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True-color night vision cameras — Source link

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True-Color Night Vision Cameras

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ABSTRACT

This paper describes True-Color Night Vision cameras that are sensitive to the visible to near-infrared (V-NIR) portion of the spectrum allowing for the "true-color" of scenes and objects to be displayed and recorded under low-light-level conditions. As compared to traditional monochrome (gray or green) night vision imagery, color imagery has increased information content and has proven to enable better situational awareness, faster response time, and more accurate target identification. Urban combat environments, where rapid situational awareness is vital, and marine operations, where there is inherent information in the color of markings and lights, are example applications that can benefit from True-Color Night Vision technology. Two different prototype cameras, employing two different true-color night vision technological approaches, are described and compared in this paper. One camera uses a fast-switching liquid crystal filter in front of a custom Gen-III image intensified camera, and the second camera is based around an EMCCD sensor with a mosaic filter applied directly to the sensor. In addition to visible light, both cameras utilize NIR to (1) increase the signal and (2) enable the viewing of laser aiming devices. The performance of the true-color cameras, along with the performance of standard (monochrome) night vision cameras, are reported and compared under various operating conditions in the lab and the field. In addition to subjective criterion, figures of merit designed specifically for the objective assessment of such cameras are used in this analysis.

Keywords: MOUT, color display, target detection, image intensifier, EMCCD, night vision, low-light-level, Color I2CCD, liquid crystal filters.

1. INTRODUCTION

Numerous DoD studies have shown that scene understanding, reaction time, and object identification are faster and more accurate with color imagery than with monochrome imagery[1,2]. Considering surveillance, reconnaissance, and security applications, color imagery has two main benefits over monochrome imagery. The first is that color improves contrast, which allows for better scene segmentation and object detection. This contrast improvement can apply to both true-color and false-color images, where false-color imagery can be formed by the fusion of images from cameras with different spectral sensitivity (e.g., image intensified with thermal IR). The second benefit of color is that it provides more information. Access to stored color knowledge in the brain or a computer database can be utilized to enable better object identification and scene understanding. This second improvement applies primarily to true-color images, since false-color images do not necessarily match the stored color information, and may in fact be detrimental in this regard.

General benefits and drawbacks of true-color night vision (TCNV) systems are listed in Table 1, and examples of the utility of true-color information are shown in Figure 1. For example, Figure 1 demonstrates that successfully finding the man with the orange shirt, determining the difference between flags, or being able to pick out the blue car are all tasks that benefit greatly from the additional information that true-color imagery provides.

To obtain true-color images a camera must be sensitive to the visible portion of the electromagnetic spectrum and there must be a mechanism to filter or split the different parts (i.e., colors) of the visible spectrum so that color information can be extracted. This need to filter the input has the consequence of reducing the available signal to a detector, which is the primary drawback of a true-color system intended for use in low-light situations. Furthermore, standard monochrome image-intensified systems are typically designed to take advantage of the relatively high near-infrared (NIR) signal available from the night sky. To mitigate the inherent reduction in signal due to filtering, a true-color system should also be able to utilize this NIR light. In addition, sensitivity to NIR is also needed for viewing of IR laser aiming devices, as demonstrated in Figure 2. The ability to produce true-color content, while maintaining sensitivity to NIR is one of the inherent challenges in making a viable true-color night vision camera.

New camera technology and image processing routines have been developed to enable the use of true-color information from the visible portion of the spectrum while utilizing the full visible to near infrared (V-NIR) range (roughly 400 to 1000 nm in wavelength) for the brightness information. Two different types of TCNV cameras are described here: one camera uses a liquid crystal filter in front of an image intensified detector and the other uses a mosaic filter deposited on the pixels of an EMCCD detector. Both cameras are based on new technologies: the liquid crystal camera uses fast switching filters with optimized transmission bands, and the mosaic filter camera relies on recent advances in CCD technology. Other filtering technologies, such as filter wheels and beamsplitters, were not considered to be viable options due to inherent drawbacks, and thus were not included in this study.

Table 1. General benefits and drawbacks of true-color night vision cameras as compared to standard monochrome low-light-level or image intensified cameras.

True Color Night Vision (TCNV)	
Benefits (compared to monochrome)	Drawbacks (compared to monochrome)
• More information – better object recognition, better scene understanding • Improved contrast – better object detection, better scene segmentation	• Reduced signal • Increased cost

Fig. 1. Monochrome and color low-light-level imagery. The images illustrate the additional information that is available with the inclusion of color.

Fig. 2. Image taken with OKSI's TCNV camera demonstrating the ability to produce color imagery while utilizing both visible and NIR signal for brightness. The bright spot on the red car is from an NIR laser aiming device.

2. DESCRIPTION OF CAMERAS

In this section a brief description of the cameras under study are given. This paper focuses on describing the cameras and comparing the basic output imagery. In addition to the camera development, novel real-time image processing routines for optimized color output and noise mitigation (e.g., for "confetti noise" due to scintillation that occurs with I2 type devices) have also been developed, but results from these routines are not presented here due to space limitations and proprietary considerations.

2.1 Liquid Crystal Filter Intensified Camera

Liquid crystal (LC) filters consist of stacks of polarizing, birefringent, and variable retardance substrates. With applied voltages, the transmission of the stack can be electronically switched to a different bandpass or "color" state (see Figure 3). A full color image is constructed by using separate images taken in 3 or 4 different color states and then mixing them with appropriate weights to form an RGB output image. Although the color information is built up over multiple exposures, the image is updated with each captured frame, rather then waiting until a complete set of 3 or 4 frames is captured.

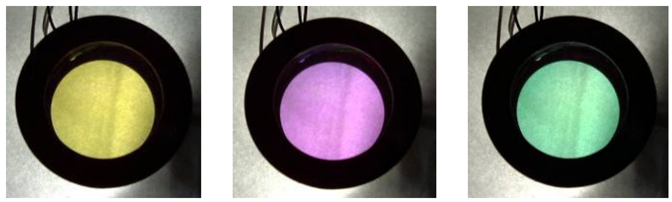


Fig. 3. A liquid crystal filter shown in 3 different color states. The color is switched by changing the applied voltages.

Table 2. Summary of the major benefits and drawbacks of a camera using fast switching liquid crystal filters.

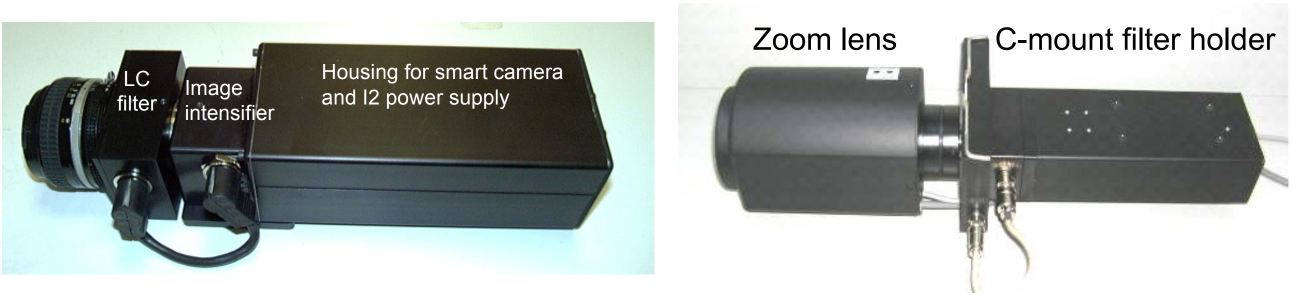
Fast Switching Liquid Crystal Filter Camera	
Benefits	Drawbacks
• Full color resolution at each pixel • Filter can be positioned out of optical path for full detector sensitivity at lowest light levels • Versatile: filter can be used with any type of VNIR low-light detector • Low power • No moving parts • Fast-switching LC: no "dead-time"	• Time-sequential image capture: it takes multiple frames to produce a full color image • Reduced signal: filters rely on polarization, which leads to an overall reduction in signal of approximately 50% — (the average transmission is less than 50% in the visible, but higher than 50% in the NIR)

OKSI has developed two different prototype cameras using two different types of fast switching liquid crystal filters. Table 2 lists the main benefits and drawbacks of a night vision cameras that use such LC filters. In addition to the visible wavelengths, the LC filters also pass NIR radiation to increase the available signal and to enable viewing of IR laser aiming devices. With the use of specifically tailored band pass states and optimized color mixing algorithms, the NIR signal contributes to the brightness of an image without destroying the true color information.

One set of LC filters developed by OKSI are extremely fast switching taking less than 1ms to switch between any two states; this is compared with nematic and cholesteric LC filters that take from 10 to 50 ms to switch. Fast switching enables the camera to operate without "dead-time" and the associated light loss while the filter is in an undefined state. With typical LC filters it is impractical to operate at video rates, i.e., 30 frames/second (fps), since the dead-time is on the same order as the frame period. However, with the fast-switching filter, rates as high as 180 fps are routinely used.

The two different prototype TCNV cameras developed by OKSI are shown in Figure 4. The two different cameras perform similarly; however, Version 2.0 has reduced production cost, has more "user friendly features" and is more versatile. Both cameras use an image intensified CMOS detector with a "smart camera" digital media processor (DMP).

The image intensifier is a Gen III blue-enhanced tube, which is bonded to the sensor via a 2:1 fiber-optic reducer (minifier). The CMOS array is a ½” format 640×480 pixel detector capable of 200 fps at full resolution. A high frame rate detector is used to enable a reduction in the image blur associated with time-sequential image capture; however, at the lowest light settings, longer exposure times (and thus lower frame rates ~ 30 fps) are used.



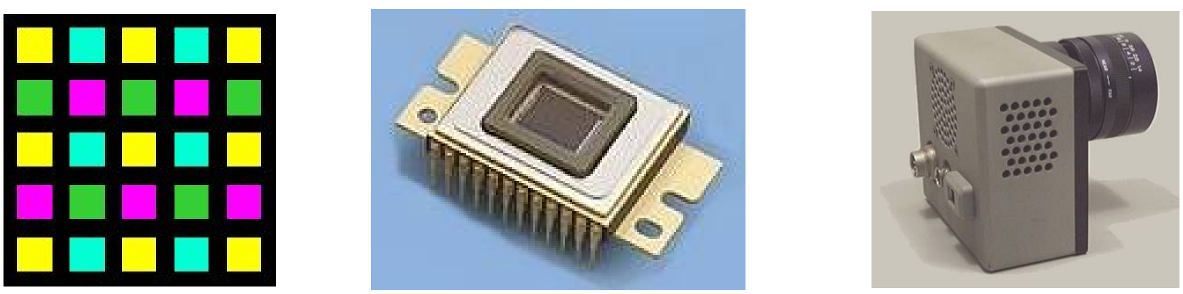
(a) LC Filter Camera Version 1.0

(b) LC filter camera Version 2.0 shown with thinner filters and an auto-iris zoom lens

Figure 2. TCNV prototypes with LC filter and image intensified CMOS.

2.2 EMCCD/mosaic camera

Electron multiplication CCD (EMCCD) technology has been steadily advancing over the last several years. These low-light sensors are basically ultra-sensitive CCD chips (there is no image intensifier tube). High amplification is achieved by employing a specialized multiplication register, where the gain occurs in the charge domain before readout and digitization by the A to D converter. Since these detectors do not use an image-intensifier tube they are not prone to burn-out/damage from bright lights. A color EMCCD is made by using a mosaic filter similar to the standard “Bayer” pattern used by commercial color CCD and CMOS sensors. With a mosaic filter, a group of neighboring pixels each “sees” a different color and interpolation is used to determine the appropriate RGB values at each pixel. For the tests presented in this paper a camera using a complimentary color pattern was used (see Figure 5).



(a) Mosaic filter pattern (b) EMCCD chip (c) Color EMCCD camera

Figure 3. EMCCD/mosaic camera: (a) Cartoon representation of the mosaic pattern that is “painted” on the pixel array, (b) picture of the ½” format chip, (c) picture of the camera used in the tests presented here.

Table 3. Summary of the primary benefits and drawbacks of an EMCCD/mosaic color camera.

EMCCD/mosaic filter	
Benefits	Drawbacks
• Full color with each image frame – reduced motion blur • No intensifier tube – no potential damage due to bright lights • Anti-bloom features – can capture images with bright lights in scene	• Higher power requirements – about 15 Watts needed to cool detector • EMCCD sensors currently have lower sensitivity than Gen III image intensifiers • Reduced spatial color resolution – need to interpolate among pixels

A summary of the major benefits and drawback of an EMCCD/mosaic camera are listed in Table 3. Most of the benefits are related to the fact that an intensifier tube is not used; however, there are three main drawbacks to this scheme: (1) the sensitivity currently does not match that achieved by a Gen III image intensifier tube, (2) cooling is needed to reduce the dark current on the chip, which equates to higher power consumption; and (3) interpolation is needed to construct ("de-mosaic") an image, resulting in reduced color resolution.

3. PERFORMANCE TESTS

In this section we describe some of the tests that have been conducted to characterize true-color night vision cameras. For these tests, quantitative results are obtained using figures of merit that were specifically designed for the objective performance analysis of TCNV imagery. The majority of tests presented here (Sections 3.1 to 3.3) were conducted in a darkened laboratory with controlled lighting at a luminance value of 0.4 lux (0.04 ft-cd). The spectral profile of the lighting contained both significant visible and NIR signal, and was representative of moonlight conditions. The effective light level to the camera was varied by closing the aperture of the camera; f-stops of f/2, f/4, f/8, and f/16 were used where each steps represents a factor of 4 reduction in light level. For example, a setting of f/16 is effectively equivalent to an f/2 system at an illumination of 0.006 lux (0.0006 ft-cd), which is roughly at a level between the illumination of quarter moon and no-moon conditions.

A frame rate of 30 fps was used in all camera configurations for all of the tests. However, since both the monochrome and color versions of the I2-CMOS cameras used multiple frames for each displayed image, the effective exposure time was longer than for the EMCCD/mosaic camera.

3.1 Contrast and Color Fidelity

As mentioned in the introduction, color imagery has two main benefits over monochrome: (1) increased contrast and (2) increased information, where the latter relies on the fidelity of the color reproduction. In this section, these two quantities are measured using figures of merit applied to images of a standardized color chart.

Example images are shown in Figure 6. Each row represents a different camera configuration and each column a different f/# setting (i.e., aperture setting) on the lens. As the light level was decreased, the gain on the camera was increased. To obtain quantitative measures of the contrast each square in the color chart is compared to all the others. The contrast between squares is calculated from the average RGB values of the display image using the formula:

$$C \equiv \Delta E_{2000} \equiv \left[\left(\frac{\Delta L}{S_L} \right)^2 + \left(\frac{\Delta Ch}{S_C} \right)^2 + \left(\frac{\Delta H}{S_H} \right)^2 \right]^{1/2} \tag{1}$$

Here, ΔE_{2000} is the current CIE (International Commission on Illumination) definition of contrast, where L, Ch, and H are luma, chroma, and hue, which are calculated from the RGB values [3].

Figure 7 displays results from this contrast analysis. The graph on the left is the median contrast for all combinations of squares. As expected, the color cameras have higher contrast compared to the monochrome. The graph on the right shows the percentage of combinations below a contrast threshold, in this case $C < 0.05$. For this figure of merit a lower number is better, and this graph shows that there are significantly fewer "undetectable" target/background combinations for the color cameras than for the monochrome camera.

In Figure 8 a measure of the color fidelity is displayed. This quantity is the median color contrast (i.e., Equation 1 without the ΔL term), which is calculated by comparing each square in the imaged color chart to a corresponding reference value. This is basically a measure of the color error, and for perfect reproduction the value should be zero (again a lower number is better). The color cameras have better color fidelity of course, and here the LC filter camera performs better than the EMCCD/mosaic camera. One reason the EMCCD/mosaic camera did not perform as well is that this version of the camera software had a limited number of available color mixing algorithms and the images could not be properly white-balanced for the lighting conditions.

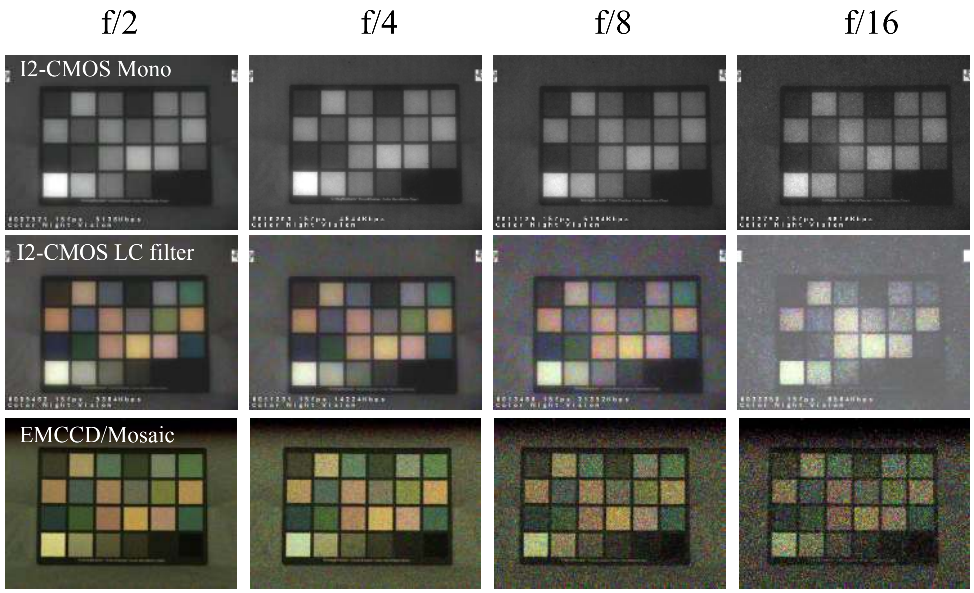


Figure 6. Images of Macbeth color chart with different camera configurations and aperture settings.

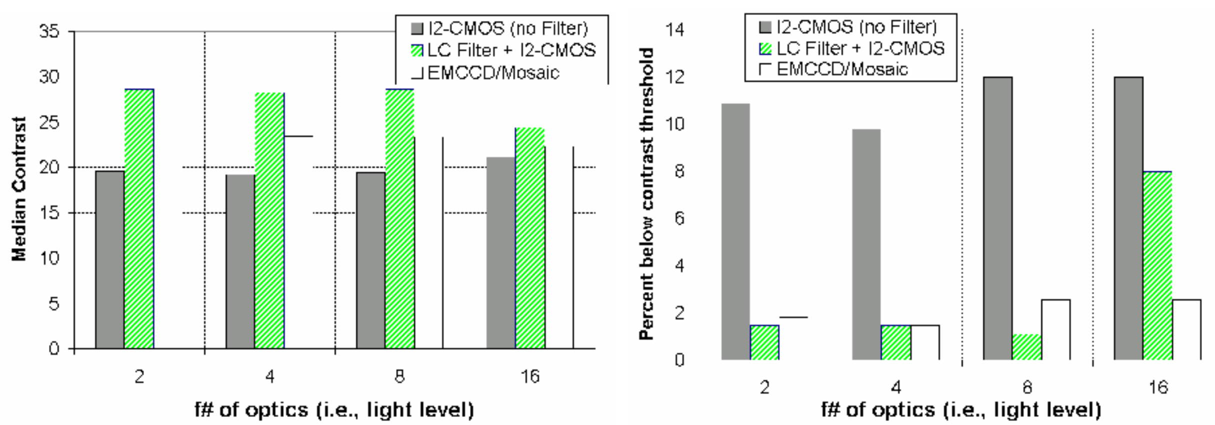


Figure 7. Contrast performance for different f/# settings calculated by comparing all possible target/background combinations of squares in the color chart. (Left) Median contrast. (Right) Percentage of “undetectable” target/background combinations that are below a contrast threshold ($C < 0.05$).

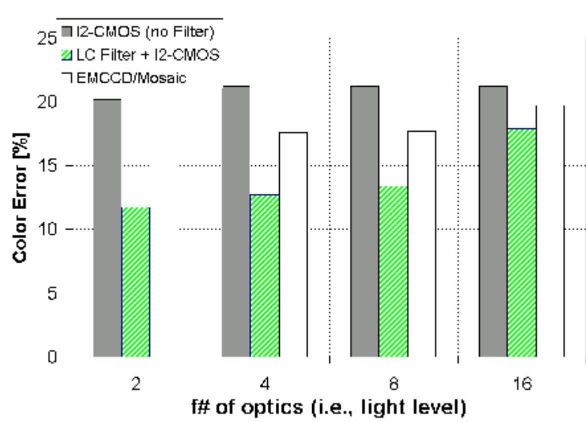


Figure 8. Color error for different f/# settings calculated by comparing each square in the color image to a corresponding reference. The LC filter camera has the lowest color error and thus the best color fidelity.

For the LC filter image taken at f/16, the color mixing algorithm was de-saturated (i.e., the color was "turned down"). This was done to decrease the color induced noise in the image, but it also had the effect of decreasing the contrast and increasing the color error. (As mentioned above, image processing routines have been developed to dramatically reduce the color noise, but these routines were not used here.) For use in the field, this trade-off between noise and color contrast/fidelity is an important consideration in optimizing the system for a given application. For the lowest light situations one may wish to sacrifice color for better signal to noise, eventually switching to monochrome in the lowest light settings. In the case of the LC filter camera, there is a distinct advantage in this regard since full sensitivity of the sensor can be obtained in a monochrome mode by physically positioning the filter out of the optical path.

Practical examples showing the benefits of color fidelity were shown back in Figure 1. One can imagine a task requiring the location of a specific object (e.g., "where is the red car?"), for such tasks having color information is vital and is difficult to quantify in terms of a specific number.

3.2 Signal to Noise Ratio

To obtain a measurement of the signal to noise ratio (*SNR*) that could be applied to both color and monochrome images alike, the luminance (L value) in the CIE La*b* space was used. For the results shown in this section, the *SNR* is taken to be the mean luminance divided by the standard deviation for pixels in the white square of the color chart,

$$SNR \equiv \frac{\overline{L}}{\sigma}. \qquad (2)$$

Values of *SNR* are shown in Figure 9. The *SNR* for the monochrome images are better as expected since there is no reduction in signal due to filtering. The EMCCD/mosaic filter performs worse than the LC filter; in part due to lower sensitivity and also due to the fact that LC based images are constructed from multiple exposures, whereas the EMCCD/mosaic camera uses a single exposure.

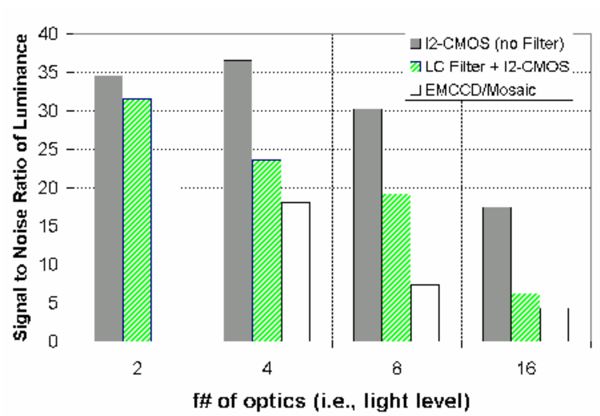


Figure 9. SNR measurements as a function of f/# (i.e., light level). The data points are calculated from the luminance values for the white square of the color chart.

3.3 Relative Range

An important figure of merit often used to characterize imaging systems is the range (or distance) at which an object can be detected, recognized, or identified. Subjective field tests involve human operators attempting to accomplish specific vision tasks. Objective formulae have also been developed to model the range [4,5]. These formulae try to include all factors involved in the imaging task including target characteristics, atmospheric conditions, lens characteristics, viewer response, etc. Here we ignore most of these factors, since we are only concerned with relative differences between imaging systems due to the inclusion of the color enabling components (i.e., filters). The differences we are considering can be taken to only affect the contrast, *C*, and the *SNR* of the output image with all other factors in the range equation unchanged. With a survey of range equations we find that, in general, the range is calculated as being linearly proportional to both the contrast and the *SNR*, and thus a relative comparison between systems can be written as

$$\text{Relative Range:} \quad R_r \equiv \frac{C_1\ SNR_1}{C_0\ SNR_0}. \qquad (3)$$

This *Relative Range* equation captures an essential tradeoff between a color and monochrome system: *contrast versus signal to noise*. Using the product of the median contrast, Equation (1), and the *SNR*, Equation (2), values for the *Relative Range* are calculated and displayed in Figure 10. Here the values are scaled (i.e., C_0 and SNR_0 in Equation 3) by the highest value of their product, which was for the LC filter camera at f/2. Based on these calculations the ranges for the color and monochrome I2-CMOS cameras are comparable, with the color camera performing better at the highest light level and the monochrome camera better at the lowest light level. The EMCCD/mosaic camera performs worse. As mentioned above, the EMCCD/mosaic camera was at a disadvantage due to the fact that it uses only a single image frame, whereas both the monochrome and color I2-CMOS cameras use multiple image frames. However, this factor alone would not completely make-up for its poorer performance.

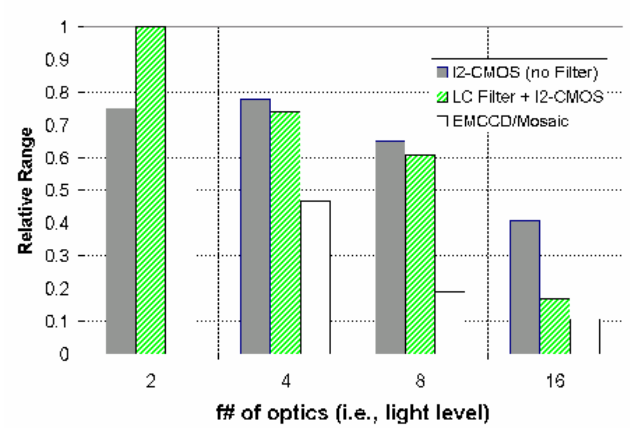


Figure 10. *Relative Range* as a function of f/# (i.e., light level) for different camera configurations.

3.4 Motion Blur

In this section we present a qualitative example of motion blur. Figure 11 shows images taken of a waving hand in front of the different cameras. This test highlights an advantage that the EMCCD/mosaic system had over the LC camera system for the specific operating conditions used here. For these tests the frame rate was set to 30fps for all of the cameras; however, both the monochrome and LC filter I2-CMOS systems used the previous 3 camera frames to construct each output image. The monochrome camera actually does not need to use such a "rolling average", it was only used in these tests to provide a straight forward comparison with the color LC filter system, where the latter does require the use of multiple frames to determine color information.

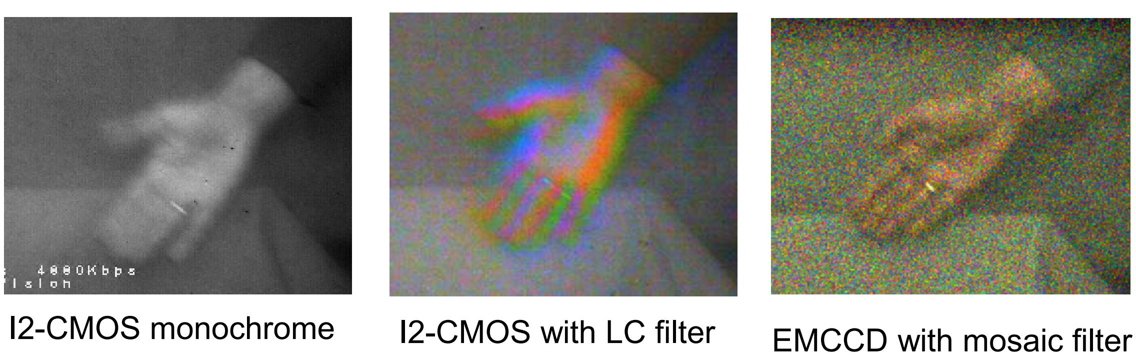


Figure 11. Images of waving hand with 3 different camera configurations. The blur with the I2-CMOS images is due to multiple frame image capture.

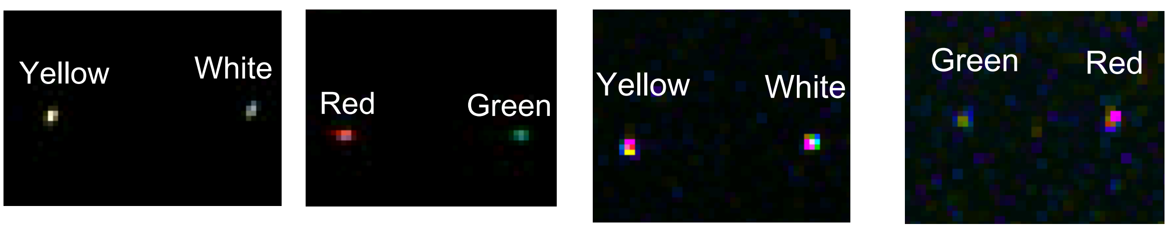
The blur for the I2-CMOS cameras is greater than for the EMCCD/mosaic camera; this is due to multiple frame capture being used by the I2-CMOS cameras. For the case of the LC filter camera, the motion produces a rainbow effect due to each frame being captured with a different color state. This test is rather severe, since the hand is so close to the camera that even a slight motion represents a change in many pixels from frame to frame. This rainbow effect will be much less pronounced for typical objects in a surveillance type application. In addition, the rainbow effect can be dramatically reduced by going to higher frame rates (here 30 fps was used) and by using real-time image processing routines.

3.5 Marine Environment Operations: Navigation Light Simulation

One specific application that can benefit from the color night vision system is the task of determining the color of navigation lights of ships in diminished viewing conditions (see Figure 12). Of particular interest is the task of distinguishing red from green and white from yellow. Standard technology uses non-intensified day-time video cameras, which typically perform no better than the unaided human eye.

Figure 12. (Right) Image of ship with navigation lights taken with a monochrome low-light-level camera. (Left) Example light used to test TCNV technology.

Example imagery taken with the two types of TCNV cameras are shown in Figure 13. The light source used in the test was basically a point source intended to simulate lights at a typical interrogation distance in marine environments. The liquid crystal system out performs the EMCCD/mosaic system. This is due to the fact that a mosaic filter system, which relies on interpolation from neighboring pixels, cannot be used to reliably determine the color of objects that only span a few pixels or less. This fact is most evident by the images of the yellow and white lights in Figure 13 (b).



(a) Liquid Crystal Filter Camera (b) EMCCD/mosaic filter Camera

Figure 13. Images taken with the TCNV cameras in a simulation of navigation lights at a distance.

4. SUMMARY AND DISCUSSION OF DEFENSE AND SECURITY APPLICATIONS

A qualitative summary of the relative performance of the 3 cameras are shown in Table 4. The comparison between the I2-CMOS with the LC filter (color) and without the filter (monochrome) is straight forward since the only difference between the two systems was the filters. All other parameters for these tests were identical, including the use of multiple frame capture. As expected, the LC filter camera performed better than the monochrome camera on the color metrics but worse on the *SNR*. An interesting result is that the two cameras had comparable performance in terms of the range.

The comparison between the EMCCD/mosaic and the LC filter camera is not as straight forward. This is due to two major factors: (1) single frame (as opposed to multiple frame) capture was used for EMCCD/mosaic camera, which places the camera at an advantage in terms of reduced motion blur, but at a disadvantage in terms of SNR; and (2) the EMCCD/mosaic camera was not white-balanced (this version of the camera did not have proper color balance provisions built in) thus placing the camera at a disadvantage in terms of the color metrics.

Due to their different strengths and weaknesses, the two different types of TCNV cameras are appropriate for different applications. Clearly both systems enable imagery with more information and increased contrast compared to monochrome imagery. These advantages lead to better scene understanding making a true color night vision camera particularly appealing for urban operations (i.e., MOUT). For applications requiring low power the LC filter system is more appropriate, but for other applications the EMCCD has advantages due to its tubeless design. In marine environments, where determining the color of point sources (i.e., navigation lights at a distance) is important, the LC filter system is appealing due to its ability to have full color resolution with each pixel. Another key difference between the two types of color technologies is that the LC filter can be physically positioned out of the optical path in extreme low-light-levels conditions allowing for full sensitivity in a monochrome mode; in contrast, once applied, the mosaic filter cannot be removed from the EMCCD detector and the full sensitivity of the detector can never be recovered.

Table 4. Qualitative summary of performance tests. A green thumbs-up represents "relatively good," a red thumbs-down represents "relatively bad," and a flat hand represents somewhere in between.

	I2-CMOS(no filter)	I2-CMOS w/ LC Filter	EMCCD / Mosaic
Color Contrast	👎	👍	👍
Color Fidelity	👎	👍	✋
Signal to Noise	👍	👎	👎
Range	👍	👍	👎
Motion Blur	👎	👎	👍
Navigation Lights	👎	👍	👎

As a final point of discussion, we come to the subject of the fusion of imagery from different types of detectors. There has been a large effort in recent years to combine the output from different types of imaging sensors; for example, visible with thermal infrared (TIR), short-wave infrared (SWIR) with mid-wave infrared (MWIR), etc. Often the composite image that is produced is displayed in "false color", where the color in the display is intended to provide more information to the viewer but does not match the true color of the objects. When the color of an object does not match the stored color in the viewers brain (e.g., when grass is red instead of green) it can actually be detrimental to scene understanding. For this reason, true color night vision cameras can be used to improve image fusion systems. Using OKSI's proprietary techniques, radiation from other portions of the spectrum (e.g., NIR, SWIR, MWIR, and/or TIR) can be combined with the visible portion for brightness information, whereas the visible alone would provide the color information. Such a "true-color" fused system would be the ultimate sensor in terms of object detection and scene understanding.

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