Optics Communications 326 (2014) 52–56

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A method for detecting the best reconstructing distance in phase-shifting digital holography

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form
10 April 2014
Accepted 15 April 2014
Available online 24 April 2014

Keywords:
Hologram reconstruction
Focal distance detection
Phase-shifting digital holography
Discrete cosine transform

ABSTRACT

In this paper, we propose a novel method to detect the best reconstructing distance in phase-shifting digital holography, which can help one to reconstruct high-quality images even though the recording distance is unkonwn. This scheme is based on an algorithm, two-dimensional discrete cosine transform (DCT). Numerical experiments for this method are shown in this paper. It is shown that this method is not only effective but also fast compared to previous schemes for detecting the focal distance in digital holography. Meanwhile, the algorithm can be effective against different types of noise.

1. Introduction

Holography was invented in 1948 by Gabor [1], recording both phase and intensity information, and has been developed as a real 3D imaging technology over the past few decades. In digital holography (DH) [2], the hologram is digitized and recorded by charge-coupled devices (CCDs). Digital holography is an attractive technique for the acquisition of 3D information for various applications, such as deformation analysis and shape measurement [3,4], particle tracking [5], microscopy [6], encryption [7], object recognition [8], and data compression [9,10]. Generally, the quality of the computer reconstructed image from digital holograms mainly depends on the recording scheme and numerical reconstruction method. For recording holograms, there are two typical setups: in-line setup by Gabor [1] and off-axis setup by Leith and Upatnieks [11]. Although the off-axis setup was proposed to overcome the suffering of twin image in the in-line setup, the presence of zero-order image and the spatial resolution requirements limit its practical use. Phase-shifting digital holography (PSDH) proposed by Yamaguchi and Zhang [12] overcomes these restrictions by using in-line setup and the reference waves with stepwise changed phase. In general, the best reconstructing distance should be equal to the actual optical-path-length, namely, the distance from the object plane to the CCD plane in the process of recording. In some cases this distance is not known exactly or the information may be lost in a series of processes. If this distance is not correct, it will appear out of focus and the reconstructed image will become low quality. Much more experimental effort should be made to detect the correct focal plane according to the kind of object under investigation and the adopted configuration. There are various methods proposed in the literature to search for the precise reconstructed distances in DH. For example, the total sum of the gradient [13], the Laplacian [14], or the variance [15] of gray-value image distribution approaches have been proposed. However, in these schemes the searching and recovery of the correct image plane are usually cumbersome and time-consuming for dynamic measurements. Ilhan et al. [16] used scaled holograms method that can speed up the detection in DH, but the holograms need preprocess. Quan et al. [17] proposed a gradient operator method that can obtain high quality images with the in-line DH, but the detection speed is not fast.

In this paper, we propose a novel method that can detect the best reconstructing distance based on discrete cosine transform (DCT) for numerical reconstruction in PSDH. We find that it is possible to obtain the best reconstructing distance accurately with this approach. The proposed method has some advantages compared to previous schemes in Refs. [13–17]. It is relatively simple and the holograms do not need to preprocess, the speed of detection is also improved. In addition, the proposed approach can detect the focal distance of the objects even though they are overlapped. Meanwhile, the algorithm can be effective against different types of noise. The theory of the proposed method is outlined and the performance of the proposed method is demonstrated using simulation results.

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http://dx.doi.org/10.1016/j.optcom.2014.04.035
0030-4018/

2. Theory

2.1. Phase-shifting digital holography

The scheme of an in-line phase-shifting digital holography (PSDH) technique often consists of a Mach–Zehnder interferometer, as shown in Fig. 1. A laser beam is split into two paths by a beam splitter, one of which illuminates an object and interferes with the other beam, called reference beam, which includes a phase shifter to introduce stepwise phase differences $\Delta\varphi(\Delta\varphi = 0, \pi/2, \pi)$. The hologram intensities are obtained at the CCD device. Thus, the complex amplitude of the object wave can be derived from it. Assume an object point located at (ε, η) in the object plane, then the object wave of that object point at the recording plane is defined by

$$E(x,y) = U_o(\varepsilon,\eta)\exp\left[ikd + ik\frac{(x-\varepsilon)^2 + (y-\eta)^2}{2d}\right], \tag{1}$$

where $U_o(\varepsilon,\eta)$ denotes the complex amplitude of the object, (ε,η) and (x,y) are the coordinates at the object plane and recording plane, respectively. $(k = 2\pi/\lambda)$ is the wave number, λ is the wavelength of the laser beam and d is the distance between the object plane and the recording plane. The distribution of the object wave at the hologram plane is given by

$$U(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U_o(\varepsilon,\eta)\exp\left[ikd + ik\frac{(x-\varepsilon)^2 + (y-\eta)^2}{2d}\right] d\varepsilon\, d\eta. \tag{2}$$

Then the object wave is superimposed upon the phase-shifted reference wave whose complex amplitude is expressed as

$$U_r(x,y;\varphi) = A(x,y)\exp(i\varphi), \quad \varphi = (\varphi = 0, \pi/2, \pi). \tag{3}$$

The intensity of the interference pattern obtained by CCD is calculated by

$$I_H(x,y;\varphi) = |U(x,y) + U_r(x,y;\varphi)|^2. \tag{4}$$

The complex amplitude of the object wavefront at the hologram plane can be calculated directly by

$$U(x,y) = \frac{1-i}{4|U_r|}\left\{I_H(x,y;0) - I_H\left(x,y;\frac{\pi}{2}\right) + i\left[I_H\left(x,y;\frac{\pi}{2}\right) - I_H(x,y;\pi)\right]\right\}. \tag{5}$$

Image reconstruction is performed by the Fresnel diffraction formula, which is represented as

$$U_I(X,Y,Z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U(x,y)\exp\left[ikZ + ik\frac{(X-x)^2 + (Y-y)^2}{2Z}\right] dx\, dy, \tag{6}$$

where (X,Y) is the coordinate in the plane located at Z distance from the hologram plane. When $Z=d$, the object in depth Z is focused. The convolution form is referred to as

$$U_I(X,Y,Z) = C\mathcal{F}^{-1}[\mathcal{F}[U(x,y)]\cdot\mathcal{F}[h(x,y)]], \tag{7}$$

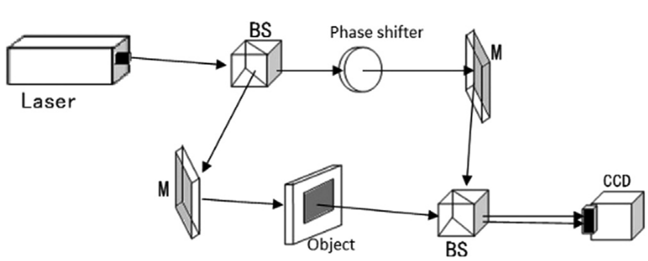

Fig. 1. Setup for recording an object of phase-shifting digital holography. BS: beam splitters; M: mirror.

where C denotes a constant factor that can be omitted, $\mathcal{F}[\,]$ and $\mathcal{F}^{-1}[\,]$ are the Fourier and inverse Fourier operators, respectively, and the impulse response $h(x,y) = \exp(i(\pi/\lambda Z)(x^2+y^2))$. The numerical calculation of Eq. (7) is accelerated by using fast Fourier transform (FFT) operations. FFT-based light propagation reduces the computational complexity to $O(N^2 \log N)$, where the resolution of the hologram is $N \times N$. However, when increasing the number of patches, the calculational cost is enormous.

2.2. The algorithm based discrete cosine transform

Discrete cosine transform (DCT) can be used in the analysis of the frequency domain signal characteristics, and it can be applied to image compression. Because it is like a Fourier transform, we can make the signal from the spatial domain into the frequency domain. As known, in frequency domain of the image analysis, image sharpness or focus degree is decided by how much high frequency component of the image is. The more high the frequency component is, the more clear the image becomes. High frequency components are enhanced in the intensity image of reflective or scattering objects when they are focused. Thus, after DCT we can judge the image sharpness according to the high frequency component of the image. For a two-dimensional discrete signal (like the reconstruction image $U_I(m\cdot n)$) its two-dimensional DCT is defined as

$$D(u,v) = a_p a_q \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} U_I(m,n)\cos\frac{\pi(2m+1)}{2M}\cos\frac{\pi(2n+1)}{2N}, \tag{8}$$

$$a_p = \begin{cases} 1/\sqrt{M}, & p=0 \\ \sqrt{2/M}, & 1 \le p \le M-1 \end{cases}; \quad a_p = \begin{cases} 1/\sqrt{N}, & q=0 \\ \sqrt{2/N}, & 1 \le q \le N-1 \end{cases}$$

where $0 \le p \le M-1$, $0 \le q \le N-1$, $D(u,v)$ is called the DCT coefficient of matrix U_I, and the reconstructed image has $(M \times N)$ pixels. In order to estimate the clearest image, namely to detect the best reconstructing distance, we use the following algorithm based on the DCT

$$G = \sum_u^M \sum_v^N |D(u,v)|, \tag{9}$$

where $D(u,v)$ is the result of the DCT, the evaluation index G is the coefficient applied to estimate the reconstructed image. The brightness and grayscale of the image itself, called the DC term, can affect the image definition, we use the improved algorithm shown as

$$G_i = \frac{\sum_u^M \sum_v^N |D_i(u,v)|}{|D_i(1,1)|}, \tag{10}$$

where i represents different reconstructed images by using different reconstructing distances, $D_i(1,1)$ is the DC term of the reconstructed images. Consequently, the maximum of G_i corresponds to the highest quality image and the best reconstructing distance.

3. Results of the numerical simulations

In this section we use our proposed DCT method to simulate two experiment processes. The numerical experiment was based on the scheme shown in Fig. 1. The light source is a He–Ne laser with a wavelength of $\lambda = 632.8$ nm. The CCD has an array of 512×512 pixels, and the size of each pixel is 10 μm × 10 μm.

Simulation experiment 1: At first, we investigate the effectiveness of the scheme by simulating the first numerical experiment. We use the gray image (characters-optics) as the virtual object shown in Fig. 2(a). Each of the letters has the same recording