Performance evaluation of image enhancement techniques on night vision imagery

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ABSTRACT

Recently new techniques for night-vision cameras are developed. Digital image-intensifiers are becoming available on the market. Also, so-called EMCCD (electro-magnified) cameras are developed, which can also record imagery in dim conditions. In this paper we present data recorded with both types of cameras (image-intensifiers and EMCCD cameras) in dim light conditions, and present the results of image enhancement on this data. The image enhancement techniques applied are noise reduction, super-resolution reconstruction and local adaptive contrast enhancement. Comparing the results from both cameras indicates that the image intensifier performs better at the dim conditions and the EMCCD camera performs somewhat better at the bright conditions.

Keywords: Image enhancement, super-resolution, contrast enhancement, image-intensifiers, EMCCD cameras, TOD

1. INTRODUCTION

For all military operations, situational awareness is of great importance. This situational awareness can be obtained using cameras. The current trend is that more and more operations are shifted from daytime to night. This increases the need for night-time imagery. Low light levels are normally not sufficient to see details of the scene with standard CCD cameras. Therefore, in night time operations other types of cameras are used. Thermal infrared cameras can be used in complete dark environments, as they visualize thermal differences in the scene. Image-intensified cameras and EMCCD cameras use light from the stars or the moon to obtain an image under low-light conditions. The advantage of these cameras with respect to infrared cameras is that they allow for visual identification. This image enables the soldier to interpret his environment. Traditionally, image-intensifiers are carried by the individual soldier. An advantage of EMCCD cameras is that also the color of the scene can be recorded. The drawback of recording colors is that the sensitivity of the camera is lower. In this paper we present only data recorded with a grey-value EMCCD.

The quality of the imagery is a topic of interest. In this paper we present data recorded on an image intensifier and a grey value EMCCD camera. One of the main characteristics of these cameras is their noise behavior. This noise can be modeled as Poisson noise, with its characteristic peaks. This results in individual pixels with a high value. This effect can be reduced by the use of image enhancement.

In 2009 we presented the performance of image enhancement techniques on image-intensifed cameras.[1] In this paper, we present also data from a grey-value EMCCD cameras. The results of both cameras are compared. The image enhancement techniques applied are described in section 2. The evaluation is done using the TOD method. Some details about this method are given in section 3. The experimental setup including details about the recordings is given in section 4. The results of the experiments are presented in section 5. Conclusions and directions for further research are presented in section 6.

2. IMAGE ENHANCEMENT TECHNIQUES

Image enhancement can be applied to an image or a sequence of images. The purpose of these techniques is to improve the quality of the images presented to an observer. In this paper we evaluate the benefits of three image enhancement techniques: temporal noise reduction, super-resolution reconstruction and local contrast enhancement. An advantage of these algorithms is that they can be implemented on hardware, as well in a real-time software application.

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2.1 Temporal noise reduction and super-resolution reconstruction

In case multiple frames of a scene are available, temporal filtering can be used to improve the images. When the camera and scene is stationary or the frames can be aligned accurately, temporal filtering will not deteriorate the scene structure such as for instance spatial filtering does. Temporal noise reduction can be done using averaging of the aligned frames, or using more complex techniques such as super resolution. With these techniques the spatial resolution of the images can also be improved. An overview of super-resolution techniques is given by Park.[2] Schutte et al.[3] presented the Dynamic Super Resolution algorithm, which can be implemented in real-time. In these experiment the DSR algorithm is used for both noise reduction, that is for enhancement without increasing the number of pixels, and for super-resolution reconstruction, that is noise reduction and resolution enhancement combined. Noise reduction is also referred to as DSR1 and super-resolution reconstruction as DSR2.

2.2 Local contrast enhancement

Next to noise reduction, a grey-value image can also be enhanced using contrast enhancement. The goal is to visualise more details in the image. To enhance the contrast in an image several methods are described in literature. The most simple way to enhance the contrast is by adjusting the image to the available range, so-called global contrast stretching. This will help in cases were only part of the available range is used, but will fail in situations were the range used in one part of the image differs much from other parts. To enhance the contrast in a part of the available contrast range gamma manipulation can be done. In this case details in part of the lightness range of the image will be enhanced, at the cost of decreasing the lightness in other parts of the image. Another global method is histogram equalization, were the lightness values are changed so that the histogram of the image are as flat as possible. The main disadvantage of this method is that the appearance of the output images is not so natural anymore.

To enhance local contrasts also local adaptive contrast enhancement can be used. The idea of local contrast enhancement is that the processing depends on features in a local region. Narenda and Fitch[4] propose a method in which the local statistics are described by its local mean and variance. Using a local region means that the contrast is enhanced in a specific scale in the image, for instance only small details. However, it is hard to decide which details are important and which are not. To avoid having to chose a specific scale, the contrast can be adjusted at several scales in the image.

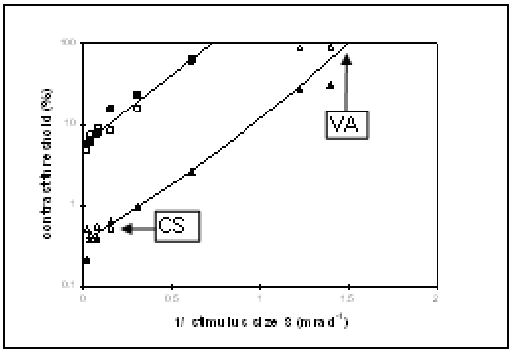
In our evaluation we use LACE,[5] a grey-value algorithm which is based on the method of Narenda and Finch, but extended to a number of scales. This algorithm can be used to obtain images showing all interesting features in an image.

3. TOD METHOD

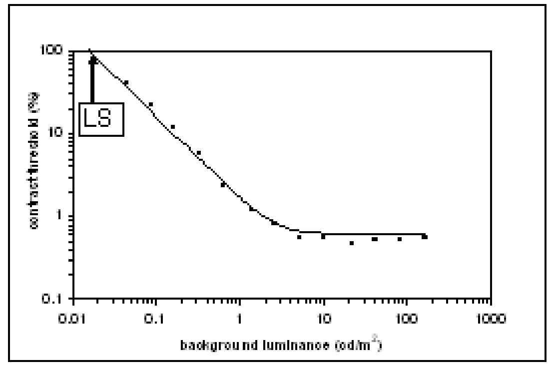
The subject response is measured using the Triangle Orientation Discrimination (TOD) method.[6] This method makes use of equilateral triangles to quantify sensor performance with a human-in-the-loop. In this case the "sensor" is both the sensor and the image enhancement that is applied. A detailed description of the TOD method is presented by Bijl et al.[7] Here we present a short overview.

The TOD is a sensor system specific curve (or set of curves) that describes the ability of a human observer using the sensor under test to discriminate between equilateral triangles of four possible orientations (apex Up, Down, Right or Left, see Figure 1). Independent variables are triangle angular size S (defined as the square-root of the triangle area, in mrad), triangle contrast (its definition depends on the spectral range of the sensor: thermal contrast $\Delta T = T_{target} - T_{background}$ for thermal imagers or visual contrast $C = |L_{target} - L_{background}|/L_{background}$ for visual or NIR devices) and background luminance $L_{background}$ for visual or NIR devices. A detailed description of the assessment procedure is given elsewhere.[8] During the test, triangle patterns of different size and contrast on a uniform background are presented to the observer who has to indicate their orientation even if he is not sure. The threshold is defined at the 75% correct level and is obtained by fitting a Weibull function through the data. Image degradations induced by the sensor (such as blur, noise and sampling) make the judgments more difficult and shift the 75% correct thresholds towards a larger test pattern size S or to a higher contrast. In this way, the method evaluates the combined effect of all

Figure 1. The test pattern or stimulus in the TOD method is an equilateral triangle with one of four possible orientations: apex Up, Down, Left or Right. The observer task is to indicate its orientation. This task is more difficult for patterns with smaller sizes or lower contrast. From Bijl &Valeton.[6]



(a) Plotted are 75% correct contrast thresholds as function of reciprocal test pattern size S^{-1} (in $mrad^{-1}$) at two different light levels: L = 165 cd/m^2 (triangle symbols) and L = 0.33 cd/m^2 (square symbols).



(b) Contrast thresholds for a large triangle (S = $32VA^{-1}$) as a function of background luminance.

Figure 2. TOD curves for a typical CCD camera system. VA is defined as the cut-off reciprocal triangle size at high contrast (C = 100S = 32VA-1. LS is defined as the luminance level at which at which a large high contrast triangle is at threshold. From Bijl &Valeton[8]

image degradations within the sensor system including the observer. The method yields a threshold curve or set of curves of contrast versus the reciprocal size of the test pattern S^{-1} (in $mrad^{-1}$). See Figure 2 a) for an example with a CCD camera system. Using reciprocal angular size is convenient for several reasons: 1) a higher value means higher acuity or better performance, 2) range is proportional this value, 3) the effects of atmospheric loss on performance in the field are easily included in the TOD plots, and 4) the curves are directly comparable to the more conventional MRTD and MRC.

Visual Acuity (VA), Contrast Sensitivity (CS) and Luminance Sensitivity (LS) are special points on the TOD curves. VA (in $mrad^{-1}$) is defined as the cut-off reciprocal triangle size at high contrast (C = 100% or $\Delta T = 2K$). CS is defined as the reciprocal of the contrast threshold for a very large test pattern (triangle angular size S = 32*VA^{-1}). LS (for visual or NIR devices) is the background luminance at which a large high contrast triangle is at threshold (i.e. the lowest luminance where anything can be seen with the device and VA and CS merge), see Figure 2 b).

Recently it was also shown[9] that the TOD is the only current end-to-end measure that is able to quantify sensor performance for dynamic imaging and dynamic image enhancement techniques. This makes this method very suitable for this test.

4. EXPERIMENTAL SETUP

4.1 Cameras

In this experiment we used two different cameras. The image-intensifier used was a monocular digital image-intensifier of Photonis, i.e. ICU PP3000L[10] (see also `www.photonis.com`). The ICU is a new generation of low light level, intensified CMOS camera. A picture of this image is presented in Figure 3 (a). The ICU is equipped with a Pentax C2514M lens, with a FOV of 30.7 x 24.8 degrees. The resolution of the system was 640x480

(a) the ICU PP3000L (b) the Raptor EMCCD (b) The setup of the rotating mirror.

Figure 3. The Image Intensifier (a), the grey-value EMCCD (b) and in the setup with the rotating mirror (c). Note that a diffent camera is mounted here.

pixels. The analogue signal was read using a Pleora interface (see www.pleora.com). The grey-value EMCCD camera used was a monocular digital EMCCD camera of Raptor (see www.raptorphotonics.com). A picture of this image is presented in Figure 3 (b). The Raptor is equipped with a Canon 13 mm lens with an f number of f1.5. The resolution of the system was 658x496 pixels. The analogue signal was also read using the Pleora interface.

For every condition both a static and a dynamic recording was made. The camera was placed on a static mount. The scene was observed through a mirror. For the static recording this mirror did not move. For the dynamic condition the mirror was rotated so that the recorded scene showed a circular motion. This circular motion was about 0.5 pixel/frame. A picture of this setup is given in Figure 3 c.

4.2 TOD charts

In the experiments two different TOD observer charts are used:

Visual Acuity (VA): with this chart the sensitivity for a 100% contrast object for different background luminance is measured. The threshold is the minimum object size for which the orientation of the full object is still visible.

Contrast Sensitivity (CS): with this chart the sensitivity for a large object or a range of object sizes for different background luminances is measured. The threshold is the minimum contrast between foreground and background for which the orientation of the object is still visible.

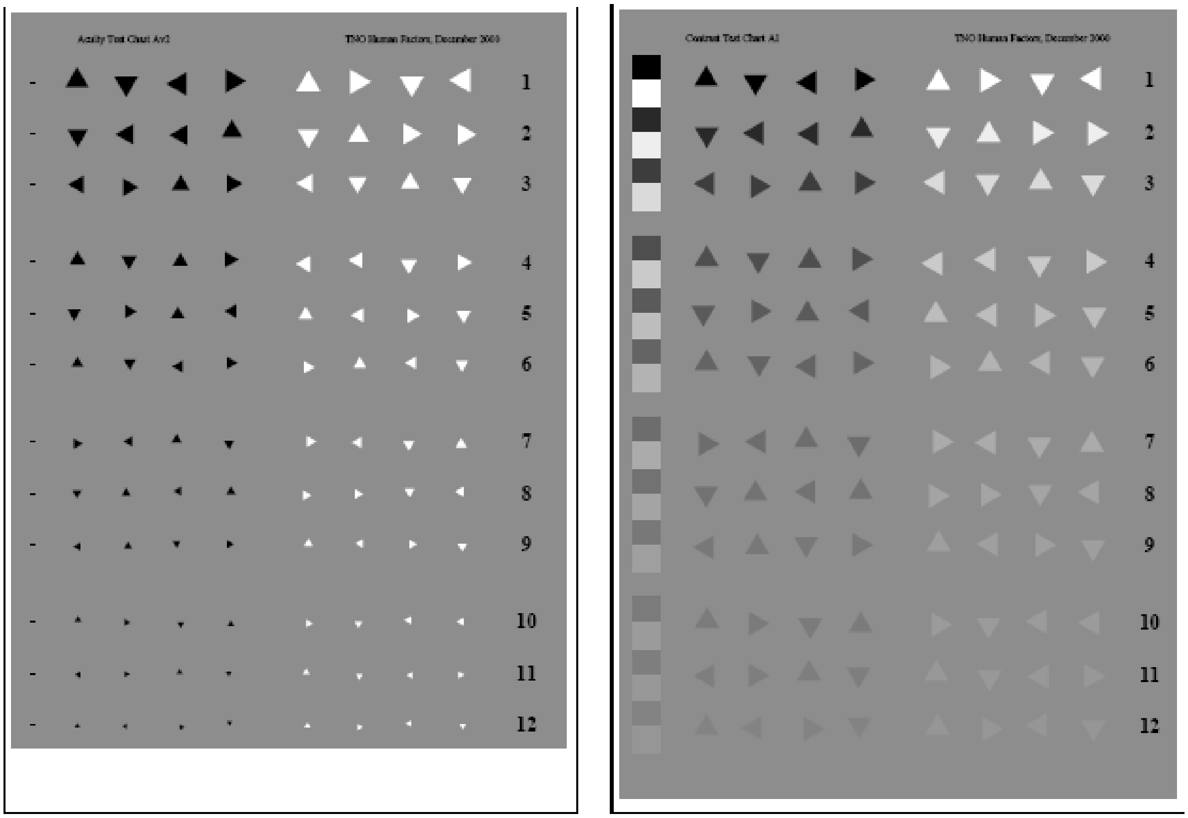
Examples of these charts are given in figure 4.

The spectra of a test chart are a combination of the reflection of the paper and the ink used. The Visual Acuity (VA) chart only has dark test patterns on a grey background. The Contrast Sensitivity (CS) chart also has a grey background, but it contains lighter and darker test patterns with a decreasing contrast. Based on the spectra of the paper and the ink we corrected for the visual contrast as described by Hogervorst et al.[11] The contrast of the test patterns can be influenced by the lighting and reflection in the Near-Infrared (NIR). However, it can be shown[11] that the spectral reflection is more or less constant for the entire light spectrum (visual and NIR) and the spectral reflection for the ink is rather low. Therefore we did not apply corrections to compensate for these effects.

The distance from the camera to the VA test chart was 320 cm. The contrast sensitivity CS was measured with the TOD CS-test chart with triangles. The CS charts were recorded at 100 cm, 160 cm, 320 cm and 480 cm.

4.3 Lighting

Images are recorded under different lighting conditions. There are two lightsources used:



Visual Acuity (VA) Contrast Sensitivity (CS)

Figure 4. Examples of the test charts used in the experiment. The visual acuity chart used in the experiments has only triangles.

Lightsource 1: A relative strong lightsource consiting of two Philips light bulbs softtone 40W/230V. The color temperature of the lightsource is 2615 L. The emission is very similar to standard lightsource A (standard lamp light). The luminance is 24 cd/m^2. This lightsource is referred to as the bright source.

Lightsource 2: A weak lightsource consising of four night lamps YR7.5W/230V. The color temperature of the lightsource is 1780 K. The luminance is 0.68 cd/m^2. This lightsource is referred to as the dim source.

Neutral Density (ND) filters were used to reduce the light level of both lightsources. The optical density d of these filters varied in steps of 0.5 from 0.5 to 6, indicating a attenuation of $10^{0.5}$-10^6. The actual attenuation of the filters was measured. Using the spectral sensitivity we can convert the luminance to the standard illuminant A. This conversion is not performed yet. For this reason we cannot perfrom an absolute sensitivity comparison between both cameras.

The lightsources in the rest of this paper are indicated by their main light source, i.e. bright or dim, and the ND filter used. The dim light source with ND 2 means for instance that the background illumination was the dim lighting which was attenuated by a factor 100.

The lighting setup is shown in figure 5. The large lamps that are attached to the frame are used for the bright lighting condition. The dim lighting condition was made using small night lamps attached just below the large lamps.

In figure 6 examples of an image under different lighting conditions are shown. It can be seen that the recognition of the triangle orientation becomes harder when the light level decreases.

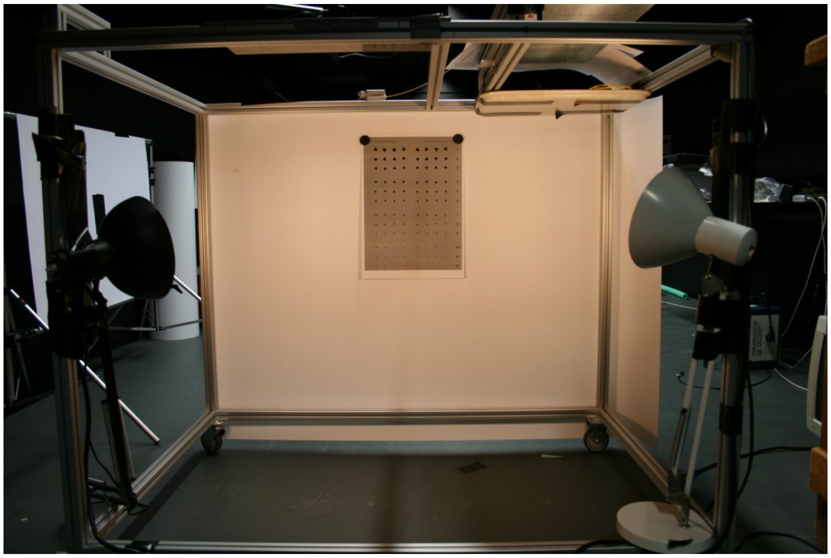


Figure 5. The lighting of the test charts. The large lamps are used for the bright lighting condition. For the dim lighting condition smaller lamps are mounted just below these large lamps. The distance from the lamps to the chart is approximately 80 cm.

Table 1. The image enhancement conditions were presented to the observers.

Static	Static recordings
Dynamic	Dynamic recordings
LACE	Contrast enhancement
DSR1	Noise reduction
DSR2	Noise reduction and resolution enhancement
DSR1 + LACE	Noise reduction and contrast enhancement
DSR2 + LACE	Noise reduction, super-resolution and contrast enhancement.

4.4 Image enhancement conditions

To enhance the images, we applied noise reduction (DSR1), super-resolution (DSR2) and local adaptive contrast enhancement (LACE). All these techniques were applied on the dynamic recordings. Together with the unprocessed static and dynamic recordings seven different conditions were presented to the observers. These conditions are listed in table 1

4.5 Subject experiments

The study was conducted as a pilot study. All images were observed by only one subject, i.e. PB or JD. They indicated the line for which they presumed 75% of the test patterns could be observed correctly. This will give an indication about the interesting parts of the data set. We plan to do an experiment with more subjects and a 4AFC (4 alternative forced choice) setup.

5. RESULTS

5.1 Image processing results

Image processing was applied on the recorded images. In this subsection we present the image enhancement results qualitatively. In the next subsection quantitative results based on the TOD measurements will be presented.

In figure 7 results for the CS chart placed at 160 cm are presented. Instead of the whole image only the region with (part of) the TOD chart is presented. The lighting was the dim lighting without ND filtering. In the top row the I^2 images are shown, in the bottom row the EMCCD images. The left images are a frame from

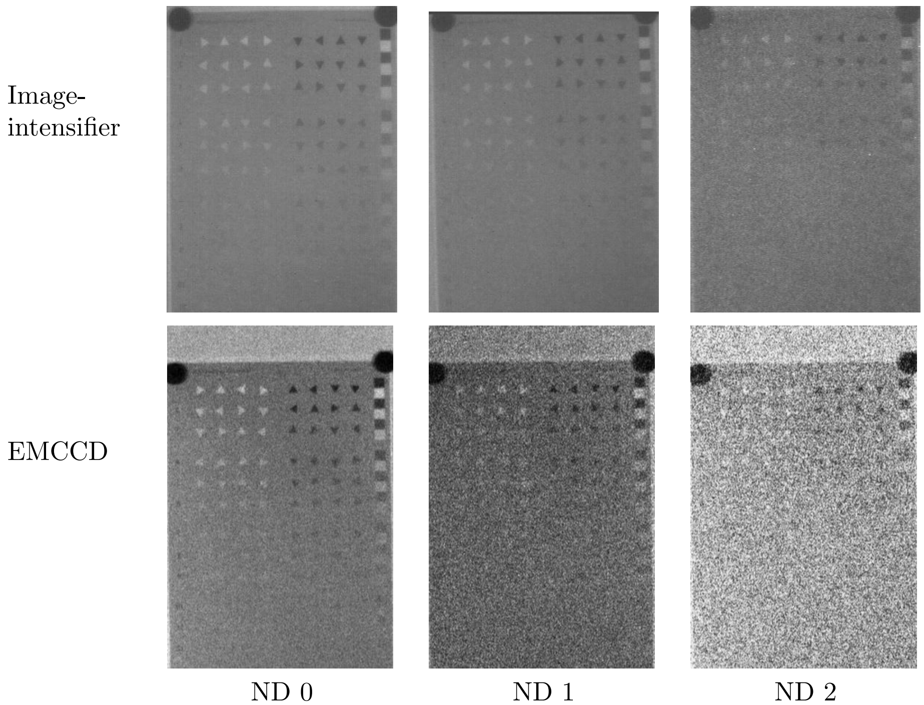


Figure 6. Examples of one of the test charts under different lighting conditions and for different cameras. The standard lighting is the dim lighting. The lighting is reduced more using a Neutral Density filter (see subscript). Note that different charts are used for different lighting and distance conditions.

the dynamic sequence. This image is not processed. On the center image noise reduction (DSR1) is applied. It can be seen that the noise is reduced, especially in the backgound. The orientation of some of the triangles may be seen better. On the right image resolution enhancement (DSR2) is applied. Here also the noise is reduced. The triangles may be somewhat sharper. In figure 8 contrast enhancement (LACE) is applied on these images. It can be seen that the contrast is indeed better. However, the question remains whether these enhancements enable an observer to see the orientation of the triangles better.

In figure 9 and figure 10 the same results are presented, but now for dim lighting with an ND filter with optical density 1.5. The results are similar as those without ND filter. The Noise Reduction for DSR1 and DSR2 can clearly be seen. The triangles after resolution enhancement seem to be sharper. Contrast enhancement makes it easier to see the triangles, but might not improve the evaluation.

In figure 11 and figure 12 these results are presented for the CS chart placed on 320 cm under dim lighing with no filtering. Because the chart is at a larger distance, the region with the TOD chart is smaller. As expected, the smaller size of the test pattern size S makes it harder to evaluate the orientation of the triangles.

5.2 Perception results

TOD contrast levels for different stimulus sizes are given in figure 13. Because the results are based on only one observer, they are not significant and may contain outliers. To obtain a significant result, an experiment with more subjects needs to be done. However, these results indicate some interesting conclusions.

In figure 13 d the results are shown for Noise Reduction (DSR1) and Dynamic Super Resolution (DSR2) applied on a EMCCD camera compared to no processing (dynamic) for a bright lighting condition (24cm/m^2). It can be seen that the Noise Reduction seems to perform worse than both other conditions, especially for small stimulus size (1/S = 0.4). DSR2 performs similar as the dynamic condition. This suggest that the DSR1 processing introduces a small blur, which can be corrected by the temporal filtering by DSR2, but also by the user when he interprets the dynamic sequence himself.

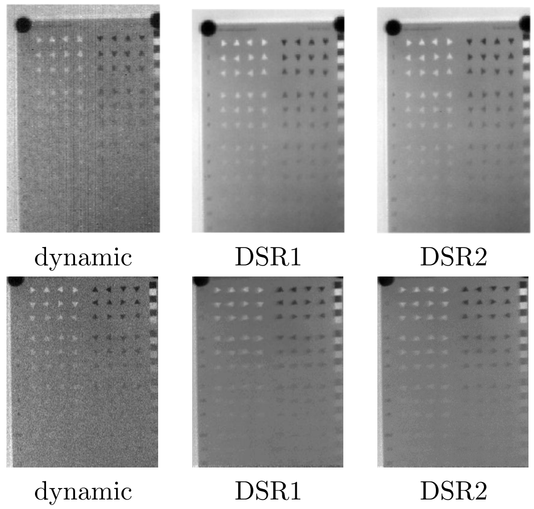


Figure 7. Image processing results for the Contrast Sensitivity chart placed at 160 cm. The image intensifier data is presented at the top row, the EMCCD data at the bottom row. The left images presents the original (dynamic) image. On the other images image enhancement techniques are applied. The lighting was the dim lighting without an ND filter.

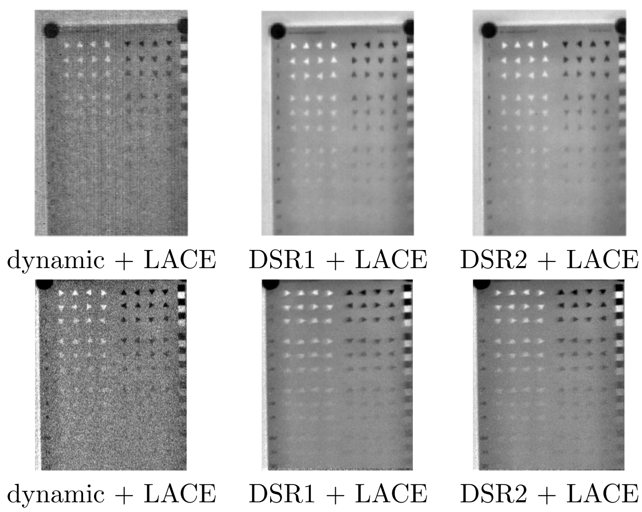


Figure 8. Image processing results for the Contrast Sensitivity chart placed at 160 cm. The image intensifier data is presented at the top row, the EMCCD data at the bottom row. The left images presents the dynamic image with LACE applied. On the other images DSR1 and DSR2 are applied. The lighting was the dim lighting without an ND filter.

In figure 13 a the same comparison is made, but now for the image intensifier. It is shown that the DSR1 algorithm performce somewhat better than the dynamic (no processing) condition, and that the DSR2 algorithm performs better than the dynamic and the DSR1 especially at the largest distance, i.e. for the smallest object size. This indicates that the estimation of the orientation of the triangles at this distance is also limited by the size of the object, instead of only the contrast. By comparing figure 13 a and d, it is shown that the dynamic condition of the EMCCD performs better for smaller stimulus sizes. When applying DSR2, the performance is the same.

In figure 13 b and e the results are shown for dim lighting. For the dynamic condition, the image intensifier outperforms the EMCCD camera. Applying DSR2 has an effect for the image intensifier, but not for the EMCCD camera.

In figure 13 c and f the results are shown for LACE in bright lighting. As expected, the contrast threshold decreased for higher lighting and smaller distances of the test chart, which corresponds to a larger test pattern

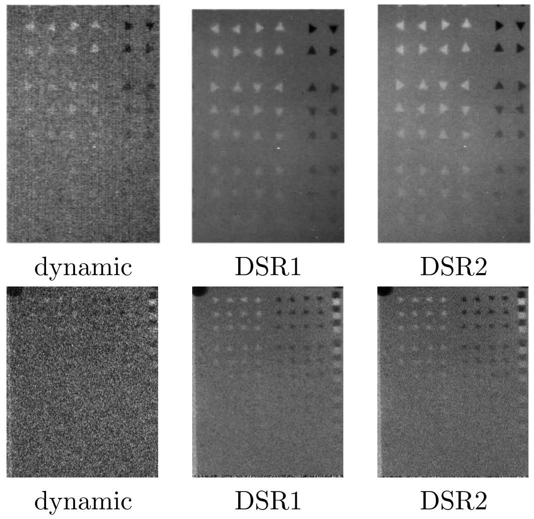


Figure 9. Image processing results for the Contrast Sensitivity chart placed at 160 cm. The image intensifier data is presented at the top row, the EMCCD data at the bottom row. The left image presents the original (dynamic) image. On the other images image enhancement techniques are applied. The lighting was the dim lighting with a 1.5 ND filter.

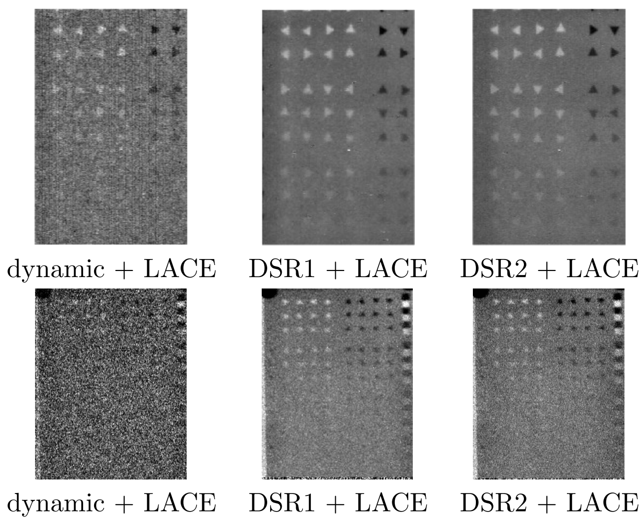


Figure 10. Image processing results for the Contrast Sensitivity chart placed at 160 cm. The image intensifier data is presented at the top row, the EMCCD data at the bottom row. The left images presents the dynamic image with LACE applied. On the other images DSR1 and DSR2 are applied. The lighting was the dim lighting with a 1.5 ND filter.

S. It can be seen that applying contrast enhancement (LACE) yields comparable results to the non-contrast enhancement case. One outlier is DSR1 on the EMCCD camera for a small stimulus size (1/S = 0.4). This seems to be an outlier in the measurements, either for the condition with or without LACE. In both conditions DSR1 performs worse than both the dynamic condition and DSR2. The other results indicate that LACE does not improve the results, but also does not deteriorate them. We expect that LACE will perform better for scenes in which contrast in two or more different lighting ranges are present. This happens for instance if parts of the scene contain shadows.

The subject results of the images recorded at 480 cm (not shown here) indicate that it is hard to evaluate the TOD orientation at this distance. This holds for both cameras. Combined with the high error in the measurements, it is hard to draw conclusions based on only one subject. In the same way, the results for the Visual Acuity seem to suffer much from the large subject-generated noise. Therefore both the results at 480

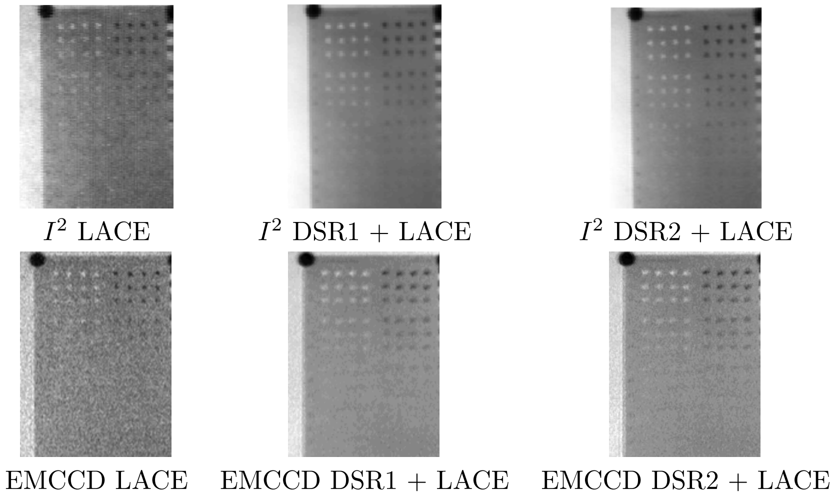


Figure 11. Image processing results with LACE for the Contrast Sensitivity chart placed at 320 cm. The left image presents the original (dynamic) image. On the other images image enhancement techniques are applied. The lighting was the dim lighting.

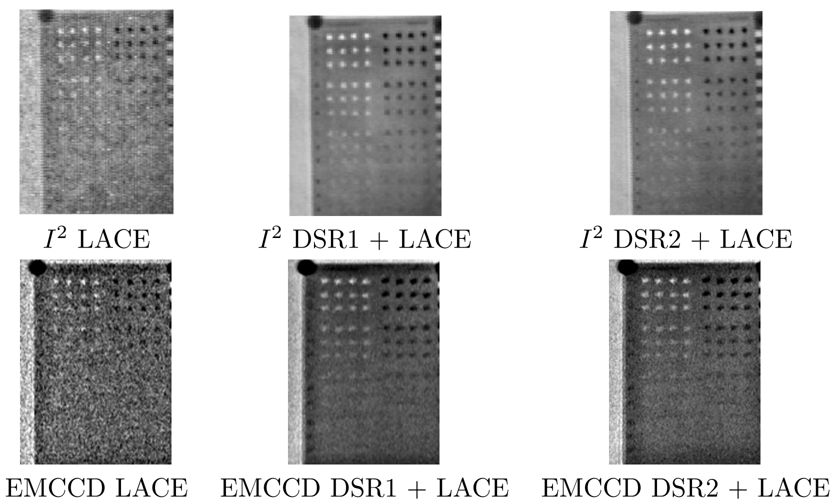
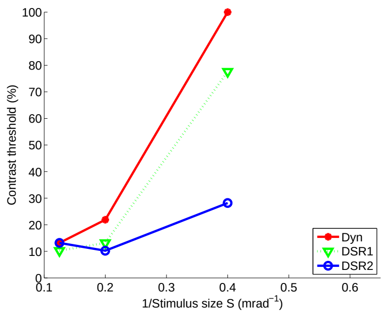


Figure 12. Image processing results with LACE for the Contrast Sensitivity chart placed at 320 cm. The left image presents the original (dynamic) image. On the other images image enhancement techniques are applied. The lighting was the dim lighting.

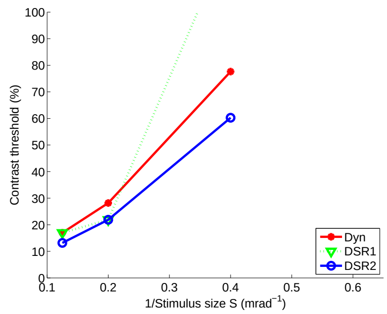
cm and for Visual Acuity are not presented here. We expect that the Visual Acuity can be measured with more subjects. The triangles of the 480 data are that small, that the triangles may be too small to determine their orientation. In that case, no contrast sensitivity can be measured at all.

6. DISCUSSION AND FUTURE WORK

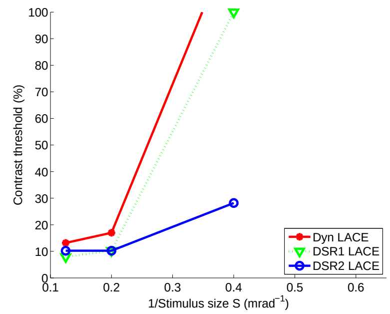
The results presented in this paper indicate that for image-intensifiers the contrast sensitivity is increased by applying noise reduction and super-resolution reconstruction. The improvement for super-resolution reconstruction (DSR2) is higher than for noise reduction (DSR1). The largest improvement for super-resolution reconstruction is found for the smallest test pattern size. These two effects indicates that a significant part of the performance increasement for super-resolution reconstruction is based on the resolution enhancement. Noise reduction without resolution enhancement, implemented by the DSR1 algorithm, also seems to improve



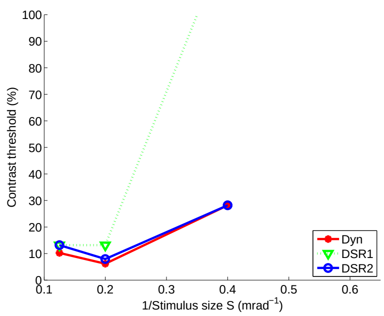
(a) bright I^2



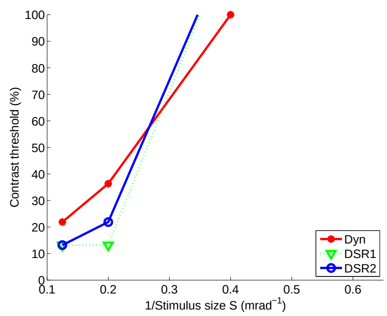
(b) dim I^2



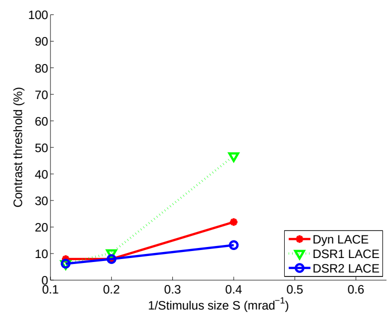
(c)bright I^2 LACE



(d) bright EMCCD



(e) dim EMCCD



(f) bright EMCCD LACE

Figure 13. The Contrast Threshold as a function of the reciprocal of the test pattern $1/S$. for different cameras and different lighting conditions. The bright condition has a lighting of 24 cd/m^2, the dim condition a lighting of 0.24 cd/m^2.

the performance, but this is not significant due to the small amount of subjects in this test. Therefore, we need to validate these results with a larger subject experiment.

For the EMCCD camera DSR1 performs worse than the condition with no processing, especially for the small stimulus size S. DSR2 performs similar as the dynamic condition. This suggest that the DSR1 processing introduces a small blur, which can be corrected by the temporal filtering by DSR2, but also by the user when he interprets the dynamic sequence himself.

Comparing the results from both cameras indicates that the image intensifier performs better at the dim conditions and the EMCCD camera performs somewhat better at the bright conditions. These results also need to be validates in the larger subject experiments, and by converting the luminance to standard illuminant A.

For both cameras, applying contrast enhancement on the dynamic imagery or after applying noise reduction or super-resolution does not improve or deteriorate the contrast thresholds. This is a good result, as it indicates that LACE performs equal to the automatic gain control of the image-intensifier for this test setup. We expect that LACE will perform better for scenes in which contrast in two or more different lighting ranges are present, for instance if parts of the scene contain shadows.

When evaluating the images quantitatively, LACE seems to enhance the contrast. However, the triangle orientation can be estimated as well in the image without contrast enhancement. Possibly LACE will enable the subject to evaluate the orientation of the triangle *faster*. In next experiments we will test this hypothesis, as this timing aspect is not incorporated in the current experimental setup. Another aspect for further investigation is whether contrast enhancement may decrease the task load of the subject, as the evaluation is easier for a higher contrast.

In next experiments we plan to also evaluate the performance of an color EMCCD camera with the same setup. In this way, we can compare the performance of a grey value EMCCD with the performance of a color EMCCD.

After the experiments reported in this paper, the image-intensifier used was build into a larger system.[12,13] This system maps the Field-of-View of three cameras on to one Field-of-View. This is done with special mirrors. In the future we will evaluate the performance of the image-intensifier within the system, to test if the performance of the camera decreases due to e.g. the mirrors in the system.

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