Phase shift extraction algorithm based on PCA method in Digital Holographic Microscopy under Structured Illumination

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Abstract: We present a phase shift extraction algorithm in digital holographic microscopy under structured illumination based on principal component analysis(PCA) method. The experiments is obtained satisfactory results by this method and shows 78% resolution improvement.

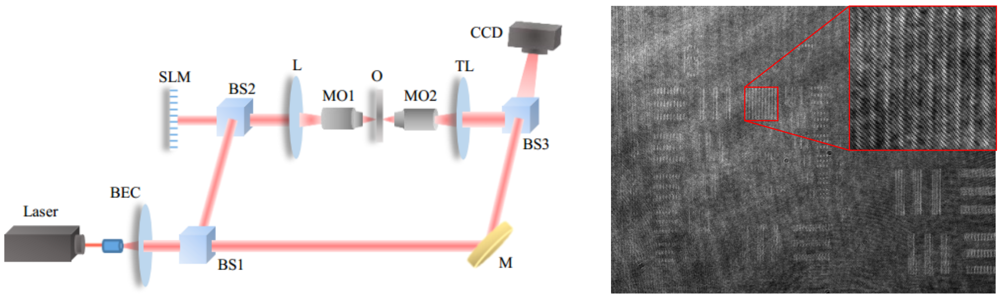
OCIS codes: (090.1995) Digital holography; (100.6640) Superresolution

1. Introduction

In recent years,digital holographic microscopy (DHM) as a powerful tool for amplitude-contrast and phase-contrast imaging has been used in biomedical imaging. The structured illumination (SI) is one of methods to overpass the diffraction limit in DHM [1]. By using SI, three images with known phase-shifting amount are required to separate low and high frequency information in each direction. Although iteration algorithm helps to retrieve the unknown phase-shifting amount, it is time-consuming and requires considerable computeraion [2].

In this paper, we propose a phase-shifting extraction algorithm based on PCA method with unknown phase-shifting which is very fast and easy to implement. We carry out the experiments to testify this method and obtain satisfactory results.

2. Principle and Experimental results



(a) (b)

Fig. 1. The experiment steup of the SI-DHM system (a), First hologram I_1 of the SI-DHM (b)

The light from He-Ne laser with $\lambda = 632nm$ is employed to illuminate the system of Fig. 1(a). The light is divided into two beams by a beam splitter(BS1). One beam is used as the reference beam. The other beam served as the object beam is reflected by BS2 and modulated by the spatial light modulator (SLM). For each orientation the phase gratings loaded on SLM are shifted at least three times. After extracting the $+1$st order from the hologram, the intensity of the projection as shown in Fig. 1(b), which can be written as

$$I_n(x,y) = a(x,y) + b(x,y)cos[\Phi(x,y) + \delta_n] \tag{1}$$

where $a(x,y)$ is the background illumination, $b(x,y)$ and $\Phi(x,y)$ are the modulation and the phase maps, respectively. δ_n are the unknown phase steps, where n denotes the phase-shifting index. The red square in Fig. 1(b) is zoomed to show two interference patterns.

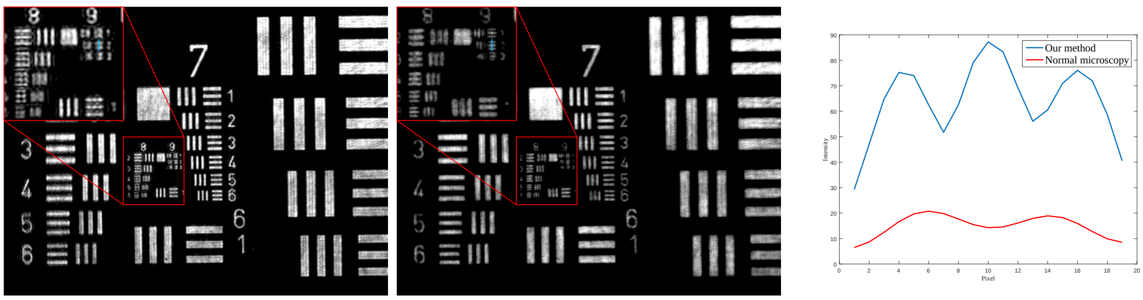
The PCA is a technique from statistics for reducing the dimensionality of an image or date set [3]. According to the analysis in Eq (1), suppose that we have constructed N images for each direction. Each image set can be expressed in a matrix form as $X = [I_1, I_2, \cdots, I_N]^T$, where $[\cdot]^T$ denotes the transposing operation.

Taking into account the background is a smooth signal, we can estimate $X_m = \frac{1}{N}\sum_{n=1}^{n=N} I_n$, where X_m is the mean value of N images. The covariance matrix C from X for PCA algorithm can be written as $C = [X - X_m][X - X_m]^T$. In practically, $X - X_m$ represent a background suppression operation. Covariance matrix C is decomposed into eigenvalues V and eigenvectors Q. From matrix theory, we can express it as $CQ = VQ$. As an orthogonal matrix, Q can be constructed by $Q = [Q_1, Q_2, \cdots, Q_N]^T$. The covariance matrix C Can be diagonalized as $D = Q^T CQ$. D is a diagonal matrix comprised by the eigenvalues V. Through the covariance matrix C and the orthogonal matrix Q, we can extract the principal components as

$$\Psi = Q(X - X_m) = [Q_1, Q_2, \cdots, Q_N]^T (X - X_m) \tag{2}$$

where $\Psi = [\Psi_1, \Psi_2, \cdots, \Psi_N]$ are the principle components of the $X - X_m$. We can extract two uncorrelated quadrature signal $I_c(x,y) = b(x,y)cos[\Phi(x,y)]$ and $I_s = b(x,y)sin[\Phi(x,y)]$ from Ψ corresponded to the biggest eigenvalues (Ψ_1 and Ψ_2). Thus the -1st diffraction order I_L and $+1$st diffraction order I_R can be extracted from the image set in each direction. The two orders can be estimated as $FT(I_L) = FT(I_s) - iFT(I_c) \quad and \quad FT(I_R) = FT(I_s) + iFT(I_c)$. where FT denotes the Fourier transform and $i = \sqrt{-1}$.

The next step is to assemble the -1st and $+1$st diffraction order in frequency domain in each direction. In this experiment, we only use three images in horizontal direction and three images in vertical direction. The information of Frequency domain in Fig.2(b) is consist of four diffraction order. The normal microscopy image is shown in Fig.2(a) for the contrast, where the Group 8, Element 3 (323Lp/mm) in the USAF test target can be resolved. The intensity distributions along the blue lines in the Group 9, Element 2 in Fig.2(a) and Fig.2(b) are plotted in Fig. 2(c). It's clear that the resolution reaches 575Lp/mm with PCA method and it shows 78% resolution improvement in experiment.



(a) (b) (c)

Fig. 2. Normal microscopy image (a), synthesized image (b), plots along the blue line of (a) and (b)

3. Conclusion

A new phase shift extraction algorithm in DHM under SI based on PCA method has been presented. This method does not need any prior knowledge and the proposed method is fast and effectively.

4. Acknowledgment

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