Using spatially varying pixels exposure technique for increasing accuracy of the optical-digital pattern recognition correlator

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ABSTRACT

The registration of correlation signals with high dynamic range leads to increase of recognition's accuracy and robustness. Digital photo sensors with common Bayer colour filter array can be used for this purpose. In case of quasimonochromatic illumination used in optical-digital correlator, it is possible to register correlation signals with high dynamic range. For signal's registration it can be used not only colour channel, which corresponded to the wavelength of illumination, but other colour channels too.

In this work the application of the spatially varying pixels exposures technique for obtaining linear high dynamic range images of correlation signals from digital photo sensors with Bayer mosaic is presented. Bayer colour filters array is considered as an array of attenuating filters in a quasimonochromatic light. Images are reconstructed using information from all colour channels and correction coefficients that obtained at the preliminary calibration step. The registered image of the correlation signal is mapped to the linear high dynamic range image using a simple and efficient algorithm. Calibration procedure for correction coefficients obtaining is described. Quantitative estimation of optical-digital correlator's accuracy is provided. Experimental results on obtaining images of correlation signals with linear high dynamic range are presented.

Keywords: high dynamic range, pattern recognition, optical-digital correlator.

1. INTRODUCTION

Many input scenes are characterised by a high dynamic range (HDR) so it is difficult to register such scenes properly for conventional solid-state photo sensors. This is especially true for CMOS image sensors, since their dark noise is typically larger than CCDs. For reference, standard CMOS sensors have a dynamic range (DR) of 40-60 dB, CCDs around 60-70 dB. Special CMOS sensors that employ continuous-time logarithmic readout and achieve DR up to 140 dB, but they suffer from the loss of contrast and an increase of noise.[1–3] To overcome the problem of photo sensors' low DR, several approaches of HDR imaging were proposed in literature. One way is to use specially designed CMOS photo sensors[2,4–6] that allow to perform computations directly on chip. As an examples of such approach, "smart sensors"[7–10] can be mentioned. More simple and inexpensive way is to use software or hybrid hardware-software approaches of HDR imaging. Such approaches are Spatially Varying pixels Exposure (SVE) technique,[11,12] Adaptive Dynamic Range technique,[13] and other methods of using light modulators for pixels' exposures attenuation.[14,15] The main idea of such methods is to use spatially controllable pixels exposure to reconstruct HDR images from neighbour pixels.

In this paper we describe the application of the SVE principle for increasing accuracy of the optical-digital pattern recognition correlator with quasimonochromatic illumination. In many digital cameras, Bayer colour filters array[16] is used for colour imaging. But in quasimonochromatic light such filters array may be considered as an array of attenuating filters. Hence, when main colour pixels (i.e., related to wavelength of the light source) are saturated, pixels covered by different colour filters (i.e., accessorial pixels) are generally not. Extracting data from such accessorial pixels, it is possible to correct the oversaturated pixel's value and provide an HDR image from the single image.

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The use of software HDR imaging methods in optical-digital correlators can significantly extend correlator's ability of registration and processing of input scenes with high dynamic range. The larger DR the correlator has, the more contrast scenes it is possible to accurately process.

A comparison of the correlation signals with and without HDR imaging is provided. Calibration procedure for correction coefficients obtaining is described. Experimental results on obtaining correlation signals with linear high dynamic range are presented.

2. LINEAR HIGH DYNAMIC RANGE IMAGING USING BAYER COLOUR FILTERS ARRAY

Input scenes for pattern recognition may have great DR, hence the ability to register correlations signals with HDR is required. But using conventional technical cameras, it is possible to register input scenes with relatively low dynamic range (40-70 dB). However, in some practical application of optical-digital correlators it is demanded to process high-contrast scenes. Registration of correlation signals with HDR can simplify the pattern recognition task for correlator. It is noteworthy that necessary condition for such purpose is linearity of registered image of correlation signals in HDR mode.

Since correlators use the quasimonochromatic light and if technical cameras with Bayer colour filters array are used, it is possible to apply HDR techniques such as Spatially Varying pixels Exposure (SVE) to increase correlator's DR. The described correlator[17–19] uses quasimonochromatic spatially incoherent light and photo sensor that has Bayer colour filters array. In quasimonochromatic light, colour pixels of Bayer array can be considered as an array of attenuating filters with different transmittance of light (see Fig. 1). Thus it is possible to apply SVE principle for DR increasing of described correlator.

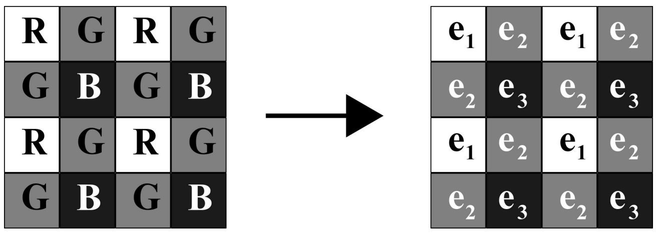

Figure 1. Bayer colour filters array in the quasimonochromatic light can be considered as an array of attenuating filters.

On the single captured image, the brighter pixels have greater exposure and the darker ones have lower exposure. If the exposure time is long enough, some of pixels may be oversaturated, but neighbour pixels under other light filters are generally not. Taking a picture with oversaturation, we can use the attenuating properties for Bayer filters of photo sensor and, consequently, to restore oversaturated regions of image utilizing data from the neighbour pixels. Thus the registered image contains information about the correlation signal as well as the exposure value information. Such approach allows the construction of HDR image of correlation signals from oversaturated pixels.

2.1 Preliminary calibration procedure

The described correlator uses He-Ne laser illumination. For such illumination and used in the correlator digital camera Canon EOS 400D with 12-bit ADC, relative transmittance of colour filter for illumination with $\lambda = 0.63\mu$m were measured. Relative transmittance of red pixels was denoted as e_1; transmittance coefficient for green pixels e_2 ($e_2 < e_1$); transmittance coefficients for blue pixels e_3 ($e_3 < e_2 < e_1$), results are presented Table 1.

Parameters	Main pixels	1^{st} accessorial pixels	2^{nd} accessorial pixels
Pixel's colour filter	red	green	blue
Relative transmittance	$e_1 = 1.000$	$e_2 = 0.114$	$e_3 = 0.007$

Table 1. Relative transmittance coefficients of Bayer-covered light filters of Canon EOS 400D digital camera for He-Ne laser radiation $\lambda = 0.63\mu$m.

Values of relative transmittance were obtained from measured response of camera to He-Ne laser's light versus exposure value. For the evaluation of the radiometric functions for each colour channel, pictures of flat-field were taken for different exposure values. An area of 256×256 pixels in each image was selected and mean value over such area was calculated. Thus radiometric functions, which are mean signal's values versus relative exposure values dependencies, were obtained. The radiometric functions for He-Ne laser radiation with $\lambda = 0.63\mu$m used in this work are presented in Fig. 2.

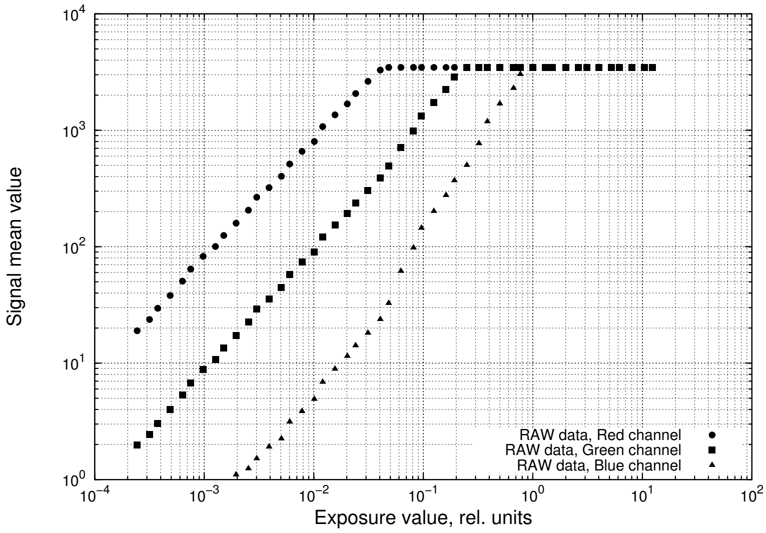

Figure 2. The radiometric functions of the camera for He-Ne laser's light $\lambda = 0.63\mu$m.

As seen on Fig. 2, responses to quasimonochromatic light are linear both for main pixels (corresponded to He-Ne laser's light) and for accessorial pixels (green and blue respectively). Hence it is possible to obtain the linear HDR image from the oversaturated pixels of correlation signals. But firstly it is necessary to perform a calibration procedure for desired light source.

The calibration procedure is required for oversaturated image data reconstruction according to transmittance of colour filters for used light. To obtain data for calibration, the radiometric functions for each colour channel were used (as seen in Fig. 2).

2.2 Reconstruction of the linear HDR images

Taking into account linearity of camera's photo sensor response to light, we can use a linear approximation of the radiometric functions. Using curve fitting methods, it is possible to evaluate parameters of HDR radiometric functions. Hence radiometric function for each colour channel (main and accessorial) are approximated by linear dependency:

$$S_n = a_n \cdot E + b_n, \tag{1}$$

where S_n is the value of the registered signal, a_n and b_n are a slope and bias of line approximation for n-th colour channel, and E is exposure value. The Trust-Region approximation mehtod[20, 21] was used because of good accuracy of fitting. For our case, coefficients of line approximations are $a_1 = 83005, a_2 = 12698, a_3 = 584$ and $b_1 = -4.4, b_2 = -2.1, b_3 = -0.3$. Using approximation coefficients a_n and b_n, it is possible to correct oversaturated value of the main pixel S_1 by value of neighbour pixels:

$$S_1 = a_1 \cdot \frac{S_2 - b_2}{a_2} + b_1, \tag{2}$$

$$S_1 = a_1 \cdot \frac{S_3 - b_3}{a_3} + b_1 \tag{3}$$

where S_2 is the signal from the green pixel (if red pixel is oversaturated), and S_3 is the signal from the blue pixel (if red and green pixels are oversaturated).

Thus, to register the correlation signals of input scene with HDR in pattern recognition correlator, we have to prolong exposure time: main pixels will be partially oversaturated, but neighbour pixels will contain a distinguishable signal. In the next section, experimental setup for HDR correlation signals obtaining is presented.

3. EXPERIMENTAL SETUP OF THE CORRELATOR

We have applied SVE principle for described[19] diffraction correlator that is intended for pattern recognition in quasimonochromatic spatially incoherent light. The correlator's hardware consists of the digital photo camera with inserted kinoform as a correlation filter. We use Canon EOS 400D consumer grade digital camera but any technical or scientific-grade camera with Bayer colour filters array is suitable. The camera is equipped with CMOS sensor with 3888×2592 pixels, $5.7 \times 5.7\mu\text{m}^2$ pixel size and interchangeable lens 4.5/55.

A convolution of the input scene's image with the kinoform point spread function (PSF) is optically provided. Such convoluted image is the correlation of the input scene's image with the reference image. The reference image is the DOE's PSF rotated on 180°. Correlation signals may be viewed through the viewfinder or registered by a digital photo camera's sensor.

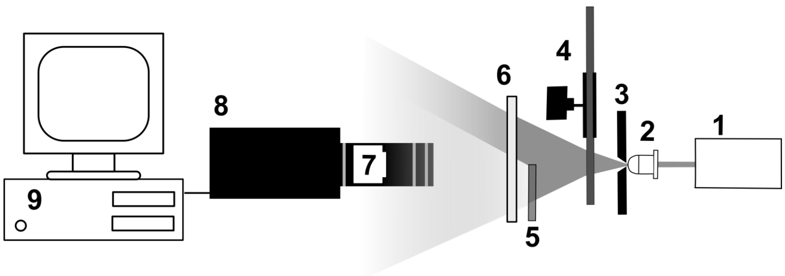

Figure 3. The scheme for optical correlator's testing: 1 - He-Ne laser, 2 - microscope objective, 3 - filtering pinhole, 4 - rotating ground glass, 5 - attenuating light filters, 6 - transparent input scene, 7 - kinoform, 8 - digital photo camera, 9 - computer.

The key diagram of the experimental setup for correlator's testing is shown in Fig. 3. Radiation of the He-Ne laser 1 is focused by the microscopic objective 2 on the filtering pinhole 3. The spatial coherency is destroyed by the rotating ground glass 4. Light passes through the attenuating light filter 5 that decreases light amplitude for part of the input scene 6. Correlator is formed by digital camera 7 with inserted kinoform 8. The camera's lens is focused on the input scene. Before shooting, correlation signals may be viewed through the viewfinder. The computer 9 allows to remotely control the digital camera 7 as well as to process provided images of correlation signals.

The input scene as a transparency and attenuating light filters are used for better control over HDR imagery. The test scene for correlation experiments (see Fig. 4) was made from the reference image recorded in the kinoform (a "snowman", see Fig. 5a). The scale of the scene's image was conformed to the size of the reference image that is recorded on the kinoform. The size of each object on a scene (see Fig. 4) was 15×22 mm. Each object of the input scene occupies an area in each colour channel of 100×150 pixels on the photo sensor. The whole image's size of the input scene registered by the camera sensor (see Fig. 4b) was 1944×1296 pixels in each colour channel.

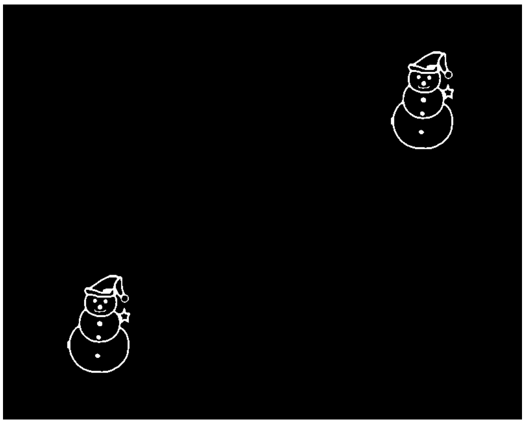

Figure 4. The test input scene for the correlator.

The reference image of “snowman” (see Fig. 5a) for input scene (see Fig. 4) was recorded on kinoform as a reference image. The real reference image reconstructed by kinoform is presented in Fig. 5b.

a) b)

Figure 5. The reference image for recognition: a) the ideal image, b) the real image reconstructed by the kinoform (the kinoform’s PSF rotated on 180°).

Correlation signals formed by the optical correlator were registered by the photo camera’s sensor. Obtained RAW-files were processed by DCRAW converter[22] that allows to receive linear unprocessed data from the commercial digital camera.[19] Processed RAW images were saved as 16-bit TIFF files for further measurements and analysis. For quantitative estimation of correlation signals’ quality as well as visual comparison, the averaging over 16 frames were carried out.

4. EXPERIMENTAL RESULTS

To provide experimental estimation of increasing accuracy and reliability of correlation signals when HDR imaging is used, two experiments were performed. In both experiments, images taken in normal DR mode contents only red pixels, and images in HDR mode contents both red and green pixels (oversaturated red pixels values are restored using data from accessorial green pixels). Results and discussion of the experiments are presented further.

4.1 Estimation of correlation signals linearity in HDR mode

In the first experiment, we used the input scene (see Fig. 4) in which DR of input objects’ radiance was within normal DR of the digital camera (DR of one colour channel). Normal DR for used camera was estimated as 58 dB (we assume[19] SNR=2 or greater, signals are from 4 DN up to 3300 DN). To achieve demanded DR of the input scene, bottom left object was covered by light filters.

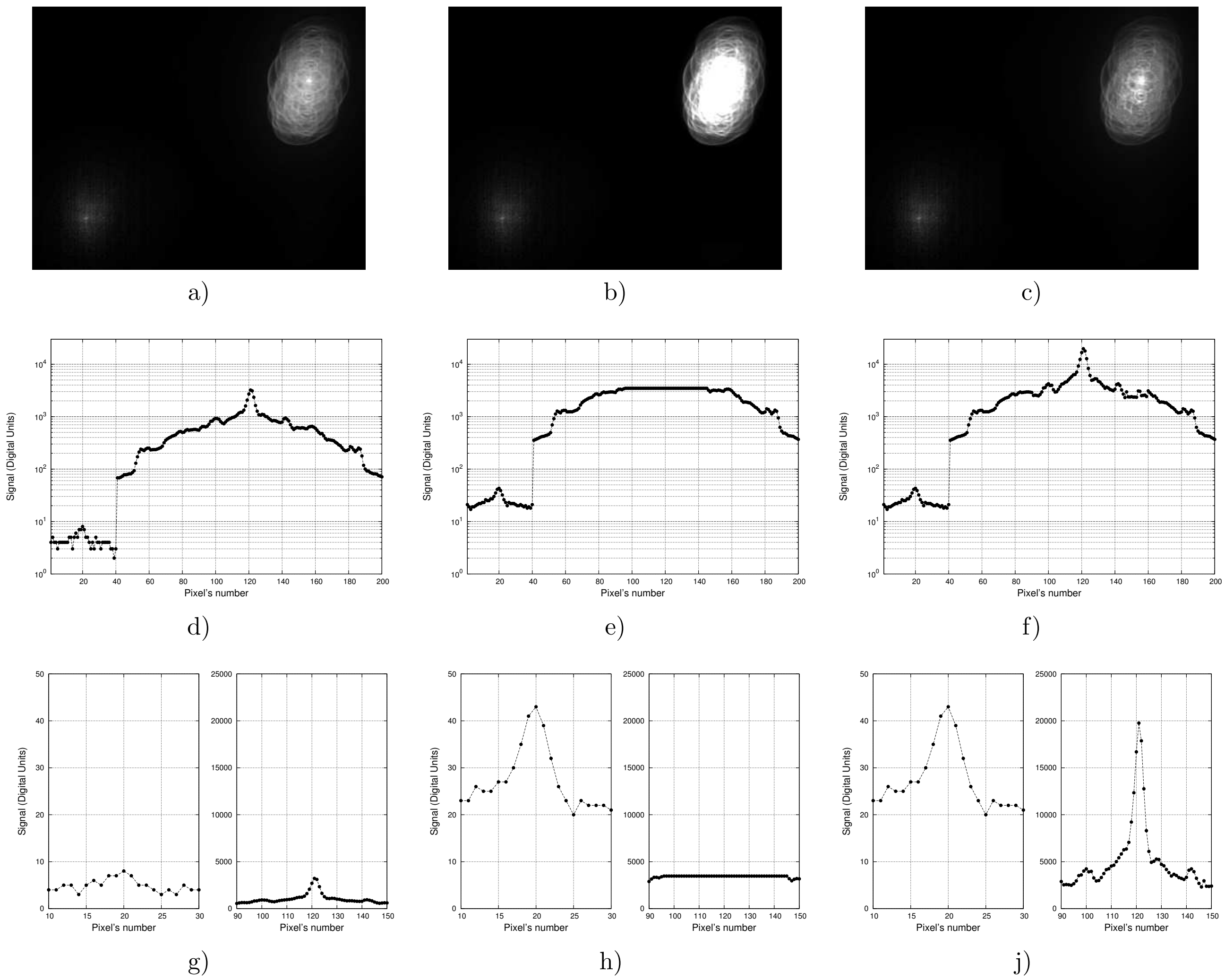

Figure 6. Experimental results for estimation of correlation signals linearity in HDR mode: image (a) and plots (d,g) of correlation signals taken in normal DR mode; image (b) and plots of correlation signals (e,h) taken from red pixels only in HDR mode; image (c) of correlation signals (f,j) reconstructed with accessorial green pixels in HDR mode.

Firstly, we have registered correlation signals in normal DR mode (only red channel without oversaturation). Because of both input objects have the same shape, DR of correlation signals is equal to DR of the input scene; hence such registration is possible. As a result, we have obtained the image with two correlation peaks (see[*] Fig. 6a. Corresponding plots are provided in Fig. 6d and Fig. 6g).

Secondly, we have registered correlation signals in HDR mode. For such purpose, we took a picture of the input scene with 5 times longer exposure time to oversaturate red pixels and received data from green pixels. In Fig. 6b and plots in Fig. 6e and Fig. 6h are presented the correlation signals registered in red channel only. As we see, the top right correlation signal is oversaturated. To reconstruct the HDR image of correlation signals, we used data from accessorial green pixels as described in Section 2. Reconstructed HDR signals are presented Fig. 6c, and plots are shown in Fig. 6f and Fig. 6j.

Values of correlation peaks for normal DR and HDR modes in this experiment are summarized in Table 2. There are also presented the background levels for the bottom left signals when the corresponded object in the

[*]The image of correlation plane was non-linearly processed for dynamic range compression for illustrative purposes and publishing. All images of correlation plane below were processed from experimental data in the same way.

input scene was covered with opaque screen for noise estimation.

Mode	**Top right signal**	**Bottom left signal**	**Background for bottom left signal**
Normal mode	2770 ± 320	7.4 ± 0.6	1.4 ± 0.6
HDR mode	16300 ± 2100	39.3 ± 2.2	7.1 ± 0.5

Table 2. Experimental data for correlation signals' registration in normal and HDR mode

From experimental data shown in Fig. 6d,g and Fig. 6f,j it is clear that both correlation signals can be identified and recognized in normal DR mode as well as in HDR mode. As above, for our digital camera noise can be regarded as 2 DN when registration is performed within the ambit 0 to 20 DN. We assume that minimal SNR must be SNR=2 because we use consumer-grade device. Thus normal DR in such case is $2270/4 = 693 \approx 57$ dB (see Table 2).

Although normal DR mode allows registration of both correlation signals, the use of HDR mode provides more reliability registration of weak bottom left signal. As seen in Fig. 6f and Fig. 6j, both correlation signals are well identifiable. Hence for HDR mode DR is $16300/4 = 4075 \approx 72$ dB according to Table 2.

To prove linearity of HDR reconstruction, we have compared correlation signals' ratio both for normal and HDR mode. For top right peak, enlargement of signal's value in HDR mode is 5.9 ± 0.7 times; for bottom left peak enlargement in HDR mode is 5.3 ± 0.5 times. Thus using the HDR mode for correlation signals' linear registration it is possible to improve accuracy of weak signals' recognition.

4.2 Registration of correlation signals with HDR

In the second experiment we used the input scene when DR of radiance of input objects was higher than normal DR of the used digital camera. To construct the HDR input scene, bottom left object was covered by additional light filters.

First, we have registered correlation signals in normal DR mode with top right peak within ambit of normal DR (see Fig. 7a, corresponding plots are provided in Fig. 7d and Fig. 7g). Then we have registered correlation signals in HDR mode by exposure prolongation. Correlation output plane registered in red channel only is presented in Fig. 7b and plots are provided in Fig. 7e and Fig. 7h. It can be seen that the top right correlation signal is oversaturated.

Reconstructed HDR image of correlation signals are presented Fig. 7c, and plots are shown in Fig. 7f and Fig. 7j. Values of correlation peaks and background levels for the bottom left signals for normal DR and HDR modes are given in Table 3.

In this experiment, the DR of the input scene and, consequently, the correlation signals values, exceeds the normal DR (see Fig. 7a). That is why bottom left peak in normal DR mode can not be detected and identified (see Fig. 7d,g). As it mentioned above, camera noise is 2 DN when signals are within the ambit 0 to 20 DN and minimal SNR must be 2 or greater. Top right peak can be easily identified, and for normal DR mode of registered correlation signal, dynamic range was estimated as $3280/4 = 820 \approx 58$ dB.

If the image of correlation signals taken in HDR mode (see Fig. 7c), weak signal (bottom left) can be identified, as seen in Fig. 7f and Fig. 7j. That is why the value of peak is now 12.7 DN (see Table 3) and camera noise remains 2 DN. In HDR mode the DR in can be estimated as $18600/4 = 4650 \approx 73$ dB. Hence the use of HDR registration mode allowed to increase dynamic range of correlation signal's registration on 15 dB in this experiment.

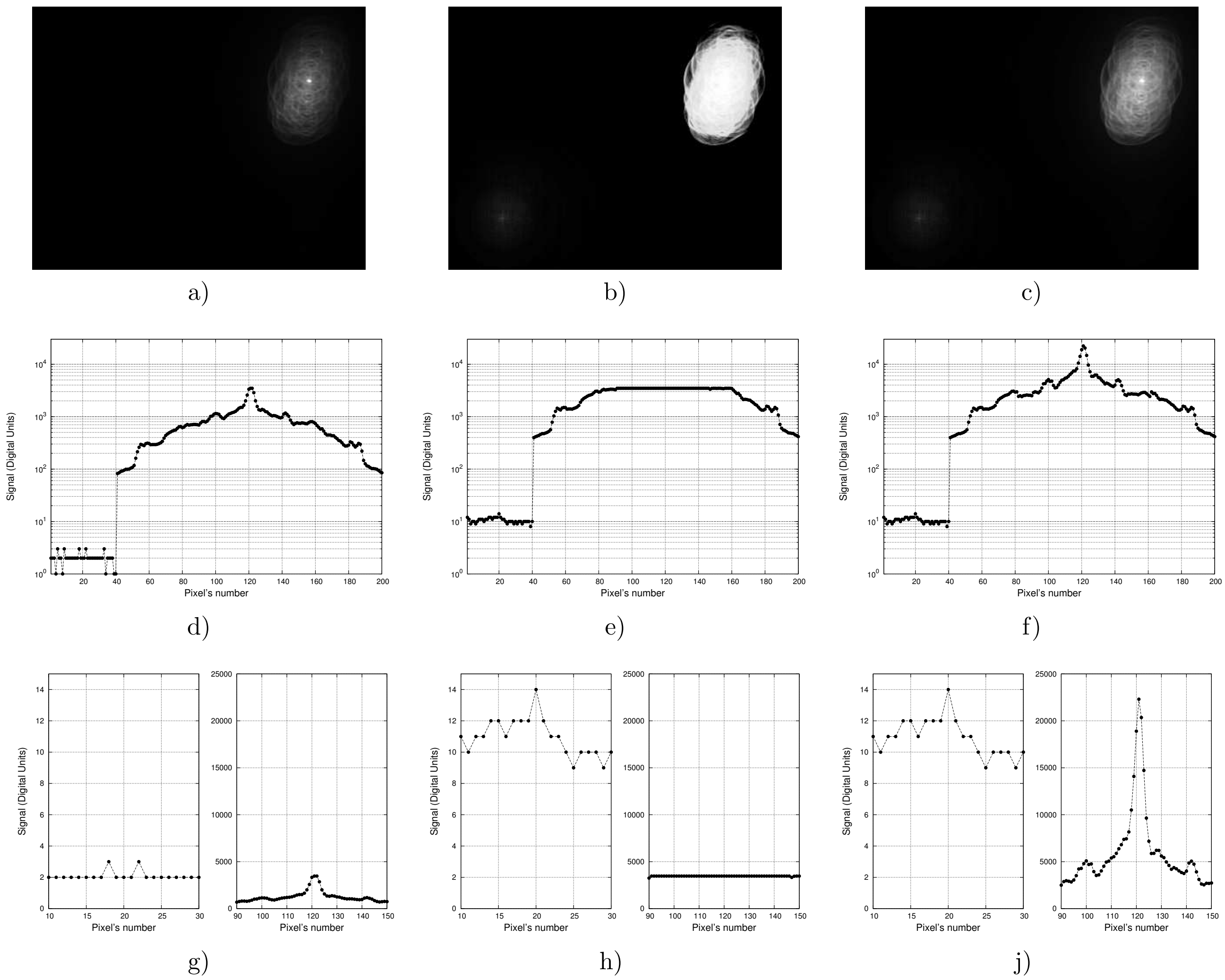

Figure 7. Experimental results for registration of correlation signals with HDR: image (a) and plots (d,g) of correlation signals taken in normal DR mode; image (b) and plots of correlation signals (e,h) taken from red pixels only in HDR mode; image (c) of correlation signals (f,j) reconstructed with accessorial green pixels in HDR mode.

Mode	**Top right signal**	**Bottom left signal**	**Background for bottom left signal**
Normal mode	3280 ± 270	2.3 ± 0.5	1.4 ± 0.6
HDR mode	18600 ± 2300	12.7 ± 0.7	7.1 ± 0.5

Table 3. Experimental data for registration of correlation signals with HDR

5. CONCLUSIONS

In this paper the application of the SVE principle for increasing accuracy and reliability of the optical-digital correlator for pattern recognition is described. Digital photo sensors with Bayer colour filter array was used for such purpose. In the quasimonochromatic light such filters array was considered as an array of attenuating filters. When main colour pixels are saturated, pixels under other colour filters are generally not. Extracting data from accessorial pixels provides the HDR image of correlation signals from the single frame.

Test experiments of correlation signal HDR registration were performed on the digital camera with Bayer colour filters array. From carried out experiments it follow that linearity of correlation signals is preserved in

HDR registration mode within the ambit of uncertainness of measures. Using HDR imaging principle such as SVE we obtained the increase DR of correlation signal's registration by 15 dB up to 73 dB that is considerable improvement over normal DR of the correlator.

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REFERENCES

[1] J. Huppertz, R. Hauschild, B. J. Hosticka, T. Kneip, S. Mïler, and M.Schwarz, "Fast CMOS imaging with high dynamic range," in [*Proc. Workshop Charge Coupled Devices & Advanced Image Sensors, Bruges, Belgium, pp. R7-1–R7-4.*], (June 1997).

[2] Michael Schanz, Christian Nitta, Arndt Bußmann, Bedrich J. Hosticka, and Reiner K. Wertheimer, "A high-dynamic-range CMOS image sensor for automotive applications," *IEEE Journal of Solid-State Circuits* **Vol. 35, No. 7**, 932–938 (July 2000).

[3] M. Schanz, W. Brockherde, R. Hauschild, B. J. Hosticka, and M.Schwarz, "Smart CMOS image sensor arrays," *IEEE Trans. Electron Devices* **44**, 1699–1705 (Oct. 1997).

[4] Yadid-Pecht, O. and Fossum, E., "Wide intrascene dynamic range CMOS APS using digital sampling," *IEEE Trans. Electron Devices* **44**, 1721–1723 (Oct. 1997).

[5] D. Yang, A. El Gamal, B. F. and Tian, H., "A 640 × 512 CMOS image sensor with ultrawide dynamic range floating-point pixel-level adc," *IEEE J. Solid-State Circuits* **34**, 1821–1834 (Dec. 1999).

[6] R. Hauschild, M. Hillebrand, B. J. Hosticka, J. Huppertz, T. Kneip, and M. Schwarz, "A cmos image sensor with local brighness adaption and high intrascene dynamic range," in [*Proc. Eur. Solid-State Circuit Conf. (ESSCIRC'98), The Hague, the Netherlands, pp. 308-311*], (Sept. 22-24, 1998).

[7] Mead, C., [*Analog VLSI implementation of neural systems*], ch. Adaptive Retina, 239–246. Kluwer (1989.).

[8] Moini, A., "Vision chips or seeing silicon," (1997).

[9] E. Funatsu et al., "An artificial retina chip with a 256 × 256 array of n-mos variable sensitivity photodetector cells," *Proc. SPIE. Machine Vision App., Arch., and Sys. Int. IV* **2597**, 283–291 (1995).

[10] Brajovic, V., "Brightness perception, dynamic range and noise: a unifying model for adaptive image sensors," *CVPR* **2(22)**, 189–196 (2004).

[11] S. K. Nayar and T. Mitsunaga, "High dynamic range imaging: Spatially varying pixel exposures," *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)* **Vol. 1**, pp.472–479 (June, 2000).

[12] Srinivasa G. Narasimhan and Shree K. Nayar, "Enhancing resolution along multiple imaging dimensions using assorted pixels," *IEEE Transactions on Pattern Analysis and Machine Intelligence* **vol. 27, No. 4**, pp. 518–530 (April 2005).

[13] S.K. Nayar and V. Branzoi., "Adaptive dynamic range imaging: Optical control of pixel exposures over space and time," *IEEE International Conference on Computer Vision* **Vol.2**, 1168–1175 (Oct, 2003).

[14] S. K. Nayar, V. B. and Boult, T., "Programmable imaging using a digital micromirror array," *CVPR.* **1**, 436–443 (2004).

[15] Hidetoshi Mannami, Ryusuke Sagawa, Yasuhiro Mukaigawa, Tomio Echigo, and Yasushi Yagi, "High dynamic range camera using reflective liquid crystal," in [*Proc. IEEE International Conference on Computer Vision Rio de Janeiro*], (October 14-20, 2007).

[16] Bayer, B. E., "U.S. Patent no. 3,971,065.," (July 1976).

[17] S.N. Starikov, N.N. Balan, V.G. Rodin, I.V. Solyakin, and E.A. Shapkarina, "Pattern recognition correlator based on digital photo camera," in [*Proc. SPIE, Optical Pattern Recognition XVII*], **6245**(1), 62450C (2006).

[18] Sergey N. Starikov, Nikita N. Balan, Mikhail V. Konnik, Vladislav G. Rodin, Ivan V. Solyakin, and Ekaterina A. Shapkarina, "Input scene restoration in pattern recognition correlator based on digital photo camera," in [*Proc. SPIE, Optical Pattern Recognition XVIII*], **6574:65740J**(1) (2007).

[19] Sergey N. Starikov and Mikhail V. Konnik, "Using commercial photo camera's raw-based images in optical-digital correlator for pattern recognition," in [*Proc. SPIE, Optical Pattern Recognition XIX*], **6977:69770R**(1) (2008).

[20] Moré, J.J. and D.C. Sorensen, "Computing a trust region step," *SIAM Journal on Scientific and Statistical Computing* **Vol. 3**, 553–572 (1983).

[21] R.H. Byrd, R. B. Schnabel, and Shultz G.A., "Approximate solution of the trust region problem by minimization over two-dimensional subspaces," *Mathematical Programming* **Vol. 40**, 247–263 (1988).

[22] Coffin, D., "Raw digital photo decoding," *http://www.cybercom.net/~dcoffin/dcraw* ((Referred 01.01.2009)).