Optics Communications 335 (2015) 183–188

Contents lists available at ScienceDirect

Optics Communications

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

A new estimation method for two-step-only quadrature phase-shifting digital holography

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ARTICLE INFO

Article history:
Received 3 June 2014
Received in revised form
25 August 2014
Accepted 29 August 2014
Available online 22 September 2014

Keywords:
Digital holography
Phase shifting
Quadrature phase shifting holography

ABSTRACT

Two-step-only quadrature phase-shifting digital holography can reconstruct the original complex object using only two holograms without the additional recording of the reference wave intensity and the object wave intensity. Its success depends on the accurate estimation of the reference wave intensity from the two acquired holograms. The previous estimation method is relatively computational expensive. In this paper, we present a novel simple and effective method for estimating the reference wave intensity with low computational load. Simulation results are presented to demonstrate the effectiveness and speedup of the proposed method.

1. Introduction

In digital holography, one of the most important tasks is to eliminate the undesired zero-order and twin image to obtain a high quality reconstruction. While there are several methods for zero-order and twin image elimination or suppression, phase-shifting holography (PSH) [1–3] has been the most widely used technique for this task. The PSH requires the recording of multiple phase-shifting holograms and phase stability at different phase shifts, where the phase shifts are usually taken as multiples of $\pi/2$. Multiple phase-shifting holograms can be recorded sequentially or in parallel [4,5]. Depending on the number of holograms acquired and used in the reconstruction, there are four-step, three-step and two-step PSH, which require four, three and two holograms, respectively. Generally the reconstruction errors increase as the number of holograms increases when acquired sequentially owing to the stability requirement among different phase shifts. Two-step PSH [4–11] is thus preferred over the three-step and four-step PSH because of fewer numbers of hologram recordings. Two-step PSH is also referred as quadrature PSH (QPSH), and a zero phase shift and a $\pi/2$ phase shift are usually used during recording. Although only two holograms are needed in the conventional QPSH, it still requires the additional measurement of the intensity of the reference wave and the intensity of the object wave in order to reconstruct the original complex object wave without the zero-order and twin image. We refer this method as the "standard" QPSH. Therefore, the number of exposures in the standard QPSH is still four, the same as the four-step PSH but the setup of the standard QPSH is easier than that of the four-step PSH because the recording of the intensity patterns is not sensitive to phase variation between the reference wave and the object wave. Meng et al. [10] showed that actually the intensity of the object light is not needed in the reconstruction as long as the reference wave intensity is large enough, but we still need to acquire the intensity of the reference wave. Recently, Liu and Poon [11] proposed an improved QPSH called two-step-only QPSH, which uses only two quadrature-phase holograms and doesn't need to record either the reference wave intensity or the object wave intensity. Instead the reference wave intensity is obtained through a numerical estimation method rather than an actual measurement. This simplifies the QPSH setup. In Ref. [12], Liu et al. slightly improved their original trial-and-error reference wave intensity estimation method. However, their proposed estimation method is relatively complex and computational expensive. In this paper, we propose a much simpler and faster method for estimating the intensity of the reference wave for the two-step-only QPSH. This is done by reducing the searching range for the reference wave intensity and simplifying the operations during the search.

2. Two-step-only quadrature phase-shifting digital holography

Fig. 1 illustrates a typical phase-shifting holographic setup. Linearly polarized light from a coherent laser is expanded and collimated, and then split by a polarizing beam splitter into reference and object beams traveling in different directions. The object beam illuminates the object, and the reference arm creates different phase shifts through varying the wave plates' orientations. The two beams are combined by a

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http://dx.doi.org/10.1016/j.optcom.2014.08.068
0030-4018/

second beam splitter, and the resulting interference pattern is captured by a CCD camera and finally stored in an image processing system. In the standard two-step QPSH, we record two quadrature-phase on-axis holograms sequentially. One hologram $I_1(x, y)$ is the interference pattern between the object wave and the reference wave, and the other hologram $I_2(x, y)$ is the interference pattern between the object wave and the $\pi/2$ phase-shifted reference wave. Let R and O be the reference plane wave and complex object wave at the CCD plane, respectively. The two holograms can be written as

$$I_1 = |R+O|^2 = |R|^2 + |O|^2 + R(O+O^*), \tag{1}$$

$$I_2 = \left|e^{j\pi/2}R+O\right|^2 = |R|^2 + |O|^2 - jR(O-O^*), \tag{2}$$

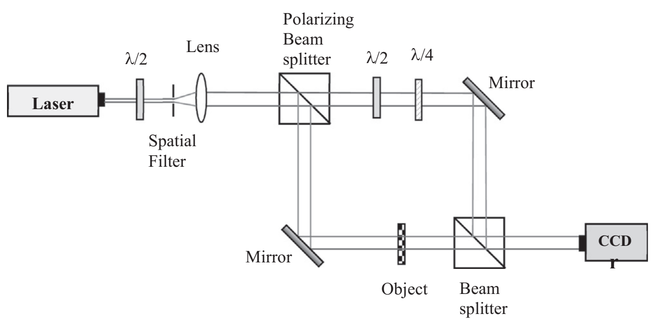

Fig. 1. Phase-shifting digital holography setup.

where the asterisk denotes the complex conjugation. The zero-order term, designated as $I_0 = |R|^2 + |O|^2$, can be removed from the two holograms as follows

$$I_1 - I_0 = R(O+O^*), \tag{3}$$

$$I_2 - I_0 = -jR(O-O^*), \tag{4}$$

Then the complex object wave at the CCD plane can be reconstructed by adding Eqs. (3) and (4) multiplied by j as

$$O = \frac{(I_1 - I_0) + j(I_2 - I_0)}{2R}. \tag{5}$$

In this reconstruction using Eq. (5), we need to know the zero order term I_0 and the reference wave R in order to obtain a zero-order- and twin-image-free reconstruction. This requires measuring the intensity of the reference wave and that of the object wave to produce I_0, and so there are four recordings in total for the standard QPSH: two phase-shifted holograms, the reference wave intensity and the object wave intensity. In order to reduce the number of recordings from four to two, Liu et al. [11,12] proposed a two-step-only QPSH which doesn't need the actual measurement of the reference wave intensity and the object wave intensity. Instead they first numerically estimate the reference wave intensity and then use it to calculate the zero-order term I_0 since I_0 can be derived as a function of R^2, I_1, and I_2 as represented by the following:

$$2I_0^2 - \left(2I_1 + 2I_2 + 4R^2\right)I_0 + \left(I_1^2 + I_2^2 + 4R^4\right) = 0. \tag{6}$$

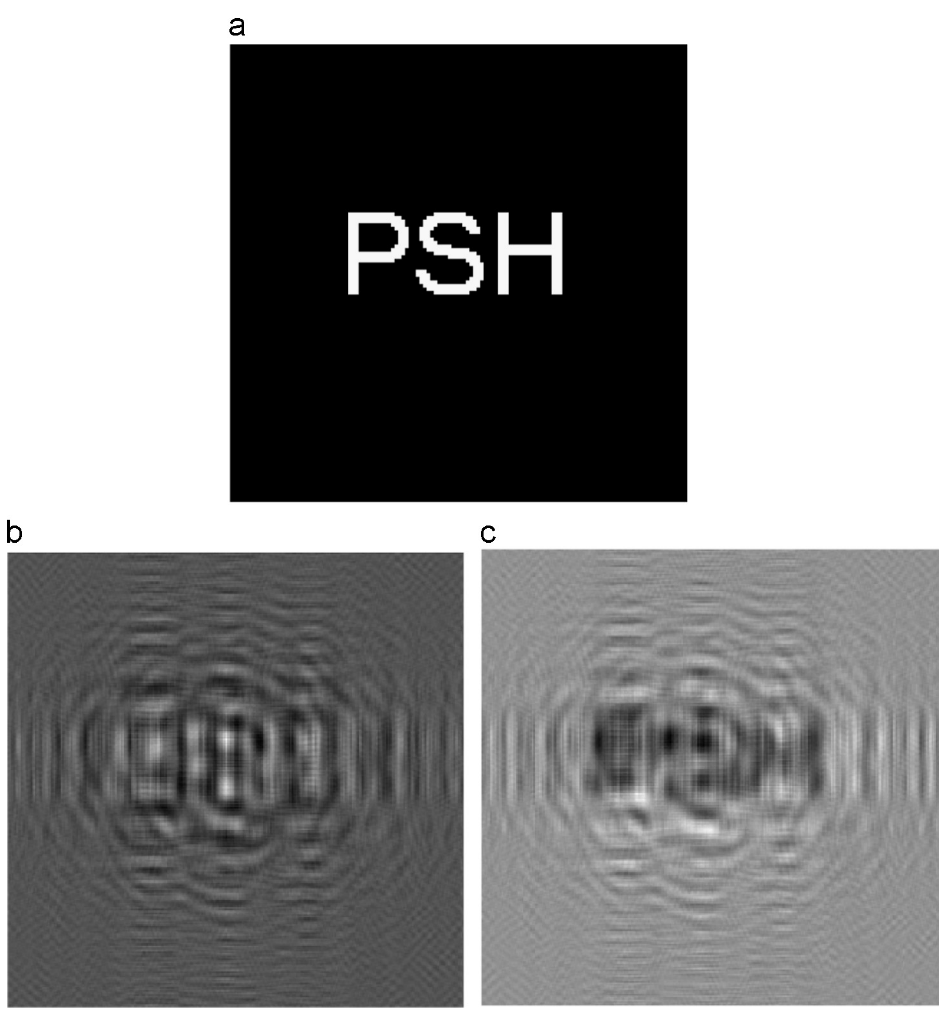

Fig. 2. Object and holograms: (a) the object used in the experiment, (b) the inline hologram obtained with zero phase shift, and (c) the hologram obtained with $\pi/2$ phase shift.