Digital holography with self-imaging by a two-step phase element

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Abstract—The paper presents a method of recording digital holograms in a single shot by illuminating the photosensitive matrix with an especially structured reference beam formed by the Talbot effect from a periodical binary-phase diffractive element. This beam projects a 2D array of rectangular areas with different phase shifts. By interfering this beam with an object beam we achieve two phase shifted holograms which are then numerically reconstructed with a classical phase-shifting technique. The main advantage over a 4-step phase element is the easiness of fabrication and its alignment against the photosensitive matrix of a digital camera.

In digital holography the object information is recorded during the interference of an object beam and a reference beam. In such a way one obtains an interferogram, which can be then numerically reconstructed by simply propagating the light field back on to the object plane. Unfortunately the viewing is obstructed by non-diffracted light and a conjugated inverted image. As a solution one can use off-axis object placement, which separates the zeroth diffractive order (DC term) from the viewing zone [1]. On the other hand in such a case the interference fringes may become too dense to be recorded on available CMOS/CCD matrices. Therefore a technique of phase-shifting has become widely applied for the cancellation of a conjugated image and a DC term [2-4]. In order to perform this technique one must have four interferograms, each recorded with a phase set to a particular value. Normally it requires either four exposures or a highly complicated optical setup to obtain the necessary data. Previously we reported the technique of one-shot acquisition of four interferograms by the use of a structured reference beam formed by a Self-Imaging Diffractive Optical Element (called SIDOE) [5, 6]. A periodical structure is self imaged directly on a CMOS matrix as a consequence of a self-imaging, yielding a periodical distribution of rectangular areas with phase states: 0, $\pi/2$, π and $3\pi/2$. Hence after a single exposure we are able to recover four interferograms and use it for the phase-shifting numerical reconstruction scheme utilizing self-imaging with the compression ratio equal to 4.

In this contribution we present a simpler method, in which the SIDOE is a chessboard-like structure and has only two phase steps: 0 and 1π. The phase transmittance of the structure is shown in Fig. 1, also showing the optical setup used for the recording. The setup is basically a Mach-Zehnder interferometer with a SIDOE structure placed in one arm and the 2D object placed in the other. The SIDOE in Fig. 1 introduces a phase shift of 1π in white areas and 0π in black areas. Obviously when such a structure is to be fabricated, the relief depth must be matched to the wavelength used for illumination of the interferometer. In the *CCD* plane a camera is placed, which acquires a single image of interference fringes.

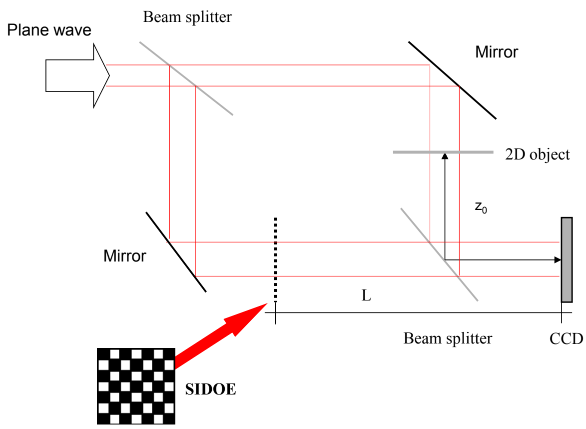

Fig. 1. The scheme of the recording setup.

The reconstruction process is analogical to the one described in [5, 6]. As a consequence of having only two phase levels the reconstruction algorithm consists of two components that are calculated separately. The calculation includes multiplying the recorded intensity distribution by an appropriate Ronchi grating in order to separate the components from each other. Then such distribution is propagated back at the ¼ of the self-imaging distance L in order to spread the light field

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distribution onto the whole hologram area (this step is an alternative to interpolation and approximation methods [9, 10]). After this propagation, the phase distribution introduced by the Ronchi grating has to be cancelled by a multiplication by a pre-calculated complex conjugated phase distribution. At this point the two components form intensity distributions which are multiplied by the corresponding reference beams and added altogether to give the final hologram, which corresponds to the phase-shifting method itself. As a final step the light field of the hologram is propagated back onto the original object plane, giving the final reconstructed 2D image. The propagation method was a modified convolution method [7, 8].

The described method provides the removal of a DC term in the reconstructed image. However, the conjugated image cannot be cancelled by using the two phase-step method. Nevertheless, the light forming the conjugated image is divergent and as can be seen in Fig. 2 it does not disturb the reconstructed image.

The numerical simulations were carried out for the binary object containing a white "A" letter on a black background. The object was imported as an intensity distribution onto a 8192x8192 points calculation array. The sampling was 3.45µm and the wavelength was 532nm. Those parameters were chosen as best matching the pixel size and sensitivity peak of our camera, which will be used for further experimental evaluation of our method in the follow-up papers. The results of the numerical simulations are shown in Fig. 2. The distance from the object to the CCD matrix - z_0 was 200mm and the size of the elementary cell of the SIDOE - *d* was: 13.8µm; 27.6µm; 69µm; 138µm; 248.4µm and 345µm.

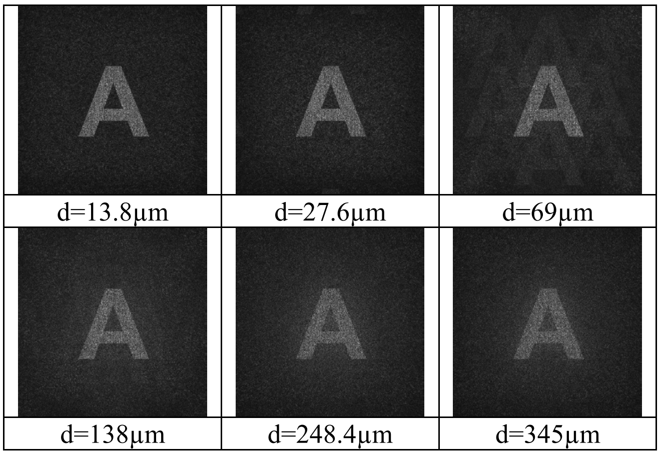

Fig. 2. The results of the numerical reconstructions of the "A" letter for different *d* values. Only a central region is shown for clarity.

The error introduced by our method is marginal, which is shown in Fig. 3 and Fig. 4(a). Figure 4(a) contains the maps of a RMS distance between the obtained images and the input bitmap. In order to present the nature of the error, the shown RMS distance maps were processed with a gamma correction and presented in Fig. 4(b). It can be seen that the mentioned errors consist of a speckle pattern, residual background envelope and the presence of the ghost images. The transversal separation of ghost images from the central image is determined by the period of SIDOE structure and the Ronchi gratings (*d*). Therefore the best image quality is obtained for small values of *d*, where the ghost images are highly separated and fall outside the viewing zone, or outside the calculation array. The speckle pattern is inevitable with diffuse objects under a coherent illumination. The residual background envelope is caused by the imperfections of a self-imaging effect at boundary regions due to the finite size of a SIDOE element.

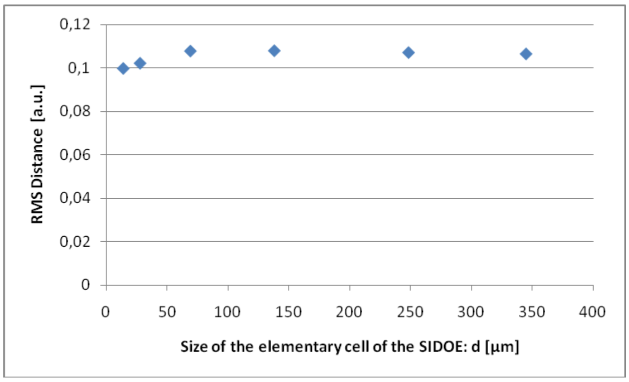

Fig. 3. The graph of RMS distance values between the obtained images and the input image for different *d* values.

From the results presented here a conclusion can be drawn that the proposed method works well for a significant size range of elementary cells of the self-imaging element (*d*). Therefore the used diffractive structure does not require sophisticated fabrication techniques (i.e. multi-step phase) to obtain satisfactory results for practical imaging distances. The only strict constraint of the fabrication is that the size *d* must be exactly a multiple of the pixel size of a CMOS camera. Otherwise, a Moiré pattern will appear, thus the quality of collected data will be very poor, resulting in a serious decrease of image quality. A similar, but less visible negative effect would appear in the case of misalignment of the mutual position of SIDOE and a CMOS camera. Therefore we consider the two mentioned constraints very crucial for the overall performance of any device based on the proposed method of digital holography.

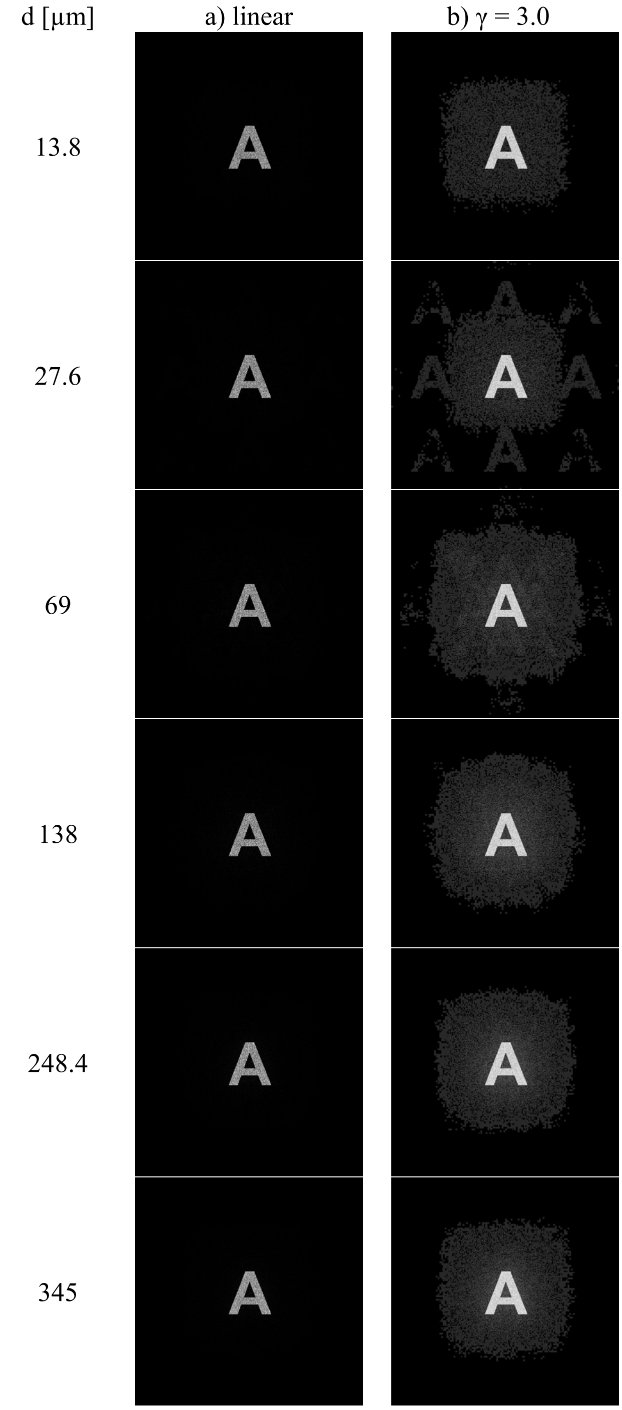

Fig. 4. The RMS distance maps between the obtained images and the input image for different size of the elementary cell of the SIDOE: a) linear; b) with gamma correction equal to 3.0 applied to underline the error in the obtained images.

In general, the quality of the obtained reconstructed images is satisfactory from the practical point of view. The results are even more promising when one takes into account the fact that the recording setup is very simple and compact, the SIDOE structure is very easy in production and only one exposure is needed for gathering all data. As a consequence of the simplicity of the optical setup and a single-shot interferogram collection, an application in ultra compact optical measuring systems has been proposed.

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