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Beyond Third Generation: A sensor fusion targeting FLIR pod for the F/A-18

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ABSTRACT

The Navy and Marine Corps F/A-18 pilots state that the targeting FLIR system does not provide enough target definition and clarity. As a result, high altitude tactics missions are the most difficult due to the limited amount of time available to identify the target. If the targeting FLIR system had a better stand-off range and an improved target contrast then the pilots' task would be easier. Unfortunately, the replacement cost of the existing FLIR equipment is prohibitive. The purpose of this study is to modify the existing F/A-18 targeting FLIR system with a dual-band color sensor to improve target contrast and stand-off ranges. Methods: A non-real-time color sensor fusion system was flown on a NASA F/A-18 in a NITE Hawk targeting FLIR pod. Flight videotape was recorded from a third generation image intensified CCD and a first generation long-wave infrared sensor. A standard visual search task was used to assess whether pilots' situational awareness was improved by combining the two sensor videotape sequences into a single fused color or grayscale representation. Results: Fleet aviators showed that color fusion improved target detection, but hindered situational awareness. Aviators reported the lack of color constancy caused the scene to be unaesthetically pleasing; however, target detection was enhanced. Conclusion: A color fusion scene may benefit targeting applications but hinder situational awareness.

Keywords: sensor fusion, electro-optics, targeting, human performance, FLIR, image enhancement

1. BACKGROUND

1.1 Objective

Since Desert Storm there has been a strong emphasis in Naval Aviation to emphasize precision weaponry on precise targets[1]. Aviators need a targeting FLIR system that will improve target discrimination in high clutter environments, provide all-weather day/night capability, improve aircraft survivability and enhance situational awareness. The current targeting FLIR systems have limited stand-off range capabilities due to poor magnification. The next generation of targeting FLIR pods, such as Lockheed Martin's Sniper and Hughes's Terminator have addressed these shortfalls by improving sensor characteristics and increasing magnification by reducing sensor field-of-view. This study proposes an alternative method that combines two different spectral bands within an existing targeting FLIR pod to enhance targeting stand-off range. It is hypothesized that this new targeting system will present information in such a way that will allow the warfighter to visualize the information quickly during operations, and provide longer stand-off ranges while enabling correct, flexible decision making, and control of weapons.

1.2 General

A random survey was sent to several fixed-wing and rotary aircraft squadrons to solicit pilots' opinions on current NVG and FLIR shortfalls in the fleet. Pilots overwhelmingly responded that the targeting FLIR has a poor stand-off range. Several F/A-18 pilots mentioned that the targeting FLIR system does not provide enough target definition and clarity. If the targeting FLIR system had better magnification, the pilots' task would be easier. Efforts are currently underway to develop improved resolution and magnification capabilities for the F/A-18 targeting FLIR system. However, the solution we propose is economical and would modify the existing FLIR system to significantly improve stand-off ranges and to improve situational awareness. The technology developed as part of this effort can be directly applied to enhance the performance of future advanced targeting FLIR systems.

During a bombing mission in which a target's exact location is unknown, the pilot must rely upon the inertial navigation, radar, and FLIR systems to find the target. The pilot may have an approximate idea where the target is located, but must rely on the aircraft sensors to find the target. Initially, the pilot relies on the inertial navigation system to point the aircraft in the general direction of the target. Once the aircraft is within radar range of the target (but not within infrared range), the pilot expands the radar image in an attempt to isolate the target. At this point, the pilot may not be able to identify the target due to poor target relief. As the aircraft nears the target location, the pilot switches from the radar sensor to the targeting FLIR system. The pilot may alternate between wide field-of-view and narrow field-of-view while searching for the target. The pilot may use the narrow field-of-view to magnify the scene, but the probability of locating the target of course decreases due to the reduced field-of-view. This method could be compared to searching for a target through a soda straw. At this point, the pilot's stress level increases due to the close proximity of the target. The pilot may have to switch back to wide field-of-view until the target can be detected. In some cases, the pilot does not verify the target until the very last moment of the target-of-opportunity window. Thus the pilot relies on experience and quick responses to accurately drop the bomb on the target and egress safely.

In order to improve mission effectiveness, the targeting system must allow the pilot to detect the target at greater distances. The next generation of targeting FLIR pods will reduce the sensor's field-of-view, which in turn, increases pilot's workload in searching for a target. If a targeting system could be designed with a wide field-of-view and had the capability of displaying the target at greater distances, this would be a significant advantage for the pilot. Once the pilot detected the target, the FLIR system could then be magnified for target verification.

Objects viewed by low-light and infrared sensors will generally have the same spatial characteristics, but will appear to have dramatically different contrast levels. Displaying these variations as color differences –sensor fusion – should improve target-background contrast and increase the dynamic range of the scene (information theory tells us sensor fusion will be superior; the real question is whether the improvement is significant). When searching for the target, color helps by giving better context to the scene (e.g., the horizon is much easier to segment due to color contrast), which allows for more efficient target search. In addition, a color target should attract the attention of the pilot, thereby reducing the pilot's workload. This is analogous to a SEAL laser designating a target so that the pilot can easily identify target location. Therefore, color fusion, as compared to monochrome devices, will allow users to quickly orient themselves to a scene and detect targets with greater accuracy. This improvement should address the targeting FLIR problems of poor target definition and clarity. In summary, the proposed sensor fusion system can be economically integrated into existing assets to increase pilot's ability in finding hidden targets, avoid target loss during periods of thermal cross-over, and improve safety and survivability because of longer stand-off ranges.

The Night Vision Electronics System Directorate (NVESD) demonstrated a sensor fusion device that combines an infrared and visible sensor on an UH-1N[2]. They showed that sensor fusion improves a pilot's situational awareness for navigation and pilotage tasks. Pilots preferred a monochrome fused scene for basic navigational flight maneuvers, such as Nap-of-the-Earth, precision hover, and right lateral hover. Furthermore, pilots reported that the fused monochrome scene performed better across the different thermal illumination conditions. The success of sensor fusion has led Texas Instruments to develop a real-time monochromatic sensor fusion processor for the RAH-66 Comanche. They anticipate that sensor fusion will improve pilots' navigation and pilotage abilities compared to either the infrared or the image intensified displays.

This study is similar to the NVESD Advanced Helicopter Pilotage (AHP) program, except that this study demonstrated a sensor fusion system on an F/A-18. The purpose of this study is to demonstrate that a sensor fusion device could be integrated within a modified F/A-18 NITE Hawk targeting FLIR pod at minimal cost. This study was divided into several phases. The first phase demonstrated a first generation scanning infrared sensor and a low-light visible camera on an F/A-18 targeting FLIR pod. The second phase substituted the low-light camera with a color CCD camera. A human performance test was used to measure the effectiveness of color fusion compared to single band imagery during a situational awareness task. It is hypothesized that a fused color scene will provide the pilot better texture information that will aid situational awareness compared to either the infrared or low-light scenes. In regard to target detection, it was hypothesized that a fused color target will automatically "pop out" from the background, thereby allowing the pilot to easily discriminate the target from the background.

2. SENSOR FUSION INTEGRATION

2.1 Test Vehicle

The NITE Hawk targeting pod, produced by Lockheed Martin for the US Navy and several foreign customers was selected as the primary flight vehicle. This selection was based on several considerations. Integration of complimentary visible sensors had been demonstrated and tested extensively as part of NASA Dryden's Advanced Video Data Acquisition System (AVDAS). The required system capabilities could be provided without any structural modifications to the pod (figure 1), which would require a detailed flight safety review. The required sensor integration could be accomplished without any modification to the pod or aircraft mission computer software. The aircraft data collection system was configured to support a NITE Hawk pod with multiple sensors.

2.2 Aircraft Selection

An F/A-18B aircraft, currently supporting research activities at NASA Dryden was selected to support the flight test activities. The aircraft was modified as part of the earlier AVDAS program. These modifications included installation of a triple recording Hi-8 tapedeck, which provided simultaneous recording of infrared, visible and position data. A color flat panel LCD display was incorporated in the aft cockpit to support simultaneous viewing of both sensors. A hand held control unit was incorporated in the aft cockpit to provide full sensor control without requiring the operator to have any interaction with the aircraft controls. The data system also incorporated Global Positioning and captured sight line angles to support post flight analysis. The system provided real time transmission of video from a selected sensor to a ground station to support real time monitoring if required.

Figure 1. NITE Hawk Advanced Video Data Acquisition System (AVDAS) was used as the system test bed. The system was installed on a NASA F/A-18B equipped with time-code recording equipment and a real-time video transmitter.

2.3 Sensor Integration

Both day and night flight data were collected using two different sensor configurations. All flights used the same targeting FLIR sensor combined with a three color CCD for day flights and an image-intensified CCD for night flights. Both sensors were installed in the stabilized optics assembly in the location normally occupied by the laser beam expander (figure 2). This configuration provided sight-line stabilization for both the infrared and visible sensors. All existing manual and auto-track functions were maintained.

The Texas Instruments, first generation, long-wave infrared sensor had a small cooled array that was scanned and re-imaged to produce an RS-343, 875 line output. The 875 line output was then converted to an RS-170 format to match the second sensor format.

The day flight configuration used a Pulnix TMC-7I color CCD. A Cosmicar motorized zoom lens with a focal length range of 16mm to 98mm was used to match the infrared wide and narrow fields-of-view. The camera output was RS-170, 525 line video output with NTSC and Y/C formats. The night flight configuration used a Pulnix 007 camera with an image intensifier fiber optically coupled to a 2/3” monochrome CCD. Both the Pulnix camera and infrared sensor fields-of-view were matched at 12 degrees. Appropriate measures were maintained to ensure that the production beam expander and conformal packaging were within the envelope requirements of the stabilized optics assembly. Both cameras had a DC to DC converter used to filter and convert 28V DC aircraft power to 12V, and were electrically isolated from the pod and aircraft ground to prevent any video noise from the 400 HZ aircraft power.

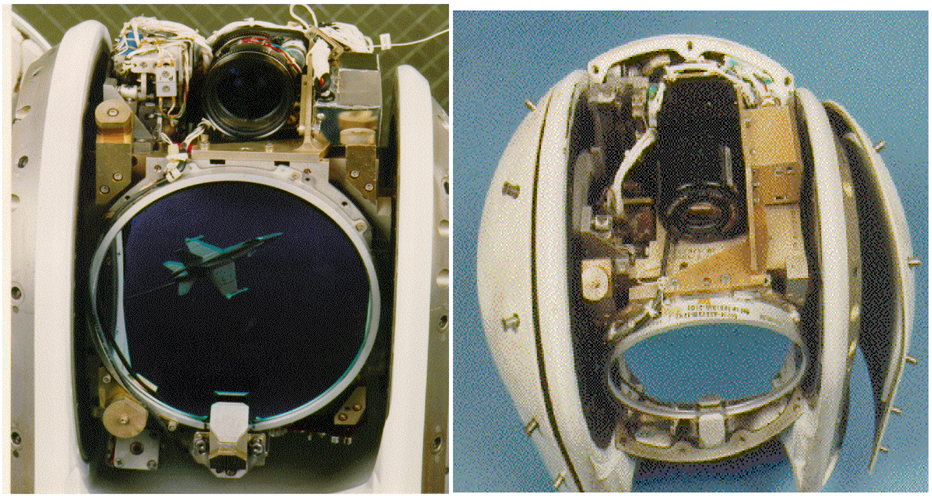


Figure 2. The AVDAS pod was modified with an intensified video camera package that was developed in cooperation with Lockheed Martin Corporation. The modified pod system enabled simultaneous intensified television and infrared data collection on the F/A-18B.

2.4 Image Registration and Derotation

The targeting pod presently provides mechanical derotation for the FLIR line of sight. For the first two data collection phases the visible sensor was aligned on the vertical and horizontal axes to within one TV line. However, derotation of the visible sensor was not provided. Consequently the FLIR and visible sensor rotation angles were only matched for limited sight line angles. Angles beyond the limit range required post processing of the images to correct rotational alignment.

3. HUMAN PERFORMANCE EVALUATION

3.1 General

In a standard visual search experiment, a target is presented against a background of distracters. The subject responds to whether the target is present or absent. If a target "pops out" from the distracters, then preattentive processing[3-5] is presumed. An objective of sensor fusion is to have the targets "pop out" at the pilot. The pilot can unconsciously identify the targets and, thus, devote more attention to other flying tasks. Several visual search experiments[6-11] have demonstrated the benefits of sensor fusion; however, the advantages are not clearly defined. To assess the benefits of sensor fusion for situational awareness, subjects' reaction time and accuracy to navigational objects embedded within several videotaped nighttime scenes were measured. It was hypothesized that a fused color scene would provide the pilot additional navigational cues compared to either the infrared or low-light visible scene.

3.2 Subjects

Twenty male military officers ranging in age from 27 to 40 with a mean age of 31.3 (σ=3.63) volunteered for this experiment. All subjects signed an informed consent and were briefed on the ethical conduct for subject participation specified in the Protection of Human Subjects, SECNAV Instruction 3900.39B. All subjects had normal or corrected to normal visual acuity (20/20) and were naive as to the purpose of the experiment. Color vision was verified with pseudo-isochromatic plates. Nine of the subjects were aeronautically adapted (received flight training a part of their job specialty) and six of this group had I^2 sensor (NVG) experience while five were experienced with IR. All subjects had used either the night vision goggle or an infrared device, while seven subjects had used both devices. The average night vision goggle experience was 101 hours and forward looking infrared experience was 17 hours.

3.3 NVESD Stimuli

Due to the image registration challenges described in section 2.4, the NITE Hawk night flight data did not produce sufficient range of fused images for the visual search task. As a result, this experiment used eight nighttime video sequences collected from an early prototype fusion sensor system developed by Texas Instruments and the Night Vision Electronic Sensor Directorate[2]. These images were collected from a low-light visible image intensifier and a first generation forward looking infrared sensor mounted on an UH-1N helicopter. The spectral response of the low-light camera and infrared sensor was .6-.9μm and 8-12μm, respectively. Images were collected during starlight (10^{-3} lux) to full moon (10^{-1} lux) conditions. The scene content varied from ocean surfaces to different types of terrain, providing a diverse selection of reflectivity and emmisitity ranges between the two sensors. Due to the problems of parallax, the visible and infrared images were not spatially registered. Objects in the near field-of-view were spatially different then those in the far field-of-view. As a result, some targets had a shadow or "halo effect" depending upon the location of the object within the fused scene. This perceptual mismatch was easily detectable and caused numerous complaints by the observers. Unfortunately, this spatial mismatch was not homogeneous across the twenty-five scenes. On average, the displacement was approximately 15 pixels in the x and y direction.

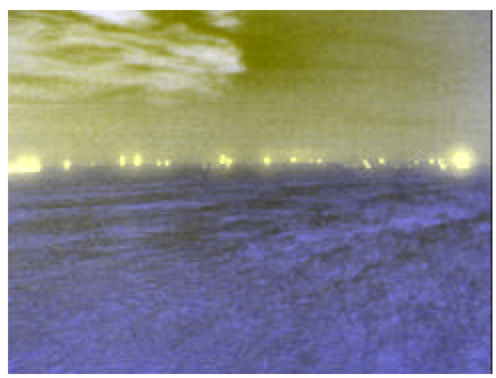
Each of the eight videotaped sequences was presented in five different image formats. The first two formats were low light visible and infrared, while the remaining three formats spatially registered each low-light visible and infrared video frame into a single fused image. The third type of image (local fused color-*lfc*) was obtained by fusing both low-light and infrared imagery using biological models of opponent-color processing[12] that is based on the Boundary Contour System/Feature Contour System (BCS/FCS) model[13]. This local fused color algorithm has been described in full and is briefly described here. The first step of the fusion procedure is to noise clean the visible imagery by a median filtering. Center-surround shunting neural networks are then used to enhance and normalize the ON and OFF channels of the IR imagery. The second step is a combination of the infrared and visible bands to form a single-opponent color contrast image, and then these opponent color images are then enhanced using center-surround nets to form two double-opponent color-contrast images. The final stage then maps the two double-opponent images and the enhanced visible image to red, green, and blue channels of a color display.

The fourth image type (fused monochrome-*fm*) was provided by Night Vision Electronic Sensor Directorate. Texas Instruments and the Night Vision Electronic Sensor Directorate developed an Advanced Helicopter Pilotage platform to test the benefits of sensor fusion for night time pilotage. Texas Instruments proprietary real-time monochrome fusion algorithm is based on a locally adaptive contrast enhancement[2,6,7].

The fifth image type (global fused color-*gfc*) was obtained by fusing low-light and infrared imagery into a two-dimensional color space. The distributions of intensity values from both bands have a spheroid distribution extending along the principal component distribution. The elongated axis, principal component direction, represents brightness, and the orthogonal axis is the chromaticity plane. Typically for infrared and visible bands, the length of the spheroid in the orthogonal direction is small. Thus, the orthogonal direction must be transformed into an expanded polar coordinate to generate a color circle with hue and saturation. For these images there will be two colors, red and cyan, along the color circle. Hue varies continuously around the circle, for example starting at 0 degrees, from pure red clockwise, through red-cyan to pure cyan at 180 degrees, then progressing back the other direction through cyan-red and back to pure red. Saturation was defined as the positive value in the radial direction. For either red or cyan, the white content could vary from zero saturation in the center and high saturation in the outer circle.

In summary, the five different image types were low-light visible (ll), infrared (ir), local fused color (lfc), fused monochrome (fm), and global fused color (gfc). The lfc was spatially registered and mapped to a specific color table based on scene characteristics for each image[7]. It was hypothesized that these images should be maximally optimized for target discrimination. However, this is an unrealistic demonstration since the algorithm has not matured enough to determine the appropriate color map for specific scenery nor was hardware accurate enough to reduce pixel displacement. Alternatively, gfc had a global spatial registration correction factor when fusing ir and ll. As a result, several of the gfc images appeared to have a halo-effect around specific objects. In addition, gfc chose red and cyan for all image types regardless of scene content, which lead to unnatural scene representations, i.e. red water. Alternatively, the lfc imagery did not have a consistent color scheme. Basic colors used in the lfc color fusion process were selected on a scene by scene basis to match the anticipated visible band colors. For example, a blue color table for ocean scenes and a green color table for mountainous scenes. As a result, this manual manipulation into the color fusion process produced a more aesthetically pleasing scene. Figure 3 is a still image from the videotaped sequences of an infrared and a global fused color scene.

infrared scene



global fused color scene

Figure 3. An infrared and global fused color scene photographed from a helicopter flying over Maryland's Chesapeake Bay. The global fused scene amplifies both the horizon and cultural lighting while the infrared scene provides adequate water and cloud discrimination.

3.4 Procedure

Subjects viewed the S-VHS videotaped sequences on a Sony PVM-8044Q color video monitor (16.0cm x 12.5cm viewable area) at a distance of one meter. All subjects received the eight videotape sequences with each subject viewing only one type of sensor input. On average, each videotape sequence was approximately 18 seconds in length. A trial consisted of the subject viewing a blank screen followed by a five second delay then the video sequence was displayed. The subject manually responded to the target with reaction time and accuracy recorded by a host personal computer. The host computer and videotaped sequences were synchronized to ensure accurate frame count. The subject did not receive any feedback for an incorrect response. The next trial began 30 seconds after the completion of proceeding trial. The experimental session lasted approximately ten minutes.

4.0 RESULTS

There was a significant main effect for sensor, $F(4, 90) = 8.03$, $p < .001$. Figure 4 illustrates the mean reaction time for each sensor type. A Tukey's pairwise comparison test showed that subjects responded significantly slower to an image intensified scene compared to the other sensor formats. Subjects responded faster to the infrared target compared to the global fused color target, while the local fused color target showed no significant difference. These results generally agree with Steele and Perconti's sensor fusion evaluation study[7] that evaluated pilot's performance using the same videotaped sequences.

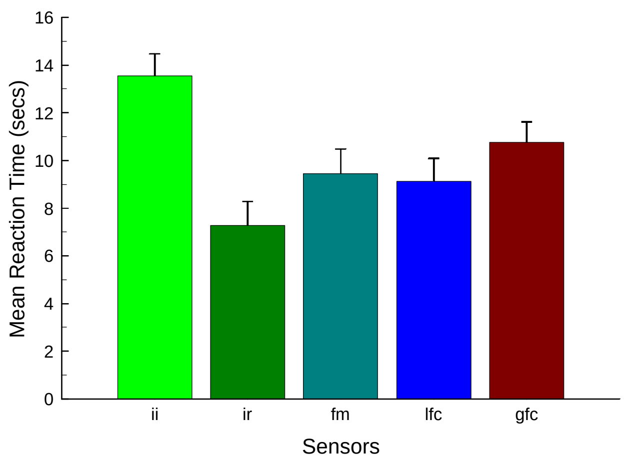


Figure 4. A significant main effect for sensor format with subjects responding slowest to an image intensified target. Subjects responded to the infrared target significantly faster than the global fused color target, but failed to show a significant difference between the local fused color target. Error bars equal one standard error of the mean.

There was a significant main effect for scene, $F(5,90) = 5.02$, $p < 0.001$ and a sensor by scene interaction $F(20,90) = 2.01$, $p < 0.013$. Due to the target's spatial and spectral characteristics there was a significant impact on the performance of the fusion algorithm. Overall, the *lfc* algorithm compensated for these inconsistencies by manipulating the spatial registration and look-up-table for each videotape. As a result, subjects' reaction times for *lfc* and *ir* were not significantly different from identifying the target. Figure 5 graphically depicts the sensor by scene interaction.

In summary, color fusion did not improve pilot's situational awareness. Pilots overwhelmingly reported that the color fused scene appeared unnatural due to the choice of colors and the problems of scene registration. The fused sequences were not able to spatially match every frame thus objects appeared distorted. However, pilots did report that color fused objects were easier to discriminate than infrared or image-intensified objects. Therefore, color fusion may be more appropriate for targeting applications compared to navigation and pilotage applications.

5.0 MATHCED FILTER ANALYSIS

A two-dimensional matched filter was used to predict aviators' target detection ability for single and dual-band sensor combinations[14]. The matched filter was a spatial filter optimized for a target's signal-to-noise power, which was shifted to several locations within an image. At each location, the filter's coefficients are multiplied by the pixels that are overlaid and summed, providing a measure of the correlation between the overlaid scene and the target. By evaluating several background areas of an image with, and then without, a target present, the filter's signal-plus-noise and noise distributions may be estimated. These empirically derived distributions can then be used to estimate the matched filter's ability to "discriminate" the target from the background noise. This ability to "discriminate" is expressed as sensitivity (*d'*), which is a direct comparison to a pilot's sensitivity to detecting a target. Figure 6 illustrates that the infrared and fused color sensors had the highest sensitivity for detecting a cylindrical tank against a forest scene compared to fused monochrome and image-intensified scene. There was a significant main effect for sensor ($F(3,210) = 17.42$, $p<.00001$), with fused color (*d'*=4.26) having the highest sensitivity for detecting the target, followed by infrared (*d'*=4.20), fused monochrome (*d'*=4.16), and image-intensified CCD (*d'*=3.73). The sensor by scene interaction was significant ($F(6,210) = 23.76$, $p<.00001$), indicating that the sensor was influenced by the target-background contrast.

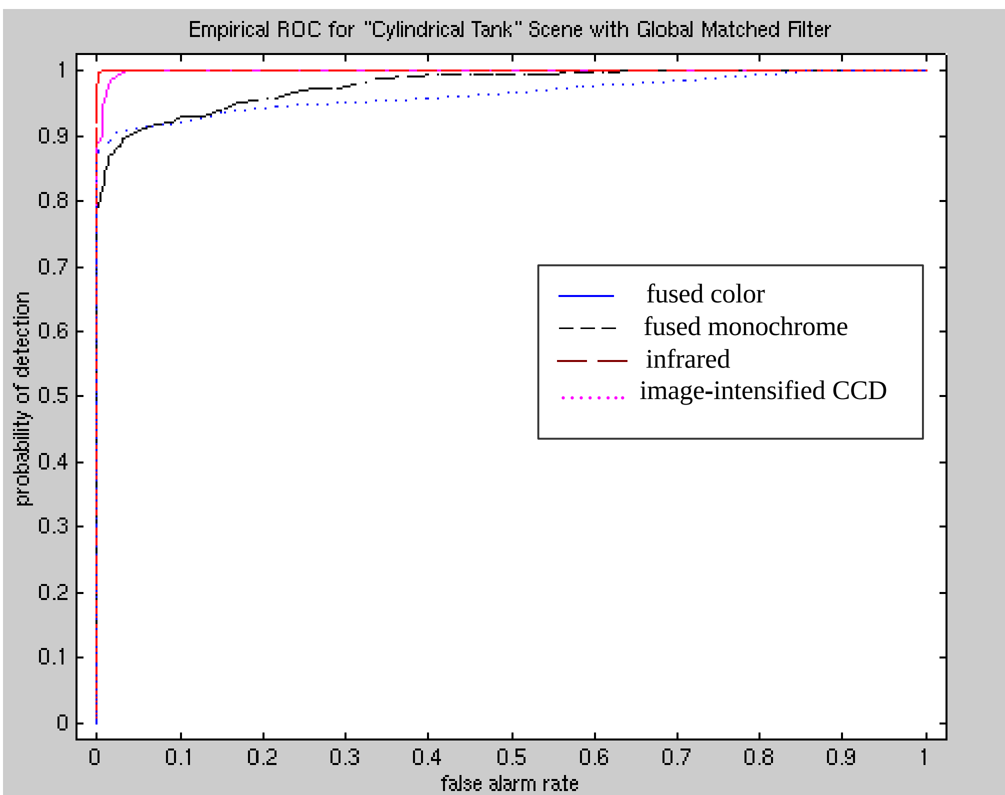


Figure 6. Empirically derived receiver operating characteristic (ROC) plot illustrating the matched filter's sensitivities to a target within a NVESD nighttime scene.

The matched filter analysis demonstrated that color fusion was significantly better at discriminating a target from the background compared to the other sensor formats. Accordingly, the pilot will be able to accurately detect a color target in the wide field-of-view significantly faster compared to the proposed next generation narrow field-of-view targeting FLIR pods. The pilot will be able to scan a large area quickly, then narrow the FLIR field-of-view on the designated target. Thus, color fusion does not improve magnification per se, rather it improves target definition and clarity.

6.0 DISCUSSION

A sensor fusion system was successfully demonstrated on a modified NITE Hawk targeting FLIR pod. Several flights used different combinations of electro-optical and visible sensors to determine if a color-fused scene increased pilots' targeting stand-off range compared to a single sensor scene. Unfortunately, the images could not be spatially registered for human performance evaluation, however the next phase of flights will correct this problem. Currently, we're replacing the existing sensors with a Raytheon Amber, Gallileo, InSb large format mid-wave sensor and a PVP Advanced EO Systems low-light monochrome CCD camera sensor. Both fields of-view will be matched at 1.5^0 with FLIR derotation disabled. This alignment configuration will enable both sensors fields-of-view to be matched; thus avoiding the problems of spatial registration. A series of flights will be conducted to determine if color fusion can improve the pilot's ability to discriminate a target at greater distances compared to the existing infrared targeting sensor.

Human performance results on the situational awareness task did not show color fusion to be superior, however this may have been due to several threats in experimental methodology. The sensor fusion algorithms were not able to adequately correct the registration problems of the NVESD images, thus causing many scenes to be spatially distorted. Furthermore, the videotaped sequences had a limited amount of navigational cues for this experimental procedure. Future experiments should use a variety of navigational and pilotage cues across different environmental and terrain conditions. Lastly, advances in sensor technology will provide better signal-to-noise ratios for the sensor fusion algorithms, which should improve image appearance. Moreover, researchers should consider combining two infrared bands rather than the visible and long-wave infrared combination. Rarely, does the visible band add information to the fusion algorithm. As a result, the visible band tends to degrade fusion performance.

Subject exit interviews overwhelmingly supported sensor fusion; however they complained about the color selection of the scenes. Subjects reported that color fusion targets had better target contrast, but were not aesthetically pleasing. Perhaps, color fusion should not be used for situational awareness rather it should be used for targeting. In a targeting task, the operator discriminates the target from the background noise. The operator is not concerned about the object's overall appearance; rather can the target be quickly and accurately detected. The matched filter analysis demonstrated that a color target was significantly easier to detect compared to the other sensors. Accordingly, color fusion should be intended for targeting applications, not situational applications. This is in agreement with Steele and Perconti's findings[7].

7.0 ACKNOWLEDGMENTS

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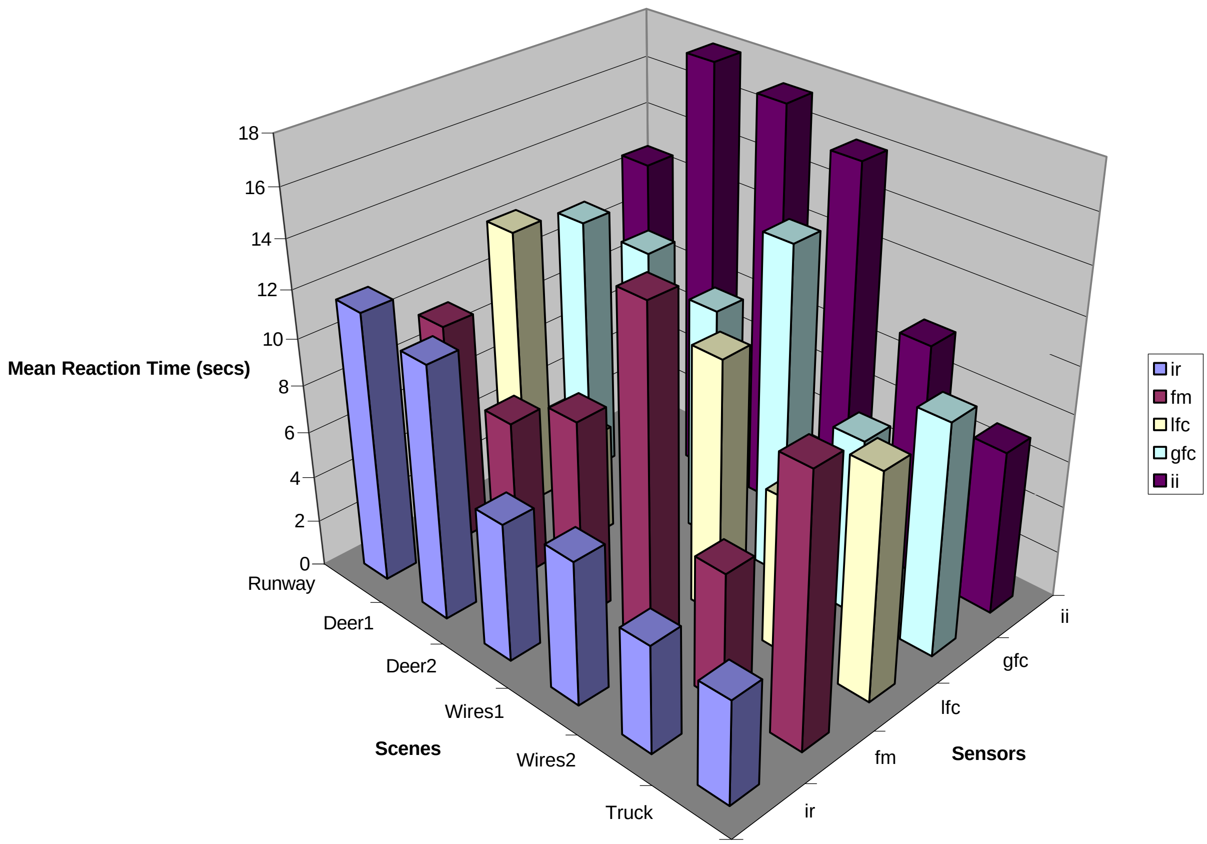

Figure 5. A significant sensor by scene interaction with subjects responding generally faster to an infrared target compared to the other target formats.