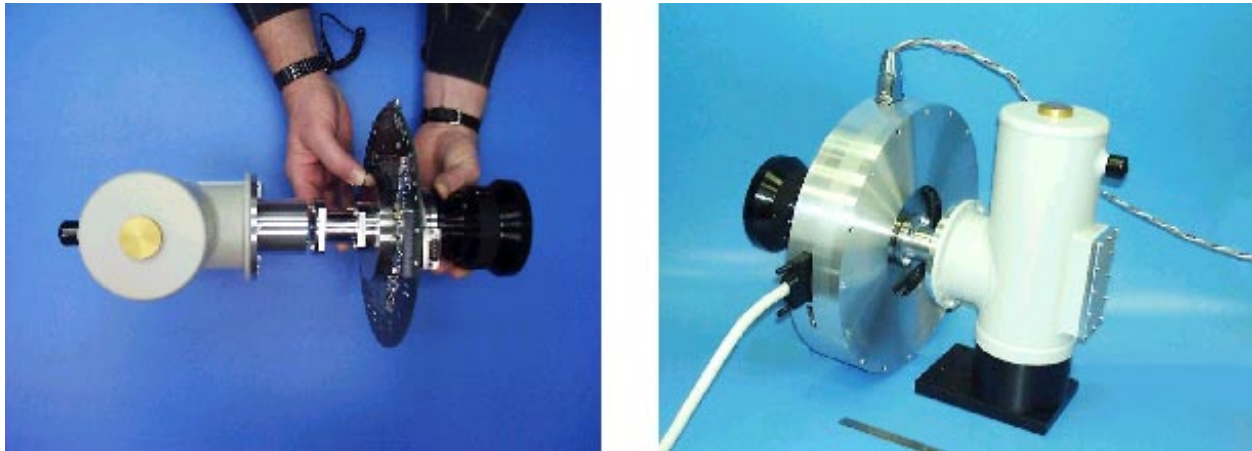


Figure 4. A high-capacity LN₂ dewar system was developed to provide long-term cooling and a horizontal mounting for the MIRIADS camera system.

2. HARDWARE DEVELOPMENT

Motherboard Camera Electronics

The MIRIADS motherboard camera electronics and mechanical design is state-of-the-art. Every element of the electronic and mechanical design of the system has concentrated on preserving modularity and flexibility such that virtually every commercially available focal plane today can be integrated into the MIRIADS system. The camera incorporates the following features:

- Four channels of gain- and offset-adjustable preamplifier circuits (with adjustable single-pole filters) supply signals to four 14-bit A/D converters. These converters can operate reliably up to 10 megapixels/second per channel. If additional video channel inputs are required, facilities have been included to permit the number of analog channels to be increased through the use of additional A/D converting daughterboards that may be plugged onto the motherboard.
- A total of ten low-noise analog bias voltages are included, eight of which are adjustable on-board.
- Up to twelve clocks are available to the focal plane. While 6 of these clocks have fixed voltage rails of 0 to 3.8 volts, the additional 6 clocks can be modified to provide clock rails to the focal plane from -2.5 to 5.0 volts.
- Current sources are included to support FPA output amplifiers that require them. These sources may also be configured as current sinks if required.
- Two eight-bit D/A converter circuits are included to support devices that require analog input control.
- FPA temperature monitor circuitry is included and supports the use of a primary and backup silicon-junction temperature sensor.
- A variety of power conditioning circuits are included to produce the required power forms with special attention paid to low-noise operation to support the 14-bit operation of the system.
- LVDS or RS-422 receivers and drivers are included to provide a convenient digital format and high noise immunity in harsh EMI environments.
- All required signals to be communicated to a variety of current and future processing daughterboards are transmitted through a limited set of daughterboard connectors.
- Pixel-based sensor fusion operations may be performed through a digital input connector.
- Previously-discussed FPA connections are designed to be modular to support a wide variety of imaging devices.
- In-system programmability of digital logic allows for simple system modifications or upgrades as requirements dictate.

Current Implementation of Camera Electronics

Two different “smart” infrared focal planes have been integrated into the MIRIADS camera system. The first is a “Neuromorphic” focal plane that was developed by Amber Engineering under AFRL sponsorship in 1991. This focal plane produces a single channel of interlaced raw and FPA processed video data as will be described below. The second focal plane that has been integrated into the MIRADS system is the Adaptive IR Sensor (AIRS) developed and demonstrated by Raytheon’s Infrared Operations (RIO) in 2000.

Neuromorphic Infrared Focal Plane Array

The “Neuromorphic” focal plane is a 64x64 pixel mid-wave infrared (MWIR) sensor referred to as NIFS. The NIFS sensor produces two images per frame, (a) the “detector-only” (DET) image that has a logarithmic photosensitivity, and (b) the “network-smoothed” image (NET) that is an electronically-blurred representation of the DET image. This electronic blurring is accomplished in a massively parallel on-FPA analog switched capacitor network that requires a minimum of electrical power (only a few milliwatts) in comparison with the power that would be required by a digital processor to perform the same function (approximately 1 watt). It is the massively parallel nature of the NIFS device that makes it unique in the sense of mimicking the form and function of biological imaging sensors. The spatial blurring response and temporal time constant of the switched-capacitor network is controlled by the user; it is the temporal “lag” of the network response that is responsible for the directional smearing as seen in the NET image. The logarithmic photo-response of the detector permits a dynamic range of over five orders of magnitude of optical incidence without saturating the detector (and without the need to adjust integration time). This is a useful characteristic for infrared sensors which must image hot jet plumes while at the same time sensing thermal variations in terrestrial backgrounds.

Figures 5 and 6 show imagery collected from the MIRIADS system and DIOP f/2.3 3-5 μ m lens while using the NIFS sensor. A desk lamp and a soldering iron are in the sensor field of view. Panels (a) and (b) show the DETECTOR image output and the spatially blurred NETWORK image output from the NIFS device.

When the NET image is subtracted from the DET image (in pixel-wise fashion), the “difference” (DIFF) image is produced and shown in panel (c). One of the important features of the DIFF image is that the speed and direction of motion of moving objects is contained in a single frame by virtue of the subtractive contribution of the network response that lags the instantaneous motion. This is clearly seen in Figure 5, showing that the soldering iron is moving UP in this single frame.

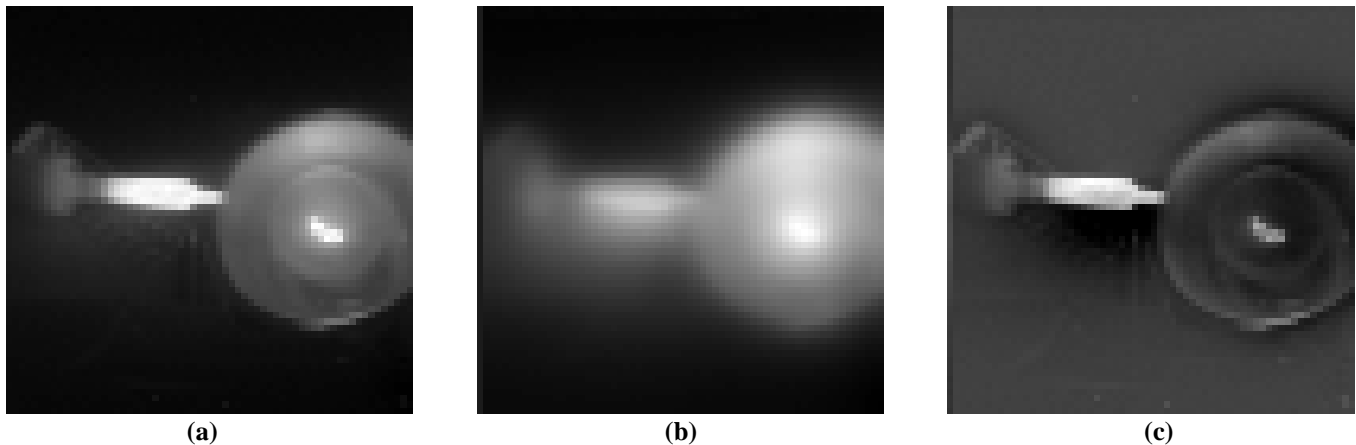


Figure 5. Optical motion sensing is demonstrated using the Neuromorphic Infrared Sensor operated by the MIRIADS camera system. A soldering iron moving UP is captured in the DIFFERENCE image (c), produced by the spatially blurred NETWORK image of (b) subtracted from the raw DETECTOR image of (a).

Figure 6 shows a different frame in the data sequence indicating that the soldering iron is moving DOWN. The subtraction process that produces the DIFF image closely approximates the “Difference of Gaussians” operation performed in nature by biological sensors which enhances spatial edges, produces an insensitivity to the ambient illumination condition, and helps the animal detect the presence of moving predators.

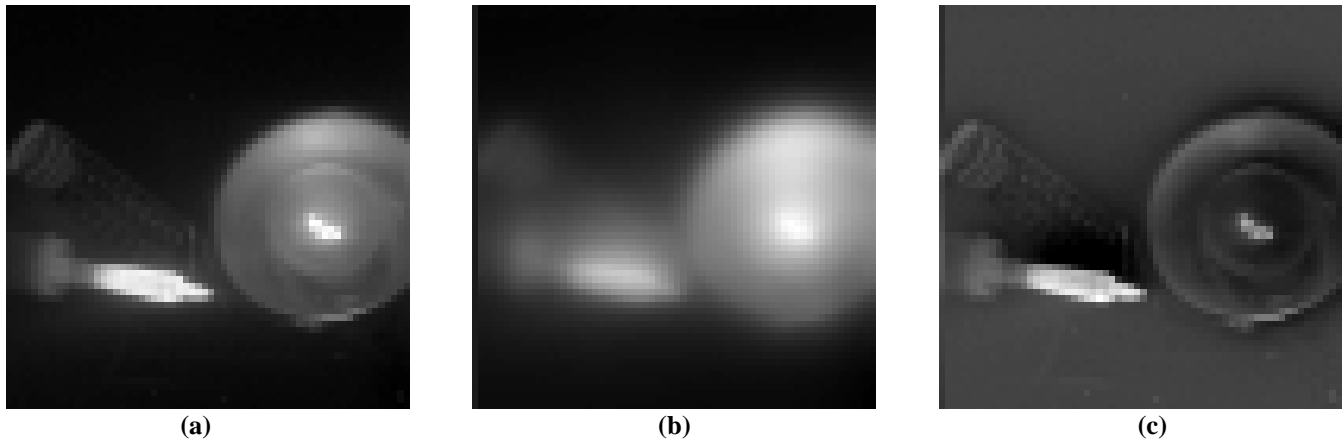


Figure 6. A soldering iron moving DOWN is captured in the DIFFERENCE image (c), produced by the spatially blurred NETWORK image of (b) subtracted from the raw DETECTOR image of (a).

AIRS Focal Plane Array

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 arrays. Additionally, the AIRS is the first ROIC to demonstrate an ability to adaptively “fix” bad pixels on the focal plane, thus improving the offset non-uniformity coming off the FPA. 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.

The second MIRIADS system has been configured to operate the AIRS focal plane. However, in this configuration a 2π -steradian field-of-view long-wave infrared “fisheye” lens designed and built by Optics 1, Inc. was used during our data collection effort. Figure 7 shows the MIRIADS system using the “fisheye” lens.

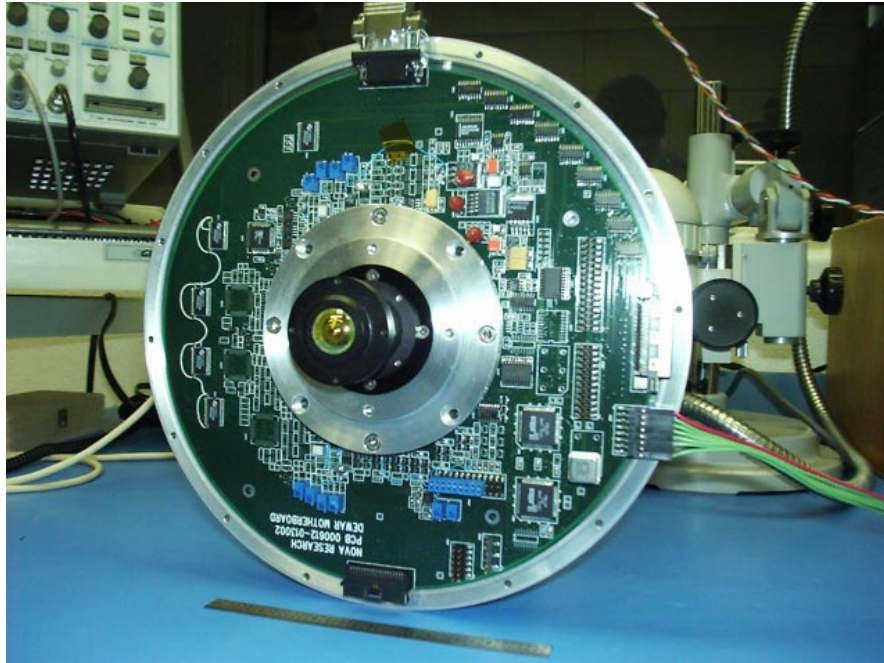


Figure 7. MIRIADS camera system operating the AIRS focal plane and using a long-wave infrared “fisheye” lens.

While operating in the Direct Injection (DI) mode, the AIRS FPA device operates as a conventional infrared focal plane device. Figure 8 shows a frame collected in the DI mode. Spatial nonuniformities in this image have been corrected out digitally, off-FPA.



Figure 8. AIRS FPA exhibits good imagery and operability in Direction Inject Mode (images courtesy of Raytheon Infrared Operations).

The AIRS focal plane has also been demonstrated while operating in the Temporal High Pass Filter (THPF) mode. Figure 9 shows a few frames collected in this mode, in which the nonuniformity correction is performed directly on the FPA itself, thereby reducing the requirement to perform this processing in external electronics.



Figure 9. Images from the AIRS device running in “Temporal High Pass Filter” (THPF) mode. When the THPF is running at a slow update rate, very few image artifacts exist (images courtesy of Raytheon Infrared Operations).

Daughterboard Image/Data Processing Electronics

The “stackable” nature of the MIRIADS electronics provides the opportunity to design multi-purpose digital and/or analog processing daughterboards that can perform a variety of useful real-time image/data processing operations on data produced by the FPA/motherboard system. Nova has designed and produced the “Real Time Processor” (RTP) daughterboard as shown in Figure 10. It has the same outside diameter as the motherboard, registered digital and analog signal connectors related to the motherboard and is designed with in-system programmable logic to permit rapid reconfiguration of the system to perform a wide variety of image-based processing algorithms on the real-time sensor data.

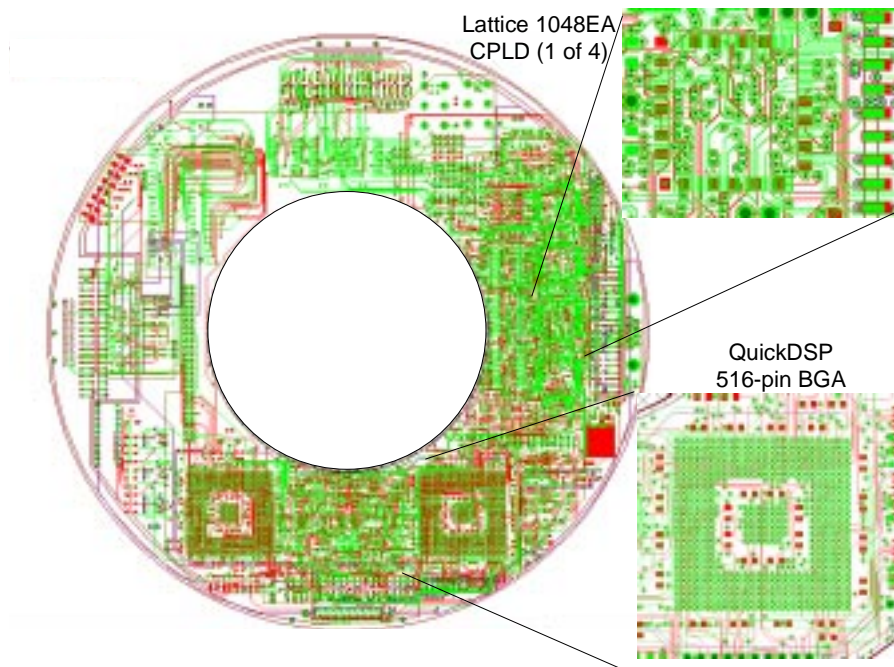


Figure 10. Nova’s “Real-Time Processing” daughterboard includes two DSPs, four CPLDs, on-board memory and a flexible, re-configurable image processing architecture.

Examples of image/data processing that can be performed by the RTP board include:

- Nonuniformity Correction
 - One-Point
 - Two-Point
 - Multi-Point Piecewise Linear
 - Scene-Based
 - FIR Filter Operations
- Arbitrary Pixel Revectoring
- Color-Space Mapping Using Lookup Tables (LUTs)
- Kernel-Based Convolution Processing
 - n x n Kernels
 - Edge Enhancement
 - Motion Detection
 - Erosion
 - Dilation
 - Smoothing/blurring
 - Frame Differencing Operations
- Kernel-Based Rank Filtering
 - Median
 - Noise Filtering
 - Centroiding Operators
- Target Tracking
- Guidance Integrated Fuzing Processing
 - Tracking, Closest Approach Determination
- Histogram Processing
 - Rayleigh Distribution Processing
 - Histogram Equalization Processing
- Multi-Spectral Operations
 - Spectral Ratio Processing to Determine Surface Temperature
 - Principal Components Analysis Operations

To accomplish these types of operations, the RTP board is equipped with two high-performance digital signal processors, in-system programmable logic with up to 32,000 PLD gates and up to 40Mb of SRAM. The flexible architecture gives the systems designer the capability to process FPA-produced digital video data in a variety of ways. The use of multiple RTP boards in a system permits parallel and/or serial processing for sophisticated high-speed operations.

The MIRIADS program has invested in the development of two DSP designs. The first design implementation is a full one-point and two-point NUC processor that computes and applies gain and offset corrections for each pixel. In addition, the device performs a bad pixel replacement operation. The second DSP has been designed to function as a general-purpose floating-point processor that may be used in conjunction with a variety of processing algorithms. The device performs 32-bit floating-point add, multiply and divide operations either in a synchronous or asynchronous manner. Any of the three floating-point operations can be disabled as required to reduce power consumption of the system.

An example of the sophistication that has been designed into the NUC processor DSP is the implementation of West's Algorithm. This algorithm has been applied in this device to numerous frames of uncorrected pixel data to compute each pixel's temporal noise (as represented by the pixel's time-based variance) as a means for identifying bad pixels.

For each pixel,

M_k is the pixel's running average,
 X_{avg} is the pixel's final mean value
 S is the pixel's standard deviation

S^2 is the pixel's variance
 K is an index over all pixels
 T is a parameter used to evaluate the temporal variation of the pixel.

West's algorithm is implemented in a recursive way for determining the pixel's mean value:

$$M_1 = X_1 \quad (1)$$

$$M_k = M_{k-1} + \frac{X_k - M_{k-1}}{k} \quad k = 2, \dots, m \quad (2)$$

$$X_{avg.} = M_m \quad (\text{Final Pixel Mean Value}) \quad (3)$$

And each pixel's variance and standard deviation are computed recursively by:

$$T_1 = 0 \quad (4)$$

$$T_k = T_{k-1} + \frac{k-1}{k} (X_k - M_{k-1})^2 \quad k = 2, \dots, m \quad (5)$$

$$S^2 = \frac{T_m}{m-1} \quad (\text{Final Pixel Variance Value}) \quad (6)$$

Fisheye Optics

Optics 1, Inc. has been very helpful in providing design requirements, hardware prototypes and other information in support of this effort. The Air Force Research Laboratory Munitions Directorate Advanced Guidance Division (AFRL/MNG) has coordinated efforts between Nova and Optics 1 so as to produce initial sensor system designs that support their long-term goals with regard to infrared detection and processing.

Optics 1 has produced an long-wave infrared fisheye lens as shown in schematic form in Figure 11. Use of this lens produces a system with complete hemispherical field of view; two such systems opposed to one another would provide a complete view of space around the sensor platform and could be used in an infrared early warning sensing system.

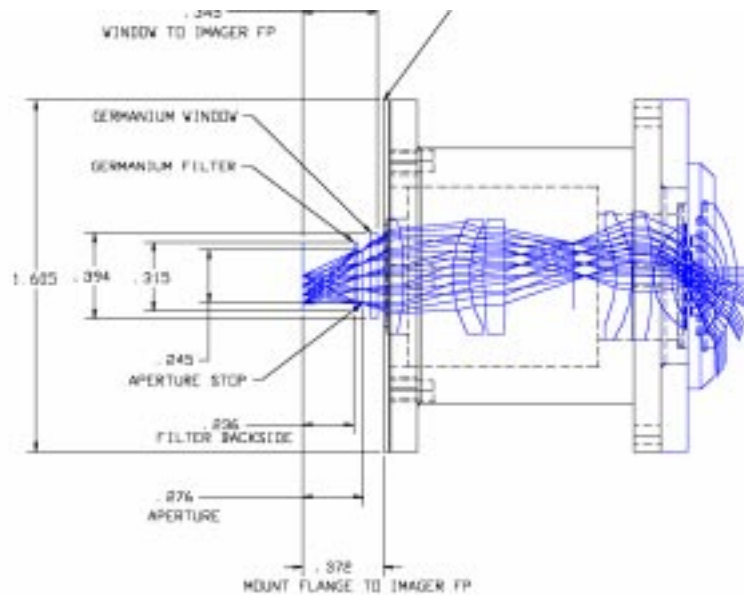


Figure 11. A multi-element refractive infrared fisheye lens system has been produced by Optics 1 that has demonstrated a full 2π -steradian field-of-view.

The MIRIADS system is capable of operating dual color FPAs. A dual-color, dual-field-of-view infrared optical system is currently being designed and fabricated at Optics 1 in support of the next generation of MIRIADS sensor systems. A conceptual drawing is pictured in Figure 12. This particular system will have 10-degree and 100-degree field-of-view settings, and will be able to switch between these two settings in approximately 20 milliseconds. Its primary use is in missile interceptor applications.

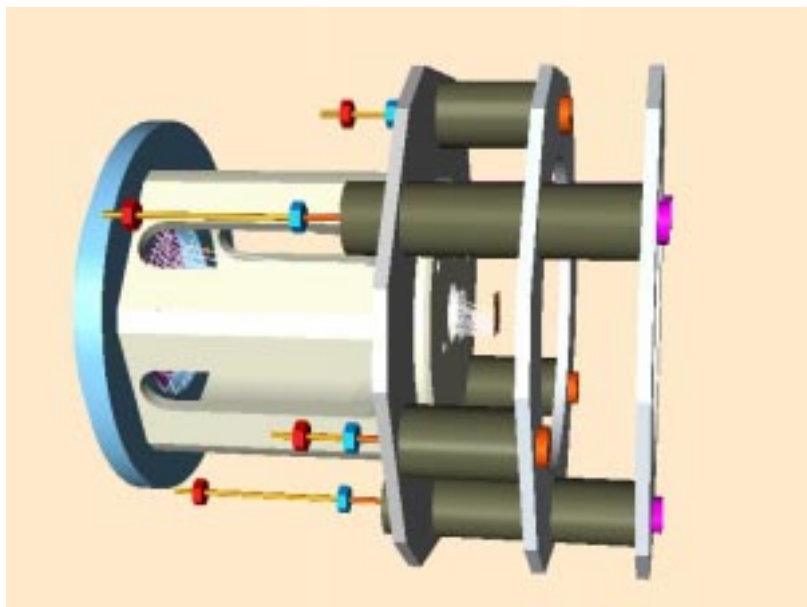


Figure 12. A future dual-color, dual-field-of-view infrared optical system is being designed at Optics 1, Inc. for use with the next generation of MIRIADS sensor systems.

The AFRL SBIR program has been instrumental in advancing the development of sophisticated infrared sensor/processing systems through their funding of small business' like Nova and Optics 1. Both Nova Research, Inc. and Optics 1, Inc. are continuing their respective efforts in advancing the state-of-the-art of these technologies.

3. ACKNOWLEDGEMENTS

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