Optics and Lasers in Engineering 86 (2016) 38–43

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Parallel phase-shifting self-interference digital holography with faithful reconstruction using compressive sensing

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ARTICLE INFO

Article history:
Received 16 November 2015
Received in revised form
25 April 2016
Accepted 7 May 2016
Available online 19 May 2016

Keywords:
Optical metrology
Holography
Digital holography
Phase shift
Compressive sensing
Image reconstruction techniques

ABSTRACT

We present a new self-interference digital holographic approach that allows single-shot capturing three-dimensional intensity distribution of the spatially incoherent objects. The Fresnel incoherent correlation holographic microscopy is combined with parallel phase-shifting technique to instantaneously obtain spatially multiplexed phase-shifting holograms. The compressive-sensing-based reconstruction algorithm is implemented to reconstruct the original object from the under sampled demultiplexed holograms. The scheme is verified with simulations. The validity of the proposed method is experimentally demonstrated in an indirectly way by simulating the use of specific parallel phase-shifting recording device.

1. Introduction

Three-dimensional (3D) microscopic imaging techniques have been significant tools for discovering the mechanisms involved in biological cells and tissues [1]. Among them, digital holography has been used for various applications because it offers the advantages of scanning-free, simplicity, and potential to track rapidly moving samples in volume [2–6]. However, the validity of the conventional digital holographic techniques is challenged while one want holographic imaging for spatially incoherent objects. To solve the problem, self-interference digital holography (SIDH) has been proposed and developed [7]. Holographic recording is implemented by exploring the spatial self-coherence property of the point object in SIDH. The performances of such kind of self-interference digital holographic systems have been investigated under different optical setups [8–10], and further used for aberration correction [11,12], confocal microscopy [13] and color imaging [14,15]. The high-resolution 3D SIDH imaging systems great benefit the biological investigation, and provide a high-efficiency tool for the 3D tracking of the fluorescent particles. Phase-shifting (PS) technique has been implemented to eliminate the twin image and zero order in digital holography. However, temporal resolution of the system is usually reduced because three or more holograms have to be recorded sequentially. Thus the imaging of rapidly moving object is of great challenge. Although off-axis hologram can be recorded using particular optical setups, the signal to noise ratio of the reconstructed image is relatively low [15], or the field of view of the system is reduced [16]. On the other hand, parallel phase-shifting (PPS) digital holography is capable of instantaneous measurement by capturing several spatially multiplexed holograms with single-shot exposure [17–19]. However, the quality of the reconstructed image is reduced because the demultiplexed holograms are under-sampled. Fortunately, by designing the holographic recording and reconstruction processes using compressive sensing (CS), the under-sampled signals can be accurately inferred [20,21].

We propose a parallel phase-shifting self-interference digital holography (PPSSIDH) which is capable of instantaneous capturing and reconstructing the three-dimensional intensity distribution of spatially incoherent object. The holographic recording in the proposed method as a CS scheme and the reconstruction of the hologram as an inverse problem are demonstrated. The CS reconstruction allows us to accurately rebuild signals at a sampling rate much lower than Shannon's limit by exploiting sparsity. In this paper, four phase-shifted holograms are spatially multiplexed in a single-shot captured PPS hologram. The PPS hologram are then demultiplexed into four under-sampled phase-shifted

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http://dx.doi.org/10.1016/j.optlaseng.2016.05.004
0143-8166/

holograms with sampling rate of only 25%. Combing with CS reconstruction, noise introduced by the under-sampling is suppressed by exploring the sparsity of the object under CS frame work.

2. Methodology

The schematic diagram of the proposed method is shown in Fig. 1. The point source located at f_0-z_s from the Lens (with focal length of f_0) emits a spherical wave. The roughly collimated beam illuminates the spatial light modulator (SLM) and is separated into two beams after reflected by the SLM. The SLM is served as a diffractive optical element (DOE) by uploaded a suitable mask. Assume the mask is designed that randomly half of the pixels are used to display the phase of a positive lenses with focal lengths of f_a, and the remaining pixels are used to display the phase of a positive lenses with focal lengths of f_b. Thus the two beams after SLM are converged to point a located at f_1 from SLM and point b located at f_2 from SLM, respectively. The two beams can interfere with each other because they originated from the same point. The interference pattern is coined as point source hologram (PSH) here. The intensity distribution of PSH is similar to Fresnel zone plate, where the 3D spatial coordinates of the corresponding point source is encoded.

For general case, the hologram of an extended object is the two dimensional convolution of the intensity distribution of the object and the PSH. At the distance of z_h from SLM, an image sensor with a PPS filter consisting of an array of 2×2 elements is used to capture the hologram. For each element, transmittance of the 4 pixels are designed in such a way that four different PS values of 0, $-\pi/2$, $-\pi$, and $-3\pi/2$ are generated between the two interference beams. The recorded hologram h can be demultiplexed into four under-sampled phase-shifted holograms h_1, h_2, h_3, and h_4 using the demultiplexing masks m_1, m_2, m_3, and m_4 as shown in Fig. 1. The twin image and zero order can be eliminated, and the complex hologram C can be obtained using the equation of [11]

$$C = (m_1 \cdot h - m_3 \cdot h) - j(m_2 \cdot h - m_4 \cdot h) = (h_1 - h_3) - j(h_2 - h_4). \tag{1}$$

The 3D object data $O(x, y, z)$ can be reconstructed from the complex hologram by calculating the Fresnel propagation formula based on angular spectrum method as

$$O(x, y, z) = F^{-1}\{F(C)\cdot \exp[-j\pi\lambda z_r(u^2 + v^2)]\}, \tag{2}$$

where F and F^{-1} denote Fourier and inverse Fourier transform, respectively; u and v are the spatial frequency coordinates, z_r is reconstruction distance. The quality of the reconstruction $O(x, y, z)$ is reduced because the four phase-shifted holograms are all under-sampled. To solve the problem, a generalized framework to acquire multichannel optical data using CS has been proposed and numerically investigated in Fresnel holography [21]. The successfully implementation of compressive sensing relies on two requirements: Sparsity and coherence of the sensing mechanism. Here the sparsity is implemented by expressing the object in some domain such as total variation (TV) and discrete Fourier transform (DFT). The second requirement "coherence" is quite different with the concept of "coherence" in the statistical optics. It means that the sensing operation and sparsifyication operation should be mutual incoherent. From another view, the coherence also can understand that the object information (such as, the diffraction pattern of the object) should be evenly spread over the set of basis that describe it at the recording plane. By exploring the spatial-self-coherence of the point object, 3D information of the spatially incoherent object can be encoded into the Fresnel hologram using SIDH system. Hence as commonly done in other compressive digital holographic applications [20,21,23,24,26], Fresnel diffraction is utilized as sensing operation in the paper. The CS reconstruction method is implemented to infer the reconstructions from the under-sampled phase-shifted holograms and improve the imaging quality in PPSSIDH. In practice, four reconstructions are inferred from the four under-sampled phase-shifted holograms using CS algorithm respectively, then the reconstructions are combined to suppress the twin image and zero order. The observation process of the system for each under-sampled hologram can be expressed with linear algebra as

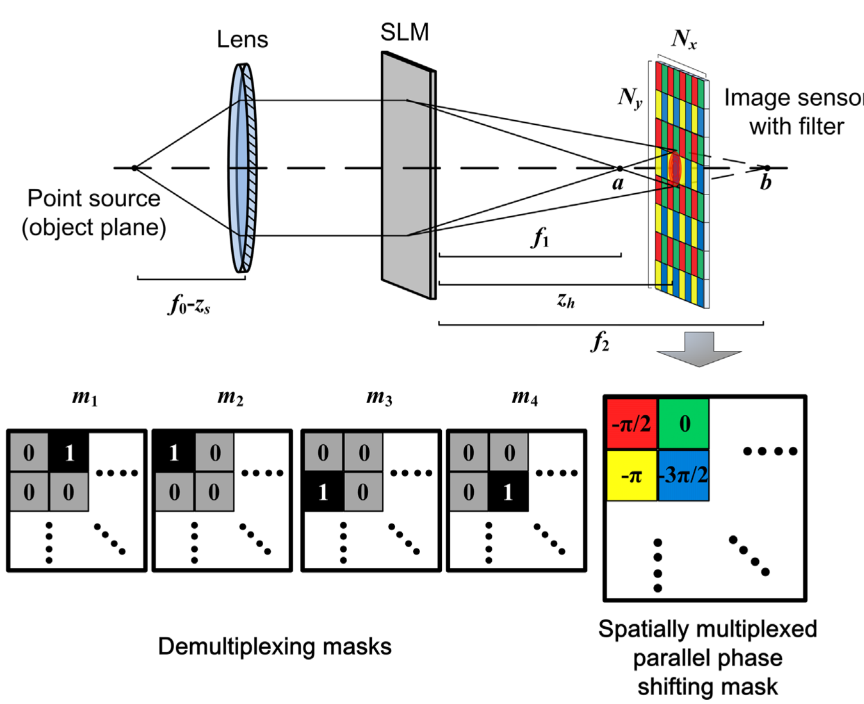

Fig. 1. Schematic of the proposed parallel phase-shifting self-interference digital holography system.