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Image Fusion for Tactical Applications

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1. Abstract

Multispectral sensors are increasingly being employed in military applications. Just as in satellite imagery of the earth, multispectral data is required in order to extract the maximum amount of information from a scene. The advantages of image fusion have been postulated for navigation, surveillance, fire control, and missile guidance to improve accuracy and contribute to mission success. The fusion process is a critical element of each of these applications.

Imagery from various sensors must be calibrated, enhanced and spatially registered in order to achieve the desired “fusion” of information into a single “picture” for rapid assessment. In a tactical military environment this fusion of data must be presented to the end user in a timely and ergonomical fashion. The end user (e.g., a combat pilot) may already be operating at maximum sensory input capacity. Does he or she really need another cockpit display?

2. Image Fusion Approaches

Lockheed Martin Electronics and Missile Division (LME&M), in cooperation with Defense Advanced Research Projects Agency (DARPA), Naval Research Laboratory (NRL), Naval Postgraduate School (NPS) and the US Army Center for Night Vision and Electro Optics (CNVEO), is actively involved in all aspects of image and data fusion (Figure 1). This involvement extends from multispectral data collection and modeling, through sensor design, software and processor design and display parameters. All aspects of the image and data fusion process involve state-of-the-art efforts in understanding the phenomenology and implementing the insertion of the technology into current and future programs. These efforts extend from design of multispectral Quantum Well Sensors, which generate accurate spatially registered imagery to extremely high speed processors to fuse and display the resultant data to the end user.

Two-band infrared (IR) detection is an important technique for determining the temperatures of objects in a scene and discriminating targets from decoys and background clutter. A single-band detector measures only the total in-band IR emittance from a scene element (i.e., it cannot discriminate variations in emissivity from variations in temperature). More importantly, for unresolved targets, single-band detectors cannot discriminate between large warm and small hot targets. By measuring the IR emittance at two or more wavelengths, the actual temperature of the object can be determined and the hot plume of a missile launch can be discriminated from a colder missile in flight. Multicolor FPAs also provide additional information about the target. By processing the spectral signature of objects in the scene together with the spatial features, recognition and identification of resolved targets may be accomplished either at a longer distance or with a higher confidence level.

Prior approaches for multicolor detection either do not permit full pixel registration or make manufacturing difficult. Because it is difficult to build two-band detector arrays using conventional IR detector materials, dual band systems typically have used two physically separated focal planes or an arrangement of filter wheels. This results in severe penalties in power consumption, size, and weight and difficulty in aligning the images. To fully use the potential of two-band detection, the two images must be fully pixel-registered. Furthermore, for some detection algorithms, the longwave IR (LWIR) and midwave IR (MWIR) signals must be time-registered (i.e., simultaneously integrated).

The recent advent of multiple Quantum Well (MQW) IR detectors offers one approach for two-band detection because MQW layers with different spectral sensitivities can be grown in a vertically integrated structure. By providing separate contact layers to the MWIR and LWIR portions of the MQW stack (Figure 2), perfect pixel registration is achieved. Furthermore, since 6-inch-diameter MQW wafers can be grown now, this approach will provide large, low-cost arrays. This capability is comparable to the 640x480 single-color and 256x256 dual band arrays already successfully fabricated by Lockheed Martin (Figure 3).

Quantum well technology provides a readily producible multicolor focal plane array (FPA). This technology allows simultaneous integration and readout of two or more "colors," each being pixel-registered on the same FPA. This pixel-registered multicolor FPA increases system capability and allows a much simpler design for other system components. Eliminating the multiple FPAs, scanners, coolers, or filter wheels of existing multicolor designs reduces system cost, weight, volume, and computational processing, providing benefits to many military applications.

3. Algorithms

Advanced automatic target recognition (ATR) and Image Enhancement algorithms are also needed to exploit and combine the complementary information that is available in multisensor imagery. The need is for new image processing techniques to combine the multispectral images so that the resultant image will have information content than any of the original images. The resultant single image presented to an already overburdened operator or pilot must be presented to the operator in such a manner that the pertinent information that he requires is instantly apparent. This requires studies in data formatting such as color coding and specific detail or object enhancements (e.g., towers or hanging power line for obstacle avoidance).

For applications not having a “human in the loop”, such as ATR, the fusion of the multispectral information into a single image stream provides enhanced capability, accuracy and possible reduced processing requirements. Other applications of image processing techniques relate to image enhancement to compensate for sensor deficiencies or to accentuate particular details (e.g., targets) in the imagery. This is an effective method to improve overall system performance. When considering the entire area of multi-band color fusion, many different band combinations are possible. For example, three general cases are combining imagery from two bands, three bands, or more than three bands. The two-band case is of special interest because there has been good progress in low-cost commercial cameras that image in the low-light-level visible and the infrared. An obvious systems concept is to fuse the imagery from two such cameras. The image processing challenge is to generate an intuitively meaningful color image on a display for a human viewer. To do this, the data must be processed and mapped into a red-green-blue (RGB) color display for a human viewer. Algorithms to perform this function in an optimum manner are currently under development[1].

A simple representation for the three-band infrared case and the accompanying color contrast enhancement, as described above, is fairly straight forward because the number of bands matches that of the human viewer. Displaying two bands of infrared to a human observer, who has three types of photoreceptors (commonly referred to as the red, green, and blue cones), is an inherently poor fit. Because the human color processing system works with color opponents (namely red-green and yellow-blue color opponency), it is possible to use color opponents to display a dual band infrared image. In the work done at NRL, a red-green color opponency was chosen. In actual fact, the longer spectral wavelength infrared band was input to a red display channel and shorter wavelength band was input to both the green and the blue display channels. The combination of equal amounts of green and blue creates cyan. In essence this is the same as red-green color opponency, red and cyan are color opponents because when they are combined they create the perception of white or some shade of gray. In this manner the relative intensities between the two bands at each pixel can be represented as a chromatic continuum starting as red, going through gray, and ending as cyan. At the same time a brightness value can be assigned in an orthogonal direction. Therefore, each pixel has a chrominant value (red-cyan) and a brightness value (black-white) as shown in Figure 4. It is interesting to note that certain snakes see in both the visible and the infrared bands and may combine the dual band information in a similar sense. That is, luminance and chromanance information maybe separated by combining (AND operations) or differencing (OR operations)[2].

There are a number of statistical processing operations that can be applied to the image data before mapping it into a color space (chrominance-brightness). One typical operation is to perform a Hotelling transform on the data[3]. If the dual band image data is highly correlated and mapped into a red-cyan color display, then there will be very little color. However if the data is processed using a Hotelling transform, then the color contrast, in terms of the red-cyan chrominant values, can be maximized. For low-light-level visible and the LWIR infrared spectral bands the surface properties (emissivities and reflectivities) of typical tactical backgrounds is such that the pixel intensities of the resulting imagery is negatively correlated. To achieve a more natural representation for the human viewer it is often useful to represent the data in a black-is-hot mode. An example of this type of processing is shown in Figure 5.

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In summary, color fusion is a visualization technique for human viewers that effectively employs their visual system to combine information from two or more bands and allows the viewer to easily discriminate objects from backgrounds. For example, in targeting applications, this technique can be used to display small differences in pixel values from correlated bands as large differences in color, making it easier to discern a targets.

Figure 6 illustrates the basic components of an image fusion algorithm architecture. The components for both Situation Awareness (SA) and Automatic Target Recognition (ATR) are shown. One has the option of fusing the information from the two sensors at various locations in the processing stream. As the information is fused further down the stream the process becomes more “data” fusion rather than “pixel” or “image” fusion. Appropriate trades must be made for specific applications.

For Situation Awareness the fusion usually is performed as soon as a pair of suitable images becomes available, i.e., after image enhancement or normalization. Image enhancement in addition to removing objectionable sensor artifacts can be used to accentuate features in the imagery which may be of interest to an observer (Figure 7). Image normalization is sometimes needed if the imagery from the various sensors differs greatly in terms of brightness, contrast, and dynamic range. The image fusion should be independent of such variations in the sensor and in the scene. The operator should have only one monitor to adjust for his individual preference; and the image fusion process should automatically adjust for any sensor which fails or goes off-line (Figure 8). The fusion process must not only fuse the information into a single output image but must present the “pertinent“ information in a form which attracts the appropriate attention from the observer. Output color control is an important aspect of the fusion process (Figure 9). LME&M uses structural extraction algorithms to extract appropriate structure from each of the multispectral inputs. These structures is then fused with appropriately selected color components. For ATR applications, image fusion can result in enhanced target detection (Figure 10) and enhanced target segmentation which leads to better classification accuracy (Figure 11).

4. Human Performance Evaluation and Modeling

Advances in night vision imaging have provided alternative methods whereby signals from image intensifiers (I^2) and uncooled infrared (IR) sensors may be combined within a single image format. This opportunity for sensor fusion allows not only that information provided by disparate bands within the electromagnetic spectrum may be efficiently combined, but that the output of multiple sensors may be used to generate chromatic imagery. The color mappings produced, however, are likely to appear unnatural, and will not demonstrate the color constancy characteristics of the human visual system. The benefits of sensor fusion appear apparent, but there have been inconsistent results demonstrating the advantages of a sensor fusion system on a military platform. NPS has been conducting ongoing research is to develop a framework for evaluating sensors, algorithms and operator performance across different but relevant combinations of spectral wavebands. In addition, existing analytical operations-research-type models are being modified to fit meaningful performance metrics that can be revised and extended where necessary to represent the data obtained during the field tests. These modified models will then be used to evaluate fused imagery systems requirements and performance. Furthermore, these models will indicate what type of data will be needed in future data collections.

Ideally, the perceptual representation allowed by night vision imaging will closely mirror that achieved under photopic illumination, where visual performance is optimal. Notably, studies demonstrating benefits of false-color imagery relative to monochromatic and unfused imagery have often measured perceptual performance in tasks demanding simple detection and/or localization of targets[4,5,6]; perceptual grouping[7,8]; and subjective assessment[9]. It is not clear, however, that these tasks alone can assess the qualitative or functional similarity between the perceptual representation that has been achieved through sensor fusion, and that which would be obtained under typical viewing conditions. Target detection, rather, might occur based on the presence of salient visual features idiosyncratic to some combination of sensor format and target, different from those that obtain within the naturally imaged scene. A human target within an IR imaged scene, for example, appears as a high contrast blob of shape similar to that of a human’s silhouette, and is thus detected more easily than an I^2 images[10]. The efficiency with which such a target is detected provides a clear measure of target salience, and presumably indicates that the rough correspondence between a shape in the image and the shape of a human has been perceived, but may unfortunately be of little use in assessing the quality with which the scene as a whole is perceived[11]. The adequacy with which naturalistic, spatially extensive stimulus arrangements are perceived through various sensor formats or combinations of sensor formats must be more directly addressed. Currently, NPS is concentrating on the quality of visual information conveyed by various image formats (long-wave IR, mid-wave IR, low-light television, and visible) by assessing the efficacy of scene perception which they allow.

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White[8] investigated whether color features (combining an infrared and visible sensor image) improved visual scene comprehension compared to single-band grayscale features during a signal detection task. Twenty-three scenes were briefly presented in four different sensor formats (infrared, visible, fused monochrome, and fused color) to measure subjects' global visual ability to detect whether a natural scene was right side up or upside down. Subjects were significantly more accurate at detecting scene orientation for an infrared and fused color scene compared to a fused monochrome and visible scene. Figure 12 illustrates that subjects responded more accurately to fused color and IR than to I^2 and FM. The boxplots show that the IR and fused color sensor types are similar in mean and interquartile range, and I^2 and fused monochrome have lower means and larger interquartile ranges. Both the infrared and fused color sensor formats provide enough essential features to allow an observer to perceptually organize a complex nighttime scene. The recent data collection performed at Fort A.P. Hill used an advanced low-light camera which and state-of-the-art uncooled LWIR camera, which is expected to yield improved results.

5. Data Collection

Ground-based data collection was conducted on April 14th and 15th, 1998 at Fort A.P. Hill, Virginia to gather data for sensor fusion development. This data collection was the second in a series which started in the Fall of 1997 and will continue through 1998. The Fort A.P. Hill data collection used four different spectral sensors boresighted within a vertical integrated sensor mount. The test consisted of a Lockheed Martin IR & Imaging Systems (LMIRIS) uncooled long-wave infrared sensor, Amber Radiance mid-wave infrared camera, Lockheed Martin (LM) Fairchild low-light camera, and a Pulnix TM-540 visible near infrared camera. The test methodology consisted of five different scenarios that varied across terrain (open field to dense forest) by target types (M2 Bradely, M60, M113 APC, M35 2.5 ton truck, and a HMMWV). Each data collection session lasted approximately eight hours with four scenarios tested each session. The majority of data was collected during full moon illumination with a couple of hours during sunrise. Meteorological and GPS data on selected targets were collected during both sessions. Within each session, analog video was continually recorded for each sensor and selected digital segments were recorded using a specially configured portable digital collection workstation. Digital sequences were limited to three minutes, thereby allowing time to archive the digital files.

This summer an AH-1W Cobra helicopter test bed supplied by National Aeronautics and Space Administration (NASA) Ames will be used for fusion data collection conducted at NASA Ames Research Center. The data collection will use a LMIRIS uncooled LWIR camera and a Fairchild visible camera to simultaneously collect navigation and targeting data in both spectral bands. The sensors and video recording equipment will be mounted within the ballast turret. Two data collection systems will be flown, one with advanced uncooled LWIR and LLLTV sensors which are being developed by LMIRIS and LM Fairchild under DARPA sponsorship, and another with high performance cryo-cooled LWIR and MWIR sensors. In addition, NRL, NPS, NASA Dryden, PVP Advanced EO, inc., and LME&M have demonstrated a multi-color night vision system on an F/A-18 Day/Night Infrared Imaging/Tracking Laser Target Designating/Ranging System (NITE Hawk) targeting FLIR pod. Five flights at the Naval Air Warfare Center (NAWC) China Lake demonstrated the potential for color fusion to improve target recognition and situation awareness for aviators[11]. The aircraft pod was configured either for day (visible and 1st generation infrared) or night (3rd generation image intensified charged coupled device (CCD) and 1st generation infrared) flight operations (REF). Figure 13 illustrates the advantage of sensor fusion for identifying texture features within a scene. The SAM site and surrounding roads are easily perceived in the color scene as compared to either the low-light or infrared scene. This videotape snapshot taken from NASA Dryden's F/A-18 modified NITE Hawk targeting FLIR pod on 30 May 1996 at Naval Air Station (NAS) China Lake. The modified pod had a first generation scanning FLIR and a Pulnix third generation image intensified CCD. The target is displayed in three formats (a) FLIR, (b) image intensified, and (c) fused color. The fused color provides improved target contrast and more texture information compared to each single band. Four flights in August 1997 collected more data under various environmental and terrain conditions to demonstrate the advantages of sensor fusion. The next flight is scheduled in July 1998, the pod will be configured with a 3rd generation mid-wave sensor and a monochrome visible camera. The field-of-view for both sensors will be set at 1.5 degrees. This test should provide excellent fusion data due to the improved sensor formats and reducing sensor misalignment.

6. Processing Requirements

Table 1 summarizes the processor operations required for a representative sampling of image fusion algorithms evaluated by LME&M. The processing requirements are listed as operations per pixels. An operation is an integer addition, subtraction, multiply, divide, or compare. A factor of X3 is included for memory access. Since memory access is highly

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processor dependent, this table is meant as a simple estimate of the relative throughput requirements. It assumes that the processing is all digital and performed on a conventional general processor. Requirements can be much reduced for processors specially designed for a specific type of operation or algorithm or even a processor specifically designed for image processing.

Figure 14 illustrates the computational requirement in terms of algorithm requirements (operations/pixel) and video data rate (pixels/second). Two digital image frames of 512 x 512 pixels each at a rate of 30 framers per second represents a data rate of 15.8 million pixels per second. On the chart this represents high end of conventional TV or low to mid HDTV data throughput.

LME&M has been involved in real time image processing processor design since 1982. The involvement started with pipeline video processors for ATR applications and has evolved to include SIMD (Single Instruction Multiple Data) parallel processors such as GAPP and PAL II (Figure 15). Special attention is applied to processors which can be easily inserted into fieldable applications. The PAL II processor is designed to perform complex multispectral fusion operations on real time video inputs. This processor is designed to occupy one slot in a 6U VME Chassis.

Table 1 Processing Requirements

Algorithm Type	Operations/Pixel
Simple Add	9
Video Boost and Add	945
LME&M Cross	2250 (750)*
LME&M Morphological	4200 (1400)*

* Special LME&M PAL II image processor

7. Conclusions

Ongoing cooperative research by LME&M, DARPA, NRL, NPS, CNVEO and PVP Advanced EO,inc. will continue to develop system engineering approaches to image fusion including system-level modeling, algorithm development, human factors evaluations, advanced sensors development and operations analysis. Data collection in 1998 is expected to provide a basis for further development in these areas, leading to real-time image fusion demonstrations in 1999.

8. References

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9. Monochrome Figures

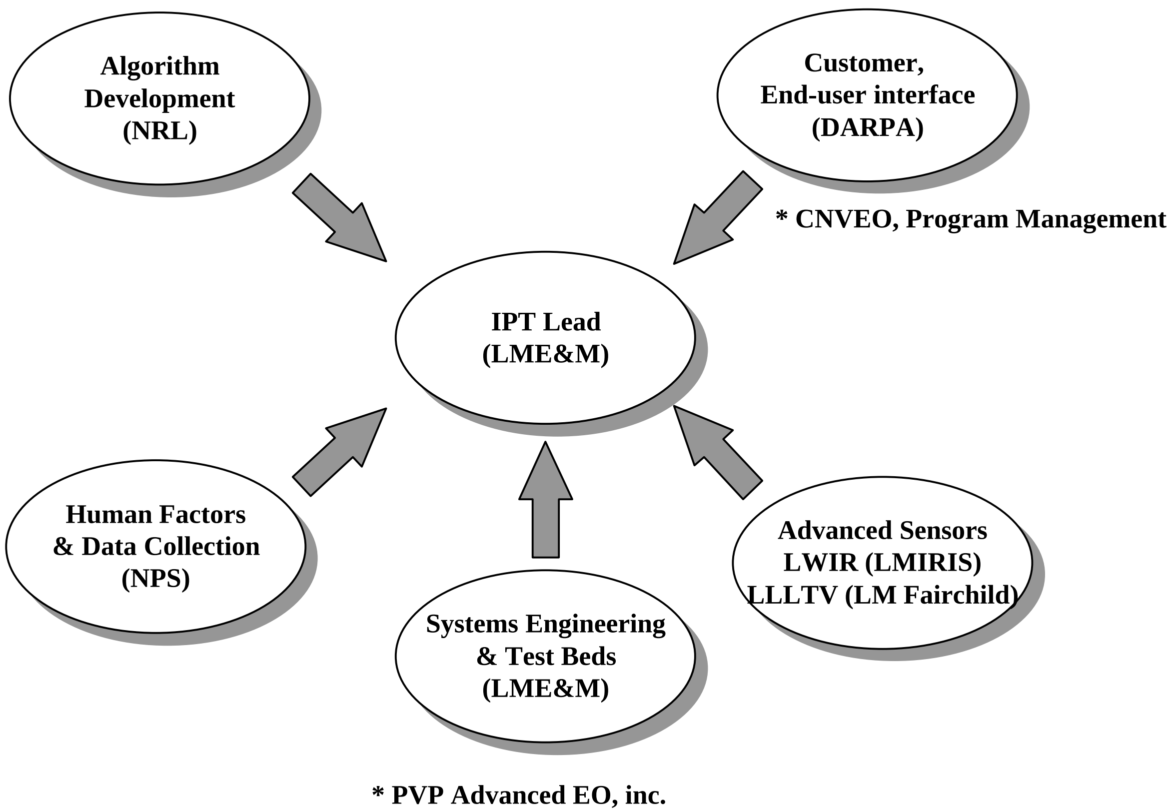

Figure 1. Image fusion team members.

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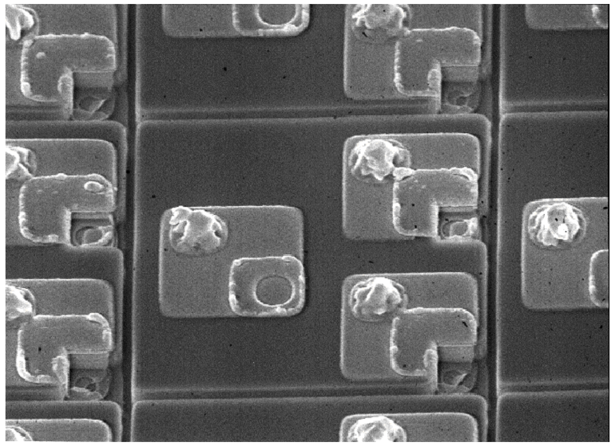

Figure 3. Multicolor Quantum Well FPAs are now being developed for image fusion applications

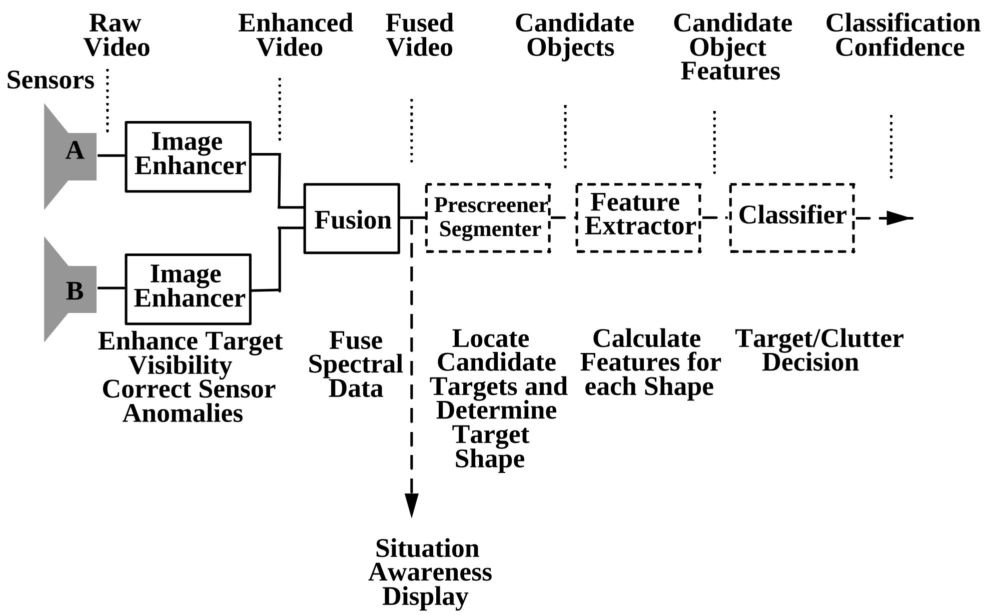

Figure 6. Fusion algorithm architecture.

Original Image **Enhanced Image 1** **Enhanced Image 2**

Figure 7. Morphological image enhancement prior to image fusion.

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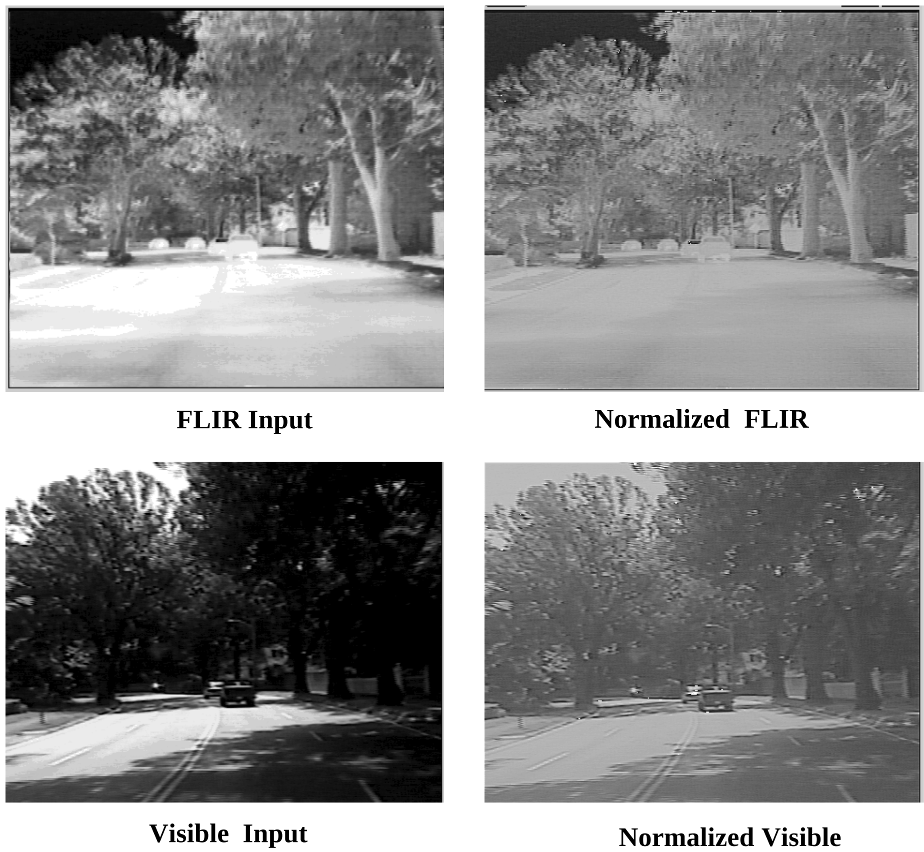

Figure 8. Image normalization prior to fusion.

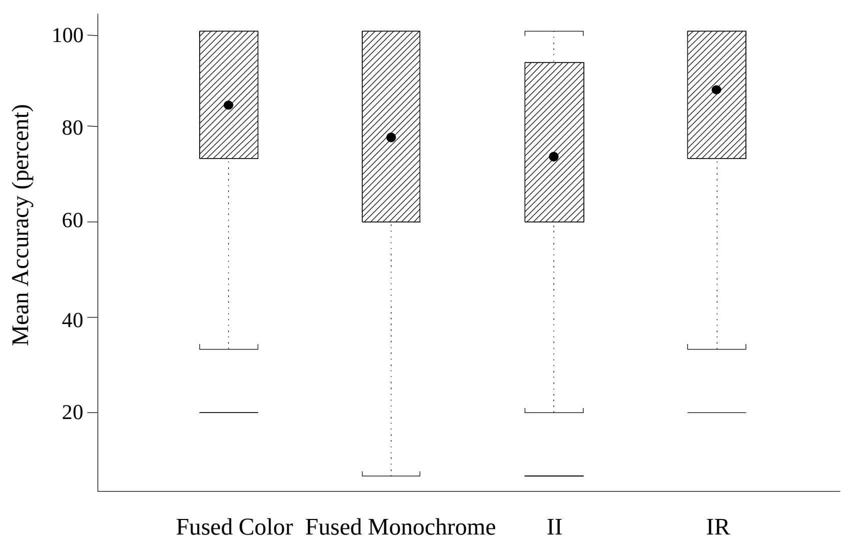

Figure 12. A significant main effect for sensor (F (3,184) = 110.0411, p = 0.0000) with accuracy as the dependent measure. The Box Plot shows the mean (dot) and interquartile range for sensor accuracy.

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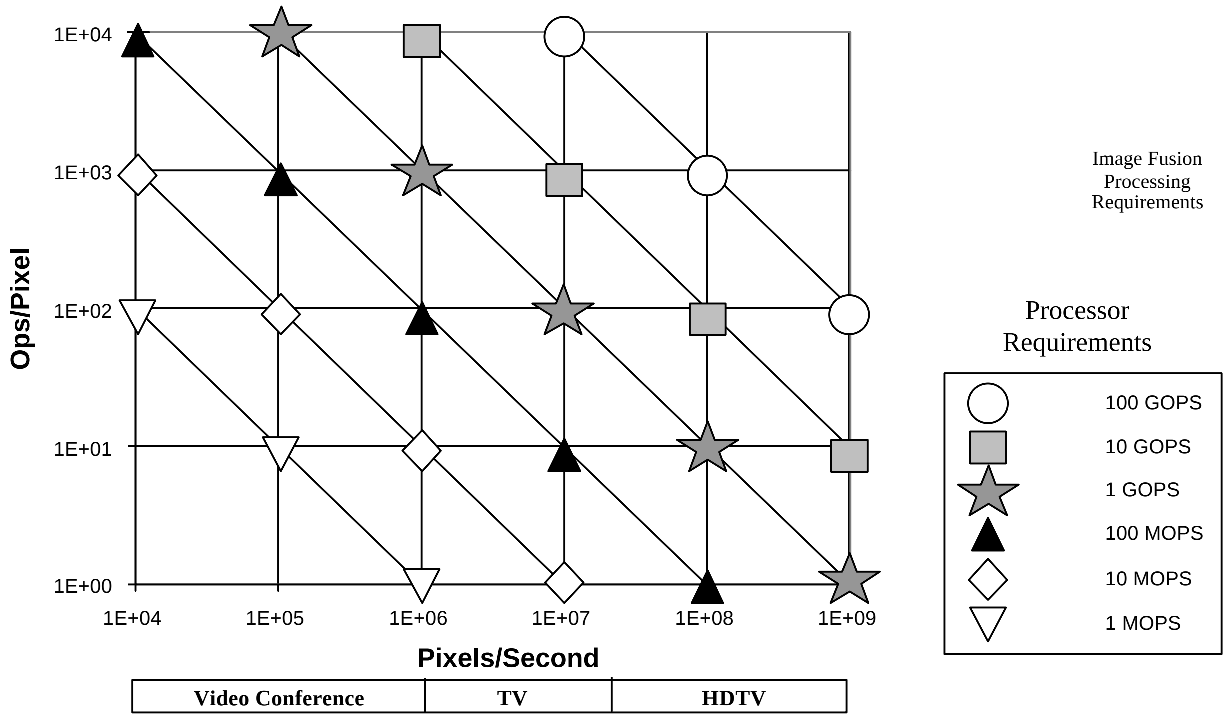

Figure 14. Image Fusion Computational Throughput Requirements.

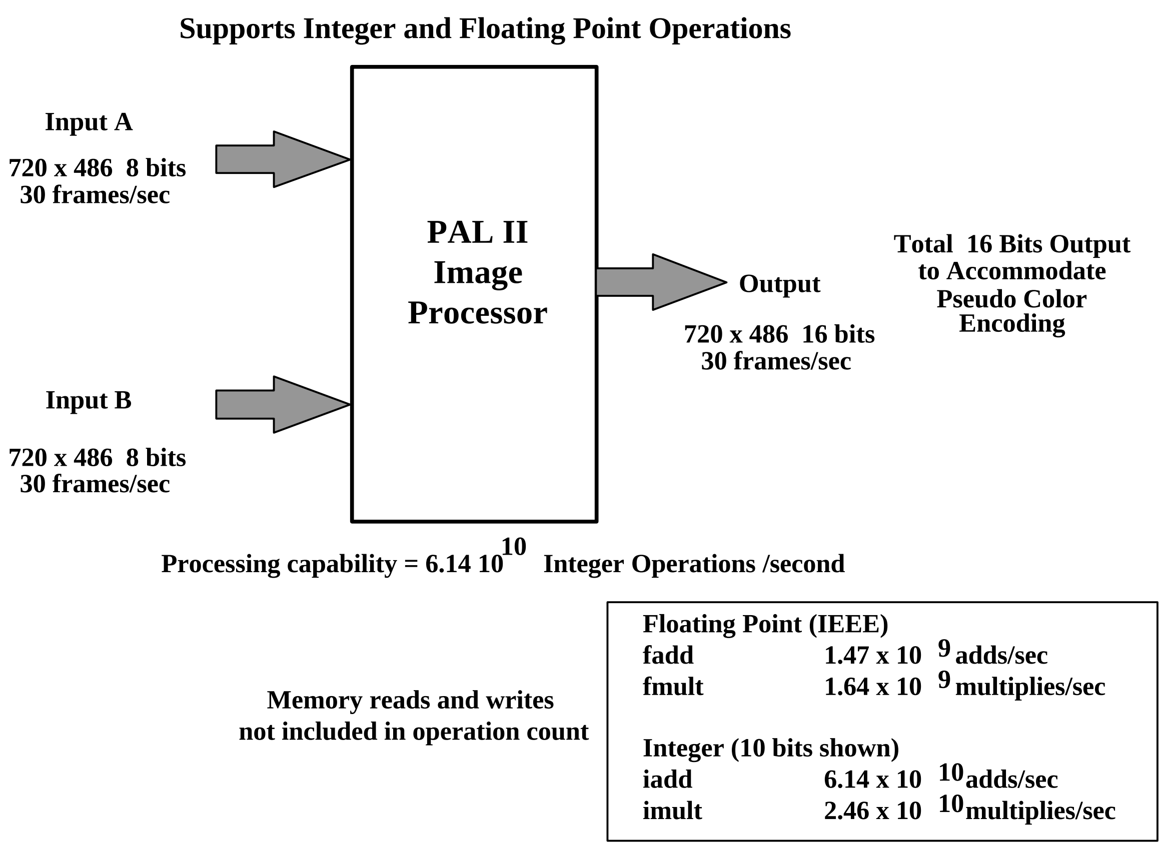

Figure 15. Parallel processor for image fusion.

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10. Color Figures

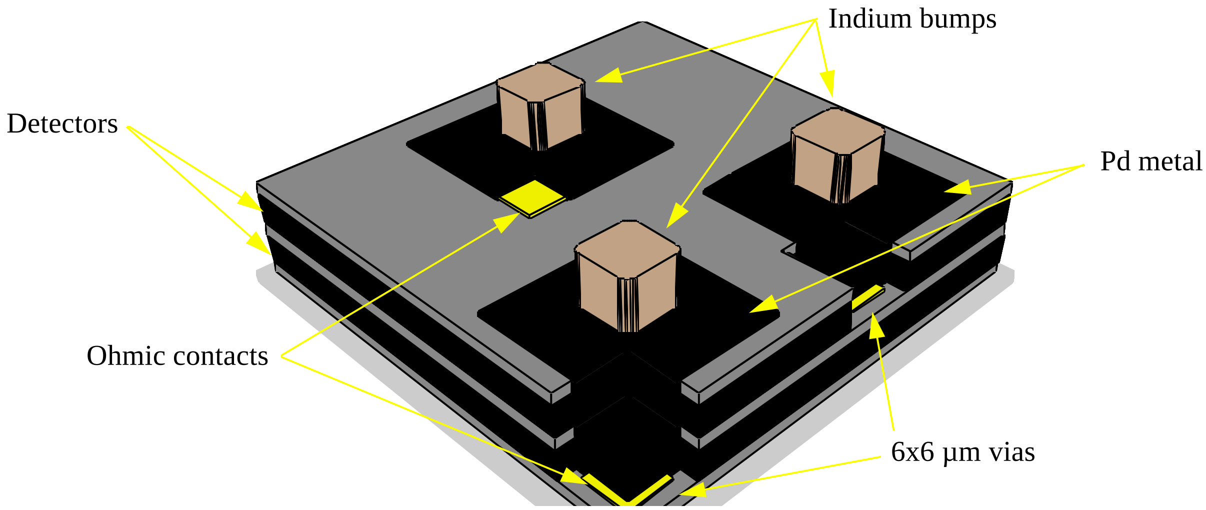

Figure 2. Multispectral sensors require advanced, multicolor focal plane arrays.

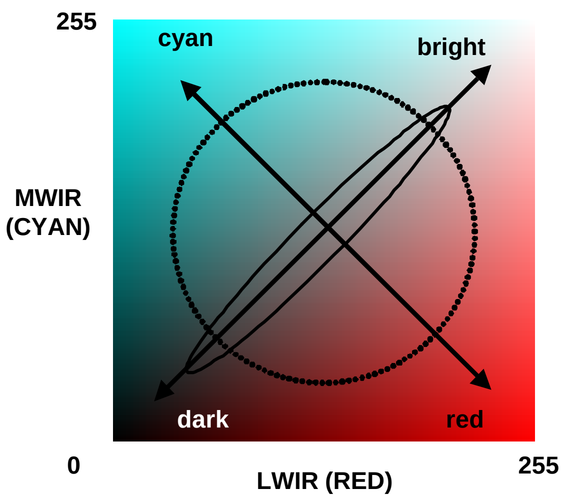

Figure 4. Color processing data space.

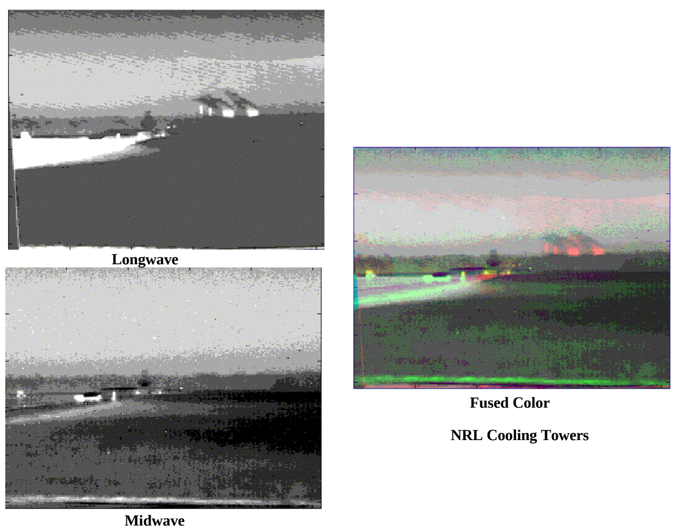

Figure 5. Hotelling transform color mapping of fused images

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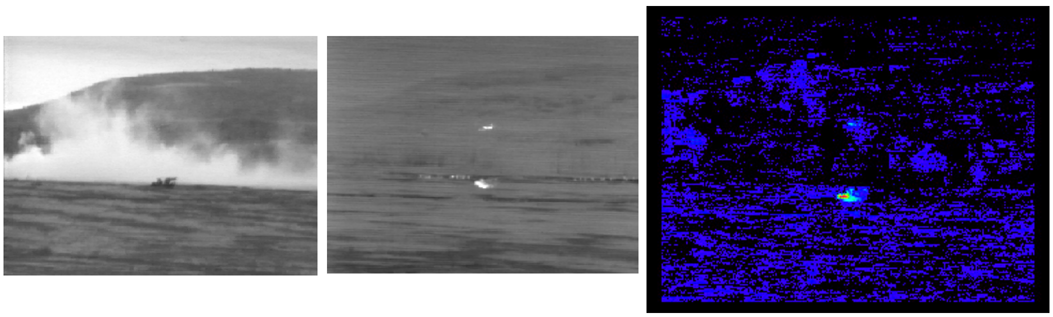
FLIR **Visible** **Fused Color**

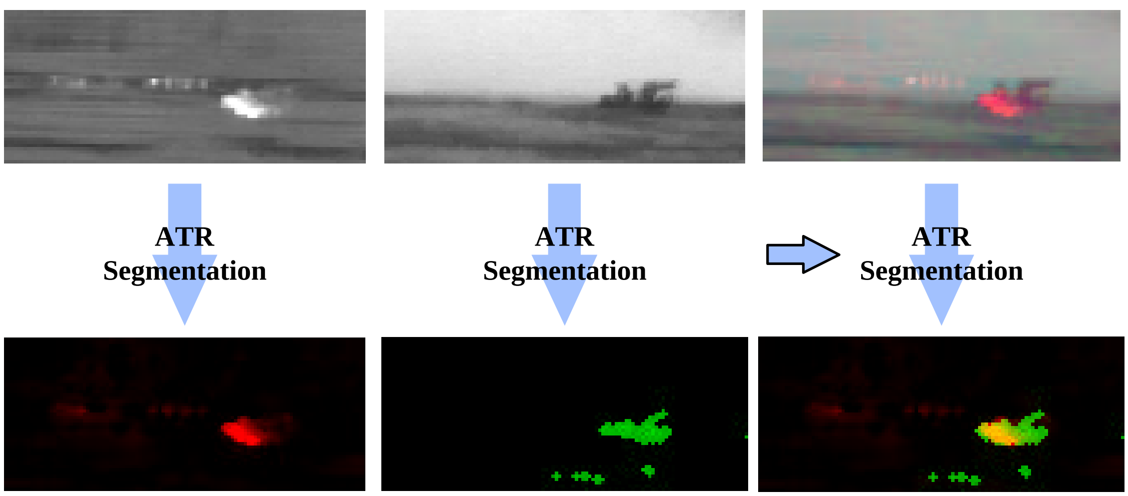
Figure 9. Color components are selected to enhance critical features.



Visible **Infrared** **Covariance Detection**

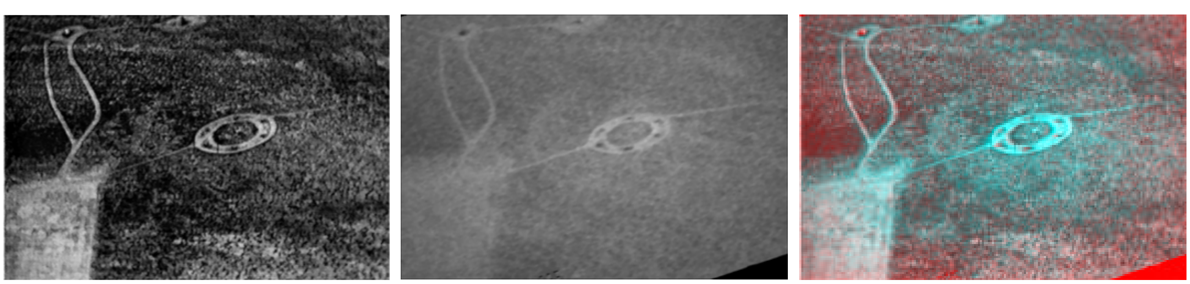
Figure 10. Multispectral target detection.

IR **Visible** **Fused IR-Visible**



IR Only **Visible Only** **IR + Visible**

Figure 11. Multispectral segmentation



(a) (b) (c)

Figure 13. NightHawk video showing color fusion enhancement of target.