Using commercial photo camera’s RAW-based images in optical-digital correlator for pattern recognition

Sergey N. Starikov, Mikhail V. Konnik
Moscow Engineering Physics Institute (State University), Russia, Moscow

ABSTRACT
In optical-digital correlators for pattern recognition, linear registration of correlation signals is significant for both of recognition reliability and possible input image restoration. This usually achieves with scientific graduated technical cameras, but most of commercial digital cameras now have an option of RAW data output. With appropriate software and parameters of processing, it is possible to get linearized image data from photo camera’s RAW file. Application of such photo cameras makes optical-digital systems cheaper, more flexible and brings along their wider propagation.

For linear registration of correlation signals, open-source Dave Coffins’s RAW converter DCRAW was used in this work. Data from photo camera were linearized by DCRAW converter in “totally RAW documental mode” with 16-bit output.

Experimental results of comparison between linearized and non-linearized correlation signals and digitally restored input scene images are presented. It is shown, that applied linearization allows to increase linear dynamic range for used Canon EOS 400D camera more that 3 times.

Keywords: diffraction correlator, imaging with wavefront coding, digital camera, pattern recognition, image restoration

1. INTRODUCTION
In present time, hybrid optical-digital imaging systems are being explored actively. Such systems can be used for aberrations correction\textsuperscript{1, 2} and in depth of filed improving\textsuperscript{3, 4} as well. However, for wider propagation of this kind of systems, using inexpensive photo cameras is important.\textsuperscript{2} Application of inexpensive consumer-grade photo cameras makes optical-digital systems cheaper, more flexible and brings along their wider spreading. As an example of optical-digital imaging systems, image correlator\textsuperscript{5} based on commercial photo camera for pattern recognition is considered.

Nowadays, photo sensors in conventional digital photo cameras achieved high pitch of excellence, with low photo response non-uniformity and fixed-pattern noise. With appropriate software, it is possible to exploit linear response to light of camera’s photo sensor and turn it into measurement device for optical-digital system. In this work, open source Dave Coffins’s RAW converter DCRAW\textsuperscript{6} was used to get unprocessed linear image data from ADC without gamma-correction, colour interpolation and other unwanted image postprocessing.

Commercial photo camera ability to output RAW data is significant for optical-digital correlators improvement. It can bring along recognition reliability and possibility of precise input image restoration with low-cost commercial imagers. Extended linear dynamic range provides better correlation peaks values and increased resolution of described optical-digital correlator.

Determination of camera’s linear dynamic range and linearization of correlation signals images with DCRAW converter are described. Examples of image’s linearization application in optical-digital correlator based on commercial photo camera are provided.

Further author information:
Mikhail V. Konnik: konnik@pico.mephi.ru,
Sergey N. Starikov: holo@pico.mephi.ru
2. IMAGE CORRELATOR FOR PATTERN RECOGNITION BASED ON COMMERCIAL PHOTO CAMERA

Diffraction image correlator based on commercial digital SLR photo camera\(^5\) is intended for preliminary recognition of the two-dimensional scenes during registration by the camera at quasimonochromatic spatially incoherent illumination. The principal optical scheme of the correlator is analogous to Lohmann's\(^7\) incoherent holographic correlator.

Correlator’s hardware consists of digital SLR camera with inserted kinoform, on which reference image is recorded. There were no modifications of photo camera had been made. Computer may be connected via camera interface to provide control of camera shooting, transmission, storage and post-processing of detected correlation signals.

Proposed correlator is intended to optically calculate correlation signals of plane 2D input scene and reference object (PSF of synthesized kinoform). Software linearization by DCRAW converter being applied to captured images is intended to produce linear signal, proportional to incident light. Such improvement allows to increase accuracy of measuring correlation signals. The scheme of the experimental setup is shown in Fig. 1.

**Figure 1.** The scheme of correlator’s experimental setup: 1 - He-Ne laser, 2 - attenuator, 3, 4 - mirrors, 5 - microscope objective, 6 - rotating ground glasses, 7 - spatial frequency filter, 8 - input scene, 9 - digital SLR photo camera, 10 - kinoform, 11 - computer.
The radiation of He-Ne laser 1 is attenuated by polariser 2 and redirected by mirrors 3 and 4 to the microscopic objective 5, which focuses beam on the filtering pinhole 7. Next, rotating ground glass 6 makes laser light spatially incoherent. Reflected light from scene 8 is registered by digital camera 9 with inserted kinoform 10. Hence, optical correlation of kinoform’s PSF (reference image) and input scene image is formed on camera photo sensor. The aim of computer 11 is to transmit and process RAW images from photo camera 10.

Using kinoform instead of amplitude or phase holograms, it is possible to achieve processing of whole area of the camera’s frame.\textsuperscript{8} As the amplitude and phase Fourier holograms have more than one diffraction order, and the reference image is formed in the lateral order, the acquisition of the correlation of whole field of frame with the reference image is impossible. If kinoforms are used, only axial diffraction order which contains the reference image is present. Thus, photo camera registers only signals of mutual correlation of input images with the reference image, which have been written on synthesized kinoform.

In our experiments, the commercial digital SLR photo camera Canon EOS 400D with following parameters was used:

- maximum resolution $3888 \times 2592$,
- sensor type - CMOS,
- pixel size - $5.7 \times 5.7$ µm (matrix size - $22.2 \times 14.8$ mm),
- sensitivity - ISO $100 \div 1600$,
- ADC - 12 bit,
- interchangeable lens - 2.8/50,
- interface - USB 2.0 for data storage and shooting control.

The characteristics of kinoform are: diameter – 5 mm, size of a recurring segment – 2 mm, pixel size – 4 µm.

### 3. COMMERCIAL PHOTO CAMERA MEASUREMENT POSSIBILITIES

To expand capabilities of optical-digital correlator based on commercial camera, several calibration steps for digital photo camera are required. Black level offset (BLO), fixed pattern noise (FPN) and photoresponse non-uniformity (PRNU) were measured. Furthermore, radiometric function was measured to estimate photo camera’s sensor linearity and saturation level. Then, flat field correction (FFC) was used to reduce FPN and PRNU influence on registered correlation signals.

For noise analysis, RAW images were processed in DCRAW converter using “document mode” without colour scaling (no colour, no interpolation, totally raw). Linearity of such conversion was established using saturation curve, out of which radiometric function was received.

#### 3.1. Camera’s photo sensor radiometric function

To obtain radiometric function of digital camera’s photo sensor, pictures of flat field scene in white light were taken. The lighting used was matrix of white power LEDs driven with DC stabilised current. Light was passed through two opal glasses to ensure of absence flat field non-uniformity, images were taken in a laboratory, where all unwanted lighting and reflections from the surrounding surfaces can be eliminated. For each exposure level, starting from 1/4000 to 10 seconds, images were taken for each exposure and averaged. ISO setting was the smallest available for Canon EOS 400D camera (ISO 100) used in this work.

All images were processed by DCRAW converter in “document mode”, which produces totally raw 12-bit image. A 64 by 64 pixel area from the centre of the image was used for the analysis for every colour-filter type (R, G and B, respectively). Mean and variance of pixels value were analysed, and results are presented in Fig.2.
Figure 2. Saturation of photo sensor: mean value of 64 by 64 square area versus relative exposure in a logarithmic scale (for smallest exposures), constant noise level of 256 digital numbers (DN) is removed.

During processing of obtained data, black level offset (BLO) of 256DN was disclosed and then removed. As evident from Fig.2, one can see that processed data are linear from near-noise level to saturation.

3.2. Noise characteristics of photo sensor

For estimation of photo sensor’s linear capabilities, scene with great contrast gradient was created, so that the whole range from completely dark to camera saturation level was covered. More than 60 pictures of this scene were taken, processed by DCRAW converter in “document mode” and averaged. After that, in MATLAB averaged values are picked up with step of 1DN, mean value and standard deviation were calculated. Results are presented in Fig.3.

Figure 3. Noise versus digital signal dependency for DCRAW converted data.
To estimate noise parameters, SNR was taken as 2DN, so minimal signal equals 4DN. Using data from radiometric function (Fig. 2, it is possible to find out relative exposure time, which conforms to minimal signal of 4DN. As seen from experimental results, presented in Fig. 2, relative exposure time, which corresponded to minimal signal, is approximately $1.3 \cdot 10^{-3}$ rel. units. End of linear dynamic range, therefore, can be estimated as 3066 DN with relative exposure time for this point is 1.0 rel. units. Consequently, linear dynamic range of camera’s photo sensor is 58 dB.

### 3.3. Camera calibration

To use maximum of photo sensors capabilities, several calibration steps were taken. More than 60 pictures of flat field were taken, averaged and correction coefficients were calculated. It was found out, that photo response non-uniformity of this camera is 4.5% for red-coated pixels, 5.2% for green-coated pixels and for blue-coated pixels PRNU is 5.3%. Averaged dark frame was subtracted, so FPN was reduced greatly. All images were processed in “document mode” of DCRAW and converted to 12-bit output, which is stored in 16-bit TIFF format. Analysis was carried out in MATLAB. Thus, with FFC calibration and dark noise reduction, SLR camera was linearized and prepared to correlation signal registration.

### 4. EXPERIMENTAL RESULTS

Test scene for correlation experiments was made from PSF image and other binary images, which partly looks like desirable reference image. For example, hokeyist have the same body as bicyclist, Olympic rings are the same diameter as bicyclist’s wheels.

To print test scene properly, additional measures were carried out. It is necessary to find out spatial resolution of image on current distance form photo camera to object plane and focal length of objective. For such purpose, laser beam had been displaced twice to known distance in object plane, and two images were taken by camera. Then, distance between two dots on two images was calculated and converted to spatial resolution of correlation’s input scene.

Correlator’s input scene with multiple objects is illustrated in Fig. 4. The size of each object on a paper, shown in Fig. 4a, is about $35 \times 32$ mm, and on a photo sensor (Fig. 4b) it occupies area $320 \times 270$ pixels.

![Figure 4. Correlation test scene for object recognition: a) printed on a paper, b) registered by photo sensor.](image)

Reference image of bicyclist recorded in the kinoform is shown on Fig. 5a, and real PSF of kinoform, obtained by point light source, is shown on Fig. 5b. The size of PSF of the kinoform (the reference image) on a camera’s photo sensor was of $5.6 \times 4.8$ mm (160×140 pixels) at wavelength of 0.63 µm and the distance from kinoform to photo sensor was equal to 30 mm. The intensity of zero-order peak exceeds intensity of other points of kinoform’s response in 5.9 times for DCRAW converted images. The reason why there is bright spot at the centre of PSF is inaccurate manufacture of kinoform.
To determine maximum correlation signals, input scene was placed on motorized rotator and correlation peaks signal value were measured by step 1-2°. Because of use red laser light and conventional Bayer-covered photo sensor, correlation peak may leave between two pixels. Such situation is illustrated on Fig. 6, were local minimum in 90° angle is observed.

Described above test scene was positioned before the photo camera and illuminated by spatially incoherent radiation of the He-Ne laser, correlation signals were registered by digital photo camera. There are two sets of images: first one is taken with longer exposure time to occupy part of linear dynamic range of photo camera, and second set taken for processing by conventional converter (as described in our previous report\cite{9}).

Numerical correlation of photographed input scene and averaged PSF of reference object (Fig. 7a) can be compared with correlation signals, registered by photo camera sensor(Fig. 7b). Images were scaled down to 256 grey levels for publishing. A local bright spots indicates positions of reference object on a test scene. As evident from Fig. 7c, correlation signal, taken for conventional Canon converter, are comparably weak and hardly be used without special postprocessing. On the other hand, DCRAW converted correlation signals are sharp and easily distinguishable from background. The sharpness of correlation signals, obtained after DCRAW conversion, may be illustrated in Fig. 7d.

Figure 5. Reference image for test objects recognition: a) recorded on kinoform, b) obtained PSF by point light source.

Figure 6. Correlation signal peak value versus angle of scene rotation, images are processed by median filter by 2 × 2 area.
4.1. Experimental results discussion

Firstly, obtained correlation signals images were converted by DCRAW and Canon conventional converter to produce TIFF images. Then images were thinned out, only red pixels which corresponds to laser wave length were taken, so new image is as twice as small than original. For analysis there were taken areas $200 \times 200$ pixels containing not only correlation signal peak, but also background. For correlation signals to be numerically measured, signal-to-background and true peak to false peaks relations were estimated.

For conventional converter shipped with digital camera, signal-to-background value for peaks were estimated as 1.23 for top left, 1.19 for top right and 1.15 for bottom right respectively. This results are consistent with previous work, were such ratio for correlation peaks was about 1.20 without special postprocessing. Next, true peak to false peaks ratio were measured, which was 0.08 for top left, 0.38 for top right and 1.07 for bottom right respectively.

Data linearized by DCRAW exhibits greater results: signal-to-background value for peaks can be estimated as 1.95 for top left, 2.03 for top right and 2.02 for bottom right respectively. This can be even more with greater exposure time, but exposure time can be more than 10 minutes with significant influence of dark noise. True peak to false peaks ratio for top left was 0.24, for top right 0.30 and for bottom right 1.19. This is comparable with conventional converter results, but it’s noteworthy that exposure time was 2 times greater for DCRAW, so dark noise influence is significant.

Figure 7. Correlation signal peaks: a) numerical experiment, b) registered correlation signals for DCRAW converter, c) correlation signals processed by conventional converter, d) intensity distribution of correlation signals processed by DCRAW.
It’s clearly that linearized by DCRAW correlation data is more suitable for correlation analysis of peaks.

4.2. Numerical experiments comparison

Obtained experimental result were compared with numerical experiments, were photographed input scene image was correlated with averaged PSF of real kinoform. All calculations were produced with double precision in MATLAB and analysed same as experimental results. Signal-to-background value for numerically calculated correlation were 2.76 for top left peak, 2.82 for top right and 3.00 for bottom right respectively. Results obtained for DCRAW data are only 30% worse than numerical experiment results. This is illustrated in Fig. 8.

![Figure 8. Comparison of correlation intensity distribution: a) numerical calculations, b) linearized experimental data.](image)

True peak to false peaks ratio were measured as well, which was 1.54 for top left, 1.64 for top right and 1.45 for bottom right respectively. Experimental results are consistent with numerical in this comparison only for last peak; the reason of this is definitely illumination non uniformity and parasitic scene reflections. But in overall on can say that experimental setup of RAW-based correlator works in consistency with theoretical predictions.

5. CONCLUSIONS

In this works, optical-digital correlator based on commercial photo camera for pattern recognition was described. It is shown that using special programs like DCRAW converter, it is possible to significantly improve capabilities of such hybrid imaging systems.

Considering conventional photo cameras as measurement devices, it is advisable to say that even with high black level offset (for Canon EOS 400D, it is 256DN) and saturation level 3726 DN (instead of 4095 for ADC limit), such photo cameras can more or less successfully be used in optical experiment. Obtained results, such as optical dynamic range equals 58dB for considered camera, allows to say that commercial photo cameras with special RAW converters can be used instead of technical cameras in many applications.

From carried out experiments it’s evident that commercial photo camera can be used as technical camera and consequently increase of optical-digital imaging system capabilities. Comparing results, obtained for images taken for conventional RAW converter, correlation peak signals taken for DCRAW converter are 2 times greater than conventional ones. This can be even more with greater exposure time, but exposure time can be more than 10 minutes with significant influence of dark noise. This is also true peak for false peak measurements - this ratio for DCRAW images is same or better than conventional converted signals.

It is notable to say that obtained results (DCRAW converted) are approximately 30% worse than numerical experiment results. Better results can be achieved using more powerful laser for shorted exposures.
ACKNOWLEDGMENTS
This work was partially supported by the Ministry of education and science of Russian Federation (Program “The development of the scientific potential of High School”, project RNP.2.1.2.5657).

REFERENCES