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Evaluation of a color fused dual-band NVG

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Abstract - *We designed and evaluated a dual-band Night Vision Goggles sensor system. The sensor system consists of two optically aligned NVGs fitted with filters splitting the sensitive range into a visual and a near-infrared band. The Color-the-night technique (Hogervorst & Toet, FUSION2008) was used to fuse the images of the two sensors, using a color scheme optimized for the detection of camouflaged targets. The added value of this system was established in an experiment in which observers detected targets (green and blue tubes). Performance was measured for daytime imagery and nighttime imagery: each of the two individual bands, standard NVG, and the color fused sensor system. We found that some of the targets were detected in the individual bands, but most targets were detected in the dual-band system. The fact that performance in the dual-band condition is comparable to the sum of the two individual bands indicates that the fusion method is (close to) optimal. An experiment in which subjective reports were gathered shows that the colored dual-band images are easier to grasp and give a better sense of depth. Our evaluation shows the added value of dual-band over single band NVG for the detection of targets, situational awareness, and perceived depth.*

Keywords: image fusion, sensor fusion, human performance, false color, natural color, target detection, intensified imagery, image intensifier.

1 Introduction

Night vision cameras are widely used for military and law enforcement applications related to surveillance, reconnaissance, intelligence gathering, and security. Most commonly used are single band cameras (e.g. Night Vision Goggles or a thermal camera) that create images with a single (one-dimensional) output per pixel. Their ability to discriminate different materials is limited. This can be improved by combining systems that are sensitive to different parts of the spectrum, such as multiband or hyperspectral imagers or by fusing different sensors. The amount of different outputs can increase dramatically by combining sensors (e.g. when the number of different outputs for each sensor is N, this can increase by up to N^2 for two sensors). This also leads to a dramatic increase in the number of materials that can be discriminated. The combination of multiple bands allows for presentation of the output in color in a meaningful way. It is therefore not surprising that the increased availability of fused and multiband infrared and visual nightvision systems has led to a growing interest in the color display of night vision imagery [3-5, 9, 11]. In principle, color imagery has several benefits over monochrome imagery for surveillance, reconnaissance, and security applications. Color may improve feature contrast, allowing better scene recognition and object detection [10]. Color can be used to discriminate between different materials (e.g. in X-Ray baggage screening the sensor output at two energies for material classification). However, the coloring method should be chosen with care, since unnatural coloring may disrupt the recognition process, resulting in observer performance that is even worse compared to with single band imagery [6]. Recently, we presented a method for applying natural daytime colors to multiband nightvision imagery [1, 2]. Our method is simple and fast, can easily be deployed in realtime, and can display night-time imagery in natural daytime colors, that are stable under variations in scene content. Different color schemes can be used, depending on the task at hand. For our application we devised a color scheme that is particularly suited for the detection of targets. We created a prototype dual-band Night Vision Goggles (NVG) system consisting of two optically aligned NVGs fitted with filters. One filter transmits the visual part (short wavelength region), the other the near infrared part (long wavelength region) of the NVG-sensitive range. The images of the two sensors are combined and color is added using the Color-the-night method. Here, we present the results of a human observer experiment to establish the added value of such a system (over standard NVG or each of the individual bands) for the detection of targets. The impact on situational awareness, perceived depth and ease of interpretation was addressed in a separate experiment in which the subjective reports were collected using a questionnaire.

2 Color Fusion Method

The color schemes that are suited for most applications produce colors that i) closely match the (natural) daytime colors and ii) lead to good discrimination of different materials. Previously we reported on ways to create fusion with natural colors [1, 2]. The two requirements mentioned are not always in line and may be contrasting. A typical example of this (as we have found) is presented by the task of finding a camouflaged soldier in a field by using a thermal sensor and NVG. When the colors are chosen such that the match with the daytime colors is optimized, this will result in a soldier that is camouflaged, which is obviously undesirable. In such cases more emphasis should be placed on the second requirement, i.e. using a color scheme that leads to better discrimination but also less natural colors. Also for our application of optimal detection of targets we found that the use of natural colors does not result in optimal detection performance. We therefore designed a color scheme that is targeted at good detection of (camouflaged) targets that do not contain chlorophyll, and leads to reasonably natural colors.

An optically aligned dual-band NVG sensor was simulated by using a NVG and recording images (with the use of a standard digital daytime camera) with various filters in front of the NVG. A "visual band" band was created by using a filter transmitting wavelengths shorter than 700 nm (Figure 1a). A "near infrared" (NIR) band was created by using a filter transmitting wavelengths longer than 700 nm (Figure 1b). For comparison we also created a standard NVG image of each scene without the use of any filters (Figure 1c). The visual band was fed into the Red channel of an RGB-image and the NIR-band was fed into the Green channel, to create a red-green representation of the dual-band sensor image (Figure 1d). Next, for each combination of sensor outputs (represented by a shade of red, green, yellow; see inset of Figure 1d) a color was chosen to display this sensor output. This process can be implemented by transforming the red-green image (Figure 1d) into an indexed image in which each pixel value refers to the entry of a color lookup table. When a color lookup table is used with different colors, the colors in the indexed image are automatically transformed into other colors, in a way that all pixels with the same index will result in the same color. Details of this can be found in Hogervorst & Toet [1, 2]. We tried several color transformations in our search for a color scheme that results in optimal detection of targets as well as natural looking images. The most suitable color transformation for our purposes is similar to the red-green representation with a few changes. The inset of Figure 1e shows the colors attributed to all dual-band outputs (represented by the inset of Figure 1d) of the chosen color scheme. This color scheme emphasizes the distinction between objects containing chlorophyll (the background plants) and objects containing no chlorophyll (e.g. our targets; notable from the sharp transition between green and red at the diagonal). To create a more natural look high responses in both channels are depicted in white (bottom right corner of the inset of Figure 1e). The result of our color fusion method is shown in Figure 1e.

3 Evaluation method

We evaluated our color fusion method using a target detection task. We recorded images with and without targets during daytime (without NVG) and nighttime (with NVG) in the same area containing grass and trees (see Figure 3 and 4). Performance for detecting targets was established for imagery of the dual-band fusion system, each of the individual NVG-bands (visual and NIR), standard NVG and daytime images (taken with a visual camera). The daytime images were matched to the NVG-images in Field of View (visual angle and display area), by using a circular mask and using the same zoom with and without NVG (see Figure 3 and 4).

The conditions for which performance was measured are:

a) *Daytime*: taken with a standard digital daytime camera

b) *NVG*: standard NVG, without filter

c) *NVG-visual*: NVG with filter transmitting short wavelengths

d) *NVG-nir*: NVG with filter transmitting long wavelengths

e) *NVG-dual band*: images resulting from the color fusion method

The targets were green (Figure 3) or blue (Figure 4) foam tubes. The reflectance of the tubes was such the green tubes were often undetectable in the standard NVG and the near infrared band (see Figure 1), but detectable (as a light object) in the visible band (see Figure 1). In contrast, the blue tubes were often undetectable in the visual band while being detectable (as a dark object) in the near infrared band and in standard NVG (see Figure 2).

In each condition 56 images were used without target, 28 with a green target and 28 with a blue target. Eight subjects participated in the experiment. Each subject participated in 5 sessions in which the stimuli of each condition were shown separately. Each subject started the session with the Daytime condition to get acquainted with the procedure. The order of the NVG-conditions was randomized across subjects to compensate for possible training effects. The images were shown on a PC monitor with a resolution of 1600x1200 pixels. Figure 3 (and 4) gives a realistic view of the display content.

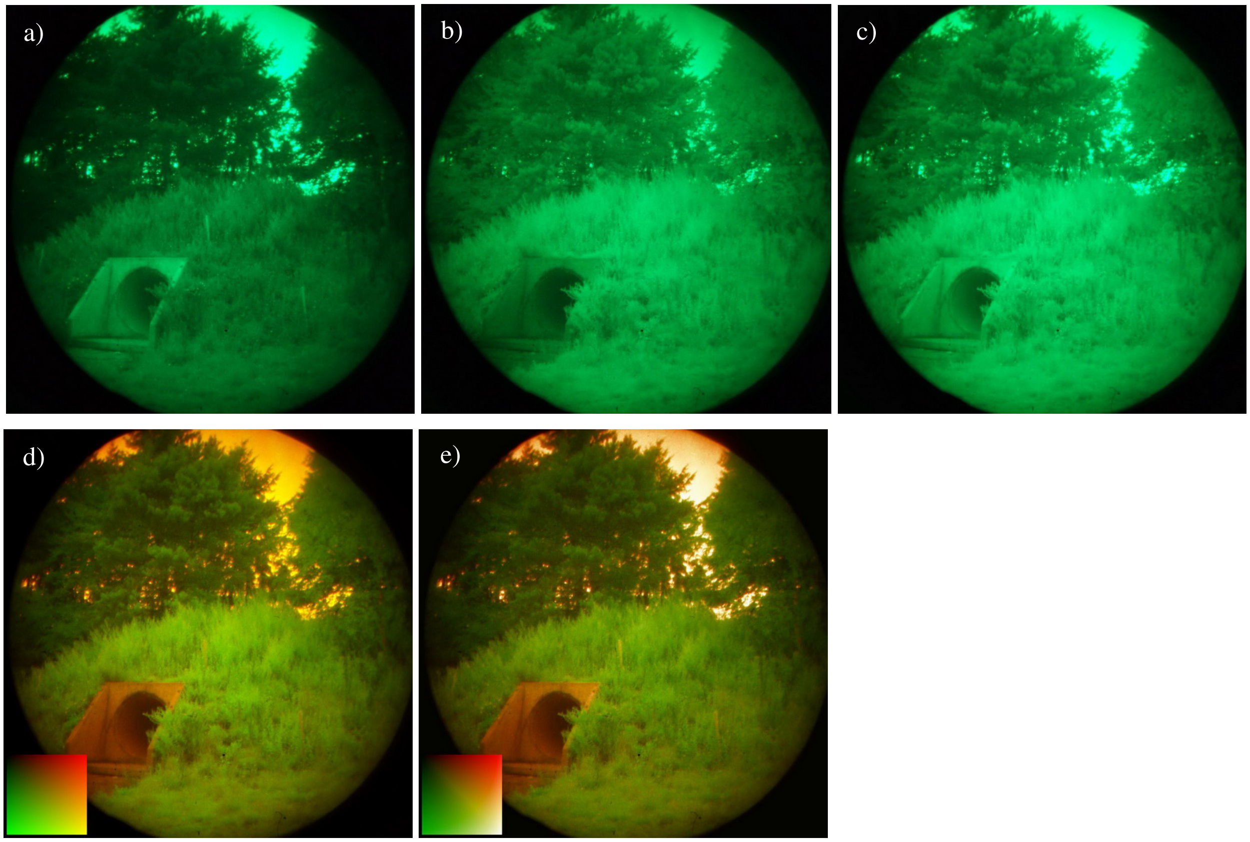

Figure 1. Example showing our color fusion method applied to a dual-band NVG sensor consisting of a NVG fitted with a filter transmitting wavelengths lower than 700 nm (Figure 1a), and an NVG sensor with filter transmitting wavelengths higher than 700 nm (Figure 1b). Figure 1d shows a representation of the dual-band image with the short wavelength band in Red and the long wavelength band in Green. The inset in Figure 1d shows all possible dual-band outputs as shades of red (large response in band 1, small in band 2), green (small response in band 1, large in band 2) and yellow (large responses in both bands). Figure 1e shows the result of our color scheme. The inset shows how the colors in the inset of Figure 1d are transformed. Figure 1c shows the image of a standard (single band) NVG for comparison.

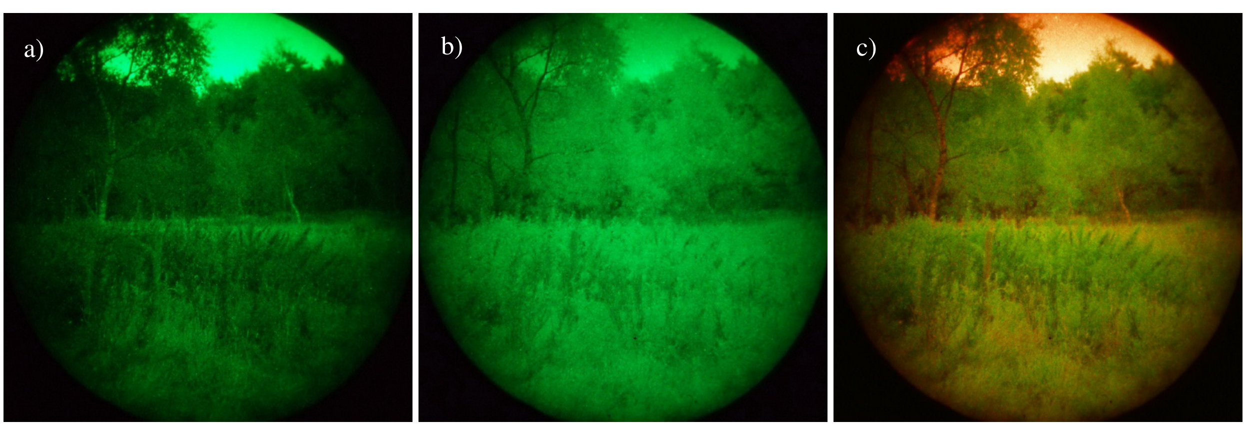

Figure 2. Example showing the visual band (Figure 2a), near-infrared band (Figure 2b) and the color fused dual-band image (Figure 2c) for a scene that includes a blue target. The target is visible in the near-infrared band as a dark tube. The dual-band image shows the target as a reddish tube.

Figure 3. Daytime photograph of a green tube/target.

Figure 4. Daytime photograph of a blue tube/target.

Each experimental session started by explaining the purpose of the experiment and by showing some example stimuli of each condition. Each trial started by showing an image. The subject was asked to decide as quickly as possible whether a target was present or not. As soon as this decision was taken he/she clicked the mouse button. Next, the image disappeared and was replaced by a low resolution equivalent of the image, consisting of 20x15 uniformly colored squares (to prevent subjects from searching for the target after responding). We registered the time between onset of the stimulus and detection (the response time). The subject then indicated the target location or clicked on an area outside the image labeled “no target found”. When the subject did not respond within 8 seconds the trial was ended automatically. The indicated target location was used to check whether the subject had detected the target or had found a false target (responses outside an ellipse with horizontal diameter of 162 and vertical diameter of 386 pixels centered round the (vertically elongated) target were treated as incorrect).

4 Results

We recorded whether the subjects detected the targets when present (Hits and Misses) and whether they judged there to be a target when no target was present (False Alarms and Correct Rejections). We also recorded the response times. No False Alarms were recorded, i.e. the False-Alarm rate was zero. Performance is therefore fully characterized by the Hit-rate, i.e. the fraction of targets that was detected (p_h = #Hits / (#Hits + #Misses)).

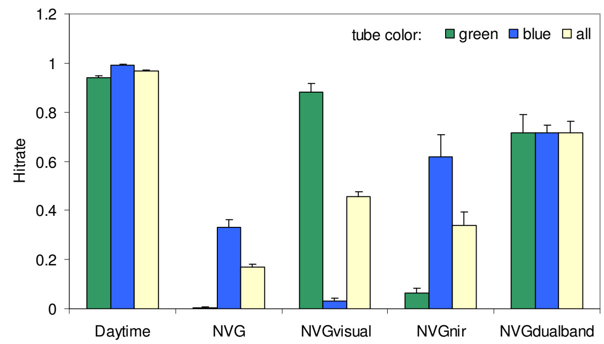

Figure 5. Average hit-rate (fraction of hits) for the various sensor conditions and target colors, including the hit-rate for all target colors (“all”). Shown are averages over all subjects. The error bars are standard errors in the mean derived from the variance between subjects.

Figure 5 shows the fraction of hits (hit-rate) for the various sensor conditions and target colors. Shown are the average hit-rates over subjects. Not surprisingly, performance is highest in the Daytime condition. As expected (see Figures 1 and 2), performance for detecting the green targets is high in the *NVGvisual* condition and low in the *NVG* and *NVGnir* sensor conditions. Performance for detecting the blue targets is somewhat poorer in the single-band conditions. These targets can be detected in the *NVGnir* condition (reasonably well) and in the *NVG* condition (poorly), while they are hardly detected in the *NVGvisual* condition. Detection performance for both targets is high with the dual-band sensor. Optimal fusion results in performance that equals maximum performance in the individual bands. The hit-rate for the green targets is somewhat lower for *NVGdual-band* than for *NVGvisual*. But the hit-rate for the blue targets is somewhat higher for *NVGdual-band* than for *NVGnir*. The average hit-rate of the *NVGdual* band sensor (0.71) is not significantly different from the average of the hit-rate for green in *NVGvisual* and the hit-rate for blue in *NVGnir* (0.75). This means that this fusion scheme is (close to) optimal. The results show that the overall performance of the dual band NVG is much better than with the separate bands or the standard NVG system.

Figure 6 shows the average response times of the trials containing a target (shown are the geometric means over the response times, i.e. the exponent of the average log response times) for all conditions, as well as separate for the hits, misses and correct rejections. Note that the hits in *NVGnir* and *NVG* correspond primarily to the trials containing blue targets; the hits in *NVGvisual* correspond primarily to the trials containing green targets. In the daytime condition the response times are the shortest. Not only do the observers detect the targets quicker than in the other conditions, they also decide quicker whether the scene contains a target. Next, we will compare the NVG conditions only. In the standard NVG condition the response times are the longest. The average response times in the dual band condition are the lowest of all NVG conditions. Not surprising, the response times for misses are longer than for hits. The response times for misses and correct rejections are comparable. Except for the standard NVG condition, the response times for the NVG conditions are similar for hits as well as for misses. Since in the dual band condition detection performance was higher, the average response time is smaller than in the single band conditions. The average response times for missed targets in the conditions do not correlate with the hit-rates (see Figure 7). In contrast, the average response times for hits in the conditions is highly correlated with the hit-rate (r = -0.92, $p < 0.01$, see Figure 7). This indicates that when targets are more easily detected, the hit-rate goes up and the response time goes down.

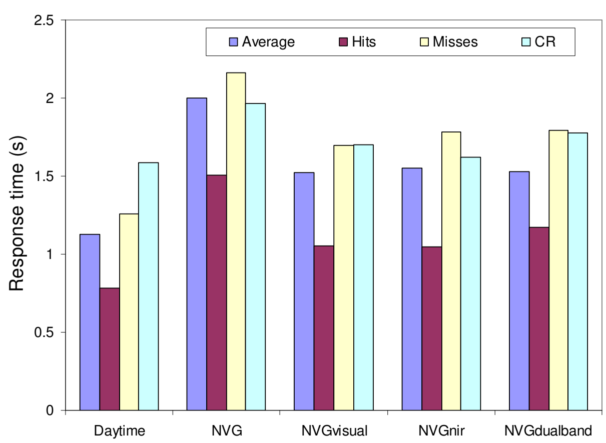

Figure 6. The average response times (displayed are geometric means, i.e. the exponent of the average of log-values) for the various sensor conditions separated as well as the response times for hits, misses and correct rejections (CR).

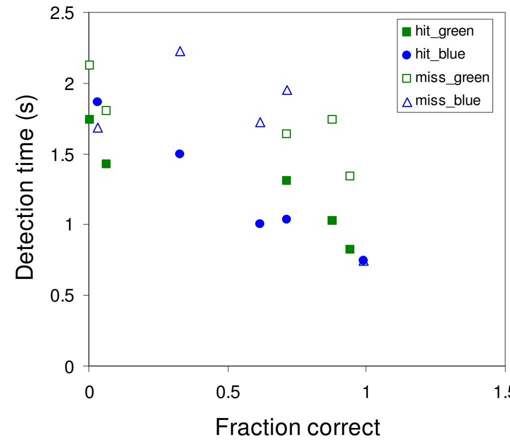

Figure 7. The relationship between the hit-rate for each sensor condition and the (geometric) mean response times for hits and misses for the two target colors.

In a separate experiment we asked 14 observers to judge 40 images on several aspects. The set of 40 images included 8 images for each sensor type that were randomly picked from the total image set (each observer was shown a different random set). In each trial an image was shown and the observer was asked to make a judgment on a 9 point scale. The same nine questions were asked for each image. The questions that were posed (in Dutch) were: 1) How easy is it to discriminate different materials? 2) How easy is to judge the depth? 3) How easy is to find your way through the bushes? 4) How well can you judge the distance to the plants? 5) How well can you judge the slant of surfaces? 6) How well can you distinguish the ground surface from the plants? 7) How well can you judge the density of the vegetation? 8) How well can you recognize the different plants? 9) How well can you detect bumps and humps?

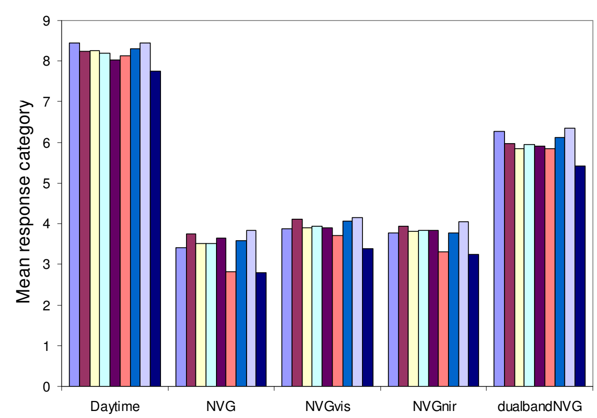

Figure 8. Mean response category (average over all observers) for each question (see text) and sensor type.

Figure 8 shows the mean response category for each question and sensor type. For a given sensor type, the average response category is largely the same for all the questions. The responses on the different questions are highly correlated: the mean response per sensor question and observer shows a correlation with correlation coefficients ranging from 0.89 to 0.98! The response categories for the daytime images are the highest followed by the dual-band NVG sensor. The response categories for the separate bands are much lower, and the response categories for the standard NVG sensor are the lowest. In line with these observations, statistical tests (student-t tests comparing the mean responses per sensor pair wise) show that all sensor types differ significantly from each other except for NVGvis and NVGnir which are not significantly different (at $p<0.05$). These results suggest that in the dual-band condition more depth is perceived, material discrimination and recognition is easier and it is easier to interpret the scene than in the single band conditions.

5 Conclusions

We have designed and evaluated a dual-band NVG system. In previous studies [1, 2] a color fusion method was used that results in an image with colors that match the natural daytime colors as closely as possible. Although such color schemes may be optimal for other tasks such as creating situational awareness, this scheme does not appear to be optimal for target detection. We designed a color scheme that is optimized for detecting (our type of) targets. Although the scheme is not optimized for matching the daytime colors, the color scheme results in colors that are intuitively in line with the daytime perception of the scene. The color scheme emphasizes the distinction between plants (containing chlorophyll) and non-plants (containing no chlorophyll). The sensor system separates the NVG sensitive region in a visual part (wavelengths shorter than 700nm) and an infrared part (wavelengths longer than 700 nm). Since chlorophyll shows a steep rise around 700nm, this dual-band NVG system is particularly suited for discriminating materials containing chlorophyll from materials containing no chlorophyll. Elements containing chlorophyll (e.g. plants) are displayed in green (i.e. in their natural color), while objects without chlorophyll are displayed in red (the perceptually opposite color). To increase the naturalness, elements with high output in both channels are displayed in white.

This prototype dual-band color fused NVG system was evaluated in a human observer experiment in which performance for detecting green and blue tubes was established. The results clearly show that performance for detecting these targets is much better with the dual-band NVG system than with standard NVG. Moreover, the results show that performance of the dual-band system is as good as the maximum performance of both individual bands. While the green targets could well be detected with the visual band of the system alone, the blue targets were largely missed when subjects had to rely on this band alone. In contrast, the blue targets could well be detected with the near-infrared band alone, but the green targets were then largely missed. With the dual-band sensor both targets could be detected. The total number of targets that was detected with the dual band system was the same as the total number of targets that was detected with the visual band plus that was detected with the near-infrared band. This indicates that the way the fusion of the two bands is implemented is (close to) optimal.

The above finding suggests that one can as well present the two bands side by side. For such a display performance can be expected to be comparable to that of the fused image. However, longer response times are expected for this alternative presentation. Also, in some situations one may encounter targets that cannot be detected in either of the individual bands. This may be the case when one part of an object is visible in one band and the other part in the other. Likewise, when several elements are available that are present in the different bands, the spatial relationship between the elements is difficult to judge. Furthermore, other advantages of sensor fusion, such as better identification of object and materials, better situational awareness and better depth perception, also do not show up in this alternative presentation with two displays. The second experiment in which subjective judgments were recorded indicated that the image of the dual-band sensor were easier to interpret and showed more depth. Also, it was judged to be easier to discriminate materials and recognize objects than in the single band NVG sensors.

The simulated prototype sensor system is highly similar to the prototype system called the Gecko we built and presented earlier [7], which consists of two optically aligned NVGs fitted with similar filters as used here. Our experiences with this dual-band NVG sensor system show that our color transformation method can be implemented in real-time. Another prototype we developed is called the Viper [7]. The Viper provides co-aligned images from a digital image intensifier and an uncooled longwave infrared microbolometer. Since the sensitive range of the dual-band NVG system is close to the visual range, the output values are well correlated with the daytime colors. Therefore, this system is suited for presenting the image in natural colors. The image of a thermal sensor is very different from the daytime image, and the output is often poorly correlated with the daytime color. However, a thermal image contains different information that can be highly useful, for instance for detecting and locating (hot) targets. We are currently investigating ways to combine a dual-band NVG system with a thermal imager [8]. We expect that the dual-band NVG can be used to create natural looking backgrounds, while the thermal imager can be used to highlight potential (hot) targets.

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