Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Optik 116 (2005) 44–48
Optik Optics
www.elsevier.de/ijleo

Reduction of speckle noise in digital holography by using digital image processing

Jorge Garcia-Sucerquia[a,b,*], Jorge Alexis Herrera Ramírez[a], Daniel Velásquez Prieto[c]

[a]Physics School, Universidad Nacional de Colombia Sede Medellín, A.A. 3840, Medellín, Colombia
[b]Department of Physics, Dalhousie University, Halifax, NS, Canada B3H 3J5
[c]Basic Sciences Department, Universidad EAFIT, A.A. 3300, Medellín, Colombia

Received 13 August 2004; accepted 3 December 2004

Abstract

A fundamental problem in optical and digital holography is the presence of speckle noise in the reconstruction process. Many approaches have been carried out in order to overcome such a problem ranging from modifying the spatial coherence of the illumination (optical techniques) to image processing techniques (digital techniques). This work shows the merged use of digital image processing techniques in order to reduce the speckle noise in digital reconstruction of optically recorded Fresnel's holograms. The proposed filtering techniques are illustrated with experimental results.

Keywords: Digital holography; Speckle free reconstruction; Fresnel's holograms

1. Introduction

The swift development of digital computers and CCD cameras has made possible the implementation of Goodman's idea of doing the register and reconstruction of the holograms by digital means [1]. This development has propelled an important field of the contemporaneous optics called the digital optics and particularly the digital holography as it was conceived by Goodman many years ago.

Naturally, the digital holography has inherited from its optical counterpart's desirable and undesirable characteristics. Between the desirable inherited characteristics could be counted its capability of doing reconstruction of wavefronts, the applicability of the typical setups in-line and off-line, etc. However, some undesirable characteristics, as for instance the zero diffraction order and the speckle noise present in the reconstructed images, were also inherited.

Great effort has been focused on getting rid of the existence of the zero diffraction order and speckle noise in the reconstructed images in both fields of the holography [2–8]. However, these two drawbacks have more devastating effects in digital than in optical holography; so it is essentially due to the fact that the systems of recording and visualization used in the digital approach are extremely sensitive to them or inclusively increase them. As a result, a lot of effort has been invested in the digital holography to overcome these drawbacks and by taking advantage of the great versatility of the digital systems, important results in overcoming these unpleasant characteristics have been achieved.

*Corresponding author.
E-mail addresses: jigarcia@unalmed.edu.co (J. Garcia-Sucerquia), develas@eafit.edu.co (D.V. Prieto).

0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2004.12.004

In this work we deal with the problem of reduction of the speckle noise in digitally recorded and reconstructed Fresnel's holograms. Essentially, we attempt this problem from a digital image processing standpoint by applying well-known filtering kernels as well some other digital approaches, here presented for the first time for our knowledge. Initially we will introduce some basic ideas about the digital holography and thereafter we will develop and apply the procedures addressed to reach the goal of reducing the speckle noise in the digital holography reconstruction.

2. The digital holography framework

Conceptually, the digital holography can be sketched by two diffraction processes, one from the object plane to the hologram plane (CCD plane) and the other from the hologram plane to the image one, according to what is shown in Fig. 1.

The object located at the plane $z = 0$ is coherently illuminated and the optical field scattered by it interferes with the plane reference wave in such a way that the interference pattern is recorded in a CCD camera located at a distance $z = d$. At this plane, only the intensity $I(x_h, y_h)$ impinging upon the CCD will be registered. The optical field at the image plane located at a distance d from the CCD camera is calculated by means of calculating the diffraction process of the plane reference wave when it illuminates the transmittance represented by $I(x_h, y_h)$. This diffraction process is described by the Kirchhoff–Fresnel diffraction integral, which due to the geometrical parameters involved in the setup fits the requirements to consider the problem in the Fresnel–Fraunhofer approximation; so it can be written as

$$E(x_i, y_i, z) = \frac{\mathrm{i}E_0}{\lambda z}\,\mathrm{e}^{-\mathrm{i}\pi/\lambda z(x_i^2+y_i^2)} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x_h, y_h)\, \mathrm{e}^{-\mathrm{i}\pi/\lambda z(x_h^2+y_h^2)}\,\mathrm{e}^{\mathrm{i}2\pi/\lambda z(x_h x_i + y_h y_i)}\,\mathrm{d}x_h\,\mathrm{d}y_h \tag{1}$$

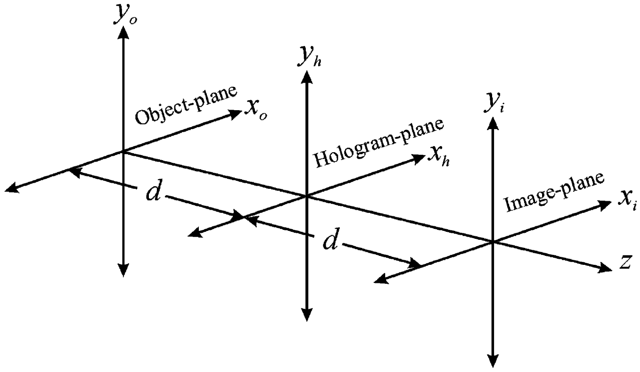

Fig. 1. Conceptual setup of the digital holographic process.

with E_0 the amplitude of the plane reference wave, λ the wavelength of the optical field, z the distance between the hologram plane and image plane. The coordinate systems are represented in Fig. 1.

The problem of determining $E(x_i, y_i, z)$ from Eq. (1) with a digital processor has been widely treated in the literature [8]. It has been shown that with a finite size of hologram $I(x_h, y_h)$ the image reconstructed from it is characterized by readings of the optical field $E(m, n, z)$, which are linked to the hologram readings $I(k, l)$ by a discrete Fresnel transformation:

$$E(m, n, z) = \frac{\mathrm{i}E_0}{\lambda z}\,\mathrm{e}^{-\mathrm{i}\pi/\lambda z\left(m^2/N_x^2\,\Delta x^2 + n^2/N_y^2\,\Delta y^2\right)} \sum_{k=0}^{N_x-1}\sum_{l=0}^{N_y-1} I(k, l)\,\mathrm{e}^{-\mathrm{i}\pi/\lambda z(k^2\,\Delta x^2 + l^2\,\Delta y^2)}\,\mathrm{e}^{\mathrm{i}2\pi\left(km/N_x + ln/N_y\right)}. \tag{2}$$

In Eq. (2) we have assumed the hologram registered by a rectangular CCD having $N_x \times N_y$ pixels with pixel dimensions $\Delta x_h \times \Delta y_h$, $m = 0, 1, \ldots N_x - 1$ and $n = 0, 1, \ldots N_y - 1$ and the image pixel dimensions $\Delta x_i \times \Delta y_i$ are related to the pixel CCD dimensions $\Delta x_h \times \Delta y_h$ by $\Delta x_i = \lambda z / N_x \Delta x_h$ and $\Delta y_i = \lambda z / N_y \Delta y_h$ [8].

This equation is the discrete Fourier transformation of the function $I(k, l)\,\mathrm{e}^{-(\mathrm{i}\pi/\lambda z)(k^2\,\Delta x^2 + l^2\,\Delta y^2)}$; so for its calculation it is just necessary to multiply the hologram readings $I(k, l)$ by the chirp function $\mathrm{e}^{-(\mathrm{i}\pi/\lambda z)(k^2\,\Delta x^2 + l^2\,\Delta y^2)}$ and make use of the Fast Fourier Transformer (FFT) algorithm.

From Eq. (2) it is possible to evaluate the intensity and the phase of the optical field by

$$I(m, n, z) = |E(m, n, z)|^2 = \Re e[E(m, n, z)]^2 + \Im m[E(m, n, z)]^2 \tag{3}$$

and

$$\phi(m, n, z) = \arctan\left(\frac{\Im m[E(m, n, z)]}{\Re e[E(m, n, z)]}\right), \tag{4}$$

respectively. In these equations $\Re e$ and $\Im m$ stand for the real and imaginary part of complex optical field in that order.

It is apparent from the former equations that the digital holography allows us to accomplish the calculation of the intensity and the phase of reconstructed holograms for a particular distance z from the hologram plane. This fact has made possible the development of new microscopic and imaging techniques of wide use in biological sciences [9]. However, in optical holography this is not possible, so that, added to the other characteristics of digital holography, this subject becomes a very active field of research in optics.

3. Speckle reduction techniques in digital holography

The regular appearance of the digitally recorded and reconstructed holograms is shown in Fig. 2. There, a well-defined real image of the scene is shown, where the elimination of the zero diffraction order had been reached successfully, but a strong speckle noise over the image is also apparent. The presence of that speckle noise arises from the coherent recording [7], as in the optical holography, and from finite size of the sampling devices, i.e., the finite size of the pixels in the CCD camera [3,8]. In this way, its reduction can be attempted by means of reducing it from the recording process itself, by improving the digital recording devices, and/or by means of digital processing of the reconstructed image. In this work we will present different methods of reducing the speckle noise, supported by digital processing of the reconstructed hologram itself.

The first approach to clear the speckle noise is based on the idea of reducing the size of the reconstructed hologram as it is sketched in Fig. 3 [5]. From the original reconstructed hologram $I(m,n)$ a shortened version of it $I'(m',n')$ is generated. Each pixel of $I'(m',n')$ is the result of averaging square regions of side p in the image $I(m,n)$. Thus, if the pixel number of the image $I(m,n)$ is $N_x \times N_y$, the pixel number of the reduced image $I'(m',n')$ will be $\mathrm{int}(N_x/p) \times \mathrm{int}(N_y/p)$, with int standing for the integer part and p the reduction order.

This reduction can be understood as a modified and localized low-pass filtering that generates a smaller output image in which all its entries are smoothed versions of corresponding square regions of size p, i.e., each pixel of $I'(m',n')$ is obtained from the weighted average of the local neighborhood of the pixel in the

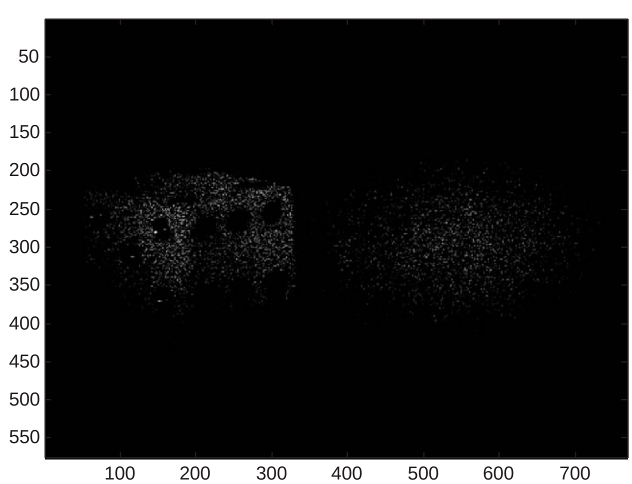

Fig. 2. Digitally reconstructed hologram with effective zero diffraction order reduction.

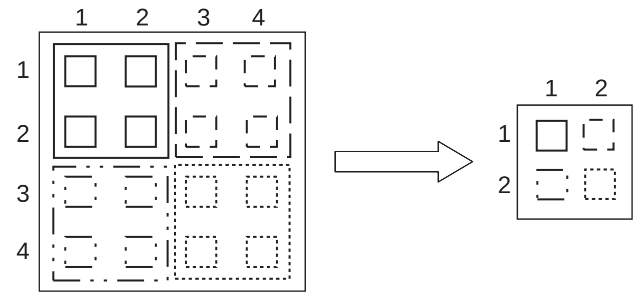

Fig. 3. Illustration of the technique of reducing the reconstructed hologram size.

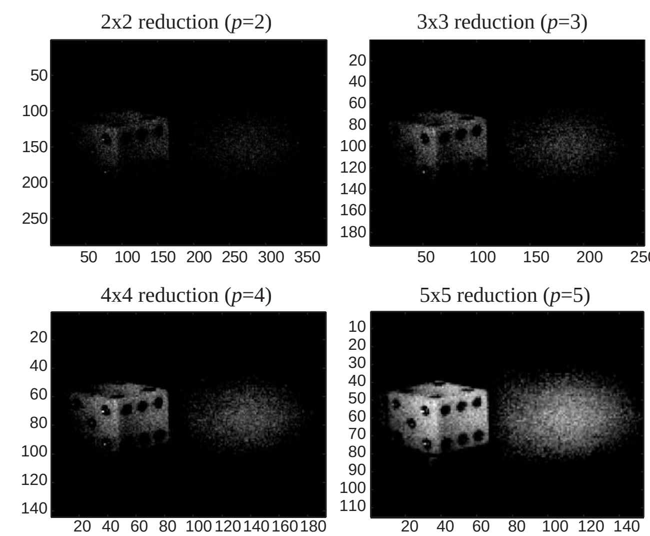

Fig. 4. Speckle noise reduction by the technique of resizing the original image shown in Fig. 2.

input $I(m,n)$:

$$I'(m',n') = \frac{1}{p^2}\sum_{i=1}^{p}\sum_{j=1}^{p} I[(p[m'-1]+i),(p[n'-1]+j)],$$
$$p = 1,\ 2,\ 3,\ 4\ \ldots,$$
$$m' = 1,\ 2,\ \ldots\mathrm{int}\left(\frac{N_x}{p}\right); \quad n' = 1,\ 2,\ \ldots\mathrm{int}\left(\frac{N_y}{p}\right) \tag{5}$$

with int the integer part, N_x, N_y the pixel number of the CCD camera along each coordinate axis and p the reduction order.

The results obtained by applying the above technique to the image shown in Fig. 2 are illustrated in Fig. 4. The reduction applied to each one as well as the effectiveness of this idea is apparent from the scales on the images. The bigger the p reduction order, the smaller the speckle noise; for $p = 5$, for instance, the detriment of the image itself does not compensate the decrease in speckle noise reached. This means that the selection of the right reduction order p will depend on the specific application, the size of the original image and the speckle noise initially present in the reconstructed image. This reasoning leads us to state that the election of the best reduction order p for a particular experiment will be addressed by the rule of thumb supported on the rigorous knowledge of the needs of the particular application.

An alternative approach to the reduction of the speckle noise in reconstructed holograms is carried out by using a conventional median kernel filter for image processing [5,10–12]. By taking advantage of its fundamental characteristic of eliminating the impulsive noise while preserving spatial resolution, we applied this convolution filter to the image shown in Fig. 2. Here, we have recorded the speckle noise similar to a binary or impulsive noise, so that it is possible to apply this type of filter to the reconstructed holograms and the results are shown in Fig. 5.

Apparently, the best compromise between the preservation of spatial frequencies and the speckle noise reduction in our input image (Fig. 2) is reached by means of 7×7 median filtering. For the others cases, either the speckle noise is still so important or the blurring up of the image begins to be very noticeable. On recording that it is a digital image processing technique, it is very difficult to state which one is the best median filter order to be applied to digital holography. This decision must be taken by the user; here we just show the median filtering approach as a feasible method to reduce the speckle noise in digital holography.

An attractive idea of reducing the speckle noise in digitally reconstructed hologram, can be constructed by merging the former approaches, i.e., by applying simultaneously the matrix reduction and the median filtering. Additionally, by considering the non-linearity of the median filter, also will be important the sequence in which these two techniques are applied over the input image. The results of applying such merged approach to Fig. 2 are shown in Fig. 6.

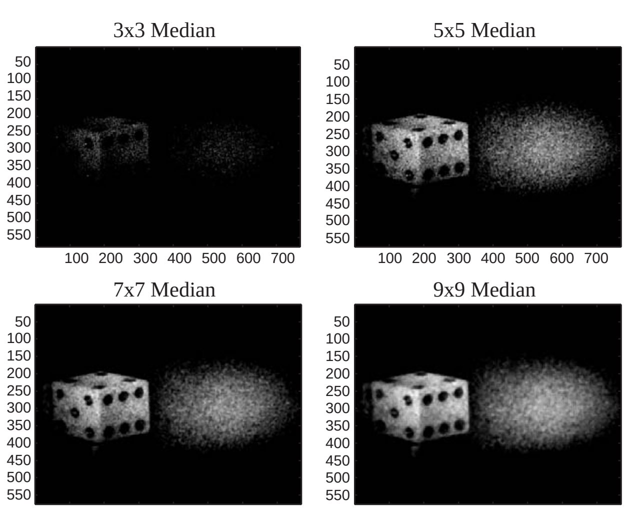

Fig. 5. Speckle noise reduction by the technique median filtering applied to the original image shown in Fig. 2.

From images shown above, it is possible to state that better results in speckle noise reduction are achieved by merging the two formerly treated techniques than by their application independently. It is apparent also from these images that the results obtained are strongly dependent on the application sequence, as it was expected. However, it is difficult to establish a fully proved recipe that guarantees success in the speckle noise reduction process; this task, in concordance with the ideas of digital image processing, is addressed by the rule of thumb.

In spite of the impossibility of establishing a well-determined recipe to reduce the speckle noise, it is noticeable that all the above procedures have been possible to carry out due to the digital manipulation of the holographic process. This situation shows the huge versatility that the digital component has added to the optical world and that has propelled the field of the digital optics.

4. Conclusion

The existence of the speckle noise is an important drawback of the digital holography for its use in many optical applications as for instance 3-D object recognition, microstructure testing, digital holographic microscopy, etc. because it reduces the performance of the system. With the idea of overcoming this drawback and by taking advantage of the digital component of digital holography, in this work we have presented different digital processing techniques focused on the idea of reducing the speckle noise of digitally reconstructed holograms, not just for displaying purposes but also to make this digital approach to the holography more accurate and versatile.

All the approaches shown in this work are supported by the idea of performing digital image processing over the reconstructed image, and the results, if good, are acceptable; however, they are not the best ones. Alternative approximations to the problem of removing the speckle noise in digital holography must be addressed, but should be more oriented to reducing the speckle noise from digital recording and reconstruction process, for instance by modifying the coherence of the illumination in the recording process and by using CCD cameras with more appropriate characteristics.

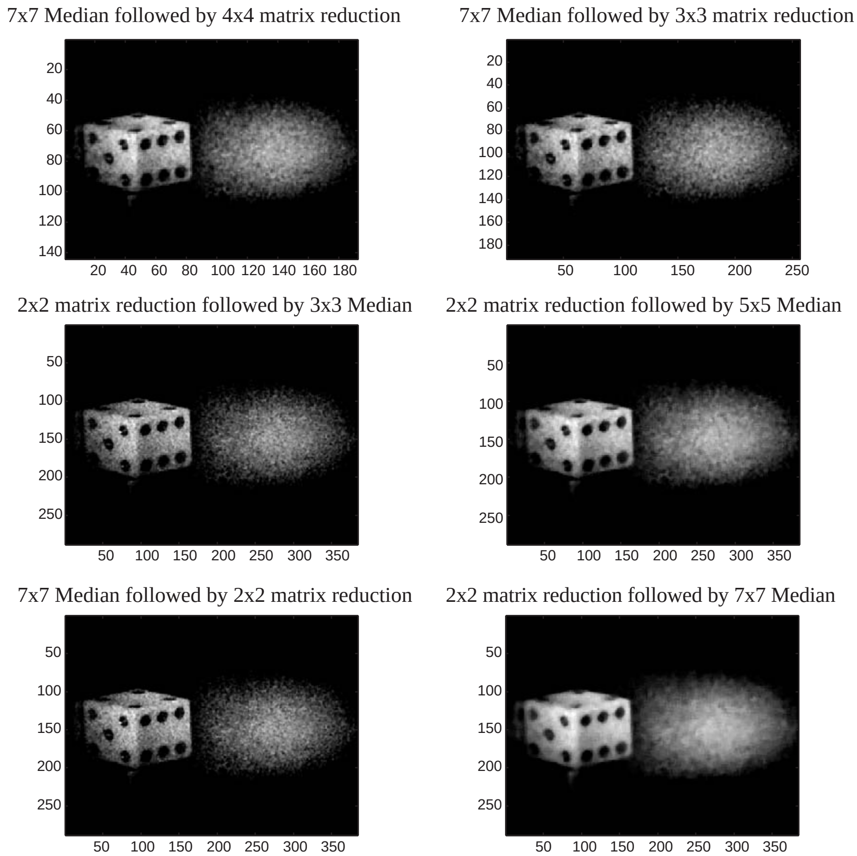

Fig. 6. Speckle noise reduction by merged application of median filtering and matrix reduction to the original image shown in Fig. 2.

Acknowledgements

The authors thank DIMED (Universidad Nacional de Colombia Sede Medellín) and Colciencias for the financial support and Professors Román Castañeda and Fernando Medina for their inspiring discussions.

References

[1] J.W. Goodman, R.W. Lawrence, Digital image formation from electronically detected holograms, Appl. Phys. Lett. 11 (1967) 77–79.
[2] T. Kreis, W. Jüptner, Suppression of the dc term in digital holography, Opt. Eng. 36 (1997) 2358–2359.
[3] L. Xu, J. Miao, A. Asundi, Properties of digital holography based on in-line configuration, Opt. Eng. 39 (2000) 3214–3219.
[4] Y. Takaki, H. Kawai, H. Ohzu, Hibrid holographic microscopy free of conjugate and zero-order images, Appl. Opt. 38 (1999) 4990–4996.
[5] Y. Frauel, E. Tajahuerce, M. Castro, B. Javidi, Distortion-tolerant three-dimensional object recognition with digital holography, Appl. Opt. 40 (2001) 3888–3889.
[6] N. Demoli, J. Mestovic, I. Sovic, Subtraction digital holography, Appl. Opt. 42 (2003) 798–804.
[7] R.J. Collier, C.B. Burckhardt, L.H. Lin, Optical Holography, Academic Press, New York, 1971.
[8] L.P. Yaroslavskii, N.S. Merzlyakov, Methods of Digital Holography (translated from Russian by D. Parsons), Consultants Bureau, New York, 1989.
[9] E. Cuche, P. Marquet, C. Depeursinge, Simultaneous amplitude-contrast and quantitative phase-contrast microscopy by numerical reconstruction of Fresnel off-axis holograms, Appl. Opt. 38 (1999) 6994–7001.
[10] K. Jain, Fundamental of Digital Image Processing, Prentice-Hall, New York, 1989.
[11] R.C. González, Digital Image Processing, Addison-Wesley, Reading, MA, 1993.
[12] W.K. Pratt, Digital Image Processing, second ed, Wiley, New York, 1991.