

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. © 2019 The Author(s)

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 beyond 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 it require considerable computeraion [2].

In this paper, we propose a phase shift extraction algorithm based on PCA method with unknown phase shift 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

The PCA is a technique from statistics for reducing the dimensionality of an image or date set [3]. For each orientation the phase gratings loaded on spatial light modulator (SLM) are shifted at least three times. After extracting the +1st order from the hologram, the intensity of the projection can be written as

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

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. According to the analysis in Eq (1), suppose that we have constructed N images of size $M_x \times M_y$ for each direction. Each image set can be expressed in a matrix form as $X = [I_1, I_2, \dots, I_N]^T$, where $[\cdot]^T$ denotes the transposing operation. Taking into account the background is a smooth signal, we can estimate X_m as

$$X_m = \frac{1}{N} \sum_{n=1}^{n=N} I_n \quad (2)$$

where X_m is the mean value of N images. In probability theory and statistics, covariance matrix is a measure of the degree of linear correlation between two variables. The covariance matrix C from X for PCA algorithm can be written as

$$C = [X - X_m][X - X_m]^T \quad (3)$$

The covariance matrix C can represent the data in a compact way from a different way. 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

$$CQ = VQ \quad (4)$$

As an orthogonal matrix, Q is constructed by $Q = [Q_1, Q_2, \dots, Q_N]^T$. when the matrix C is a square matrix, the covariance matrix C Can be diagonalized as

$$D = Q^T C Q \quad (5)$$

According to Eq (5), D is a diagonal matrix comprised by the eigenvalues λ . This diagonalization process is achieved by the singular value decomposition (SVD) algorithm in PCA method. Through the covariance matrix C and the orthogonal matrix Q , we can extract the principal components by Hotelling Transform as

$$\Psi = Q(X - X_m) = [Q_1, Q_2, \dots, Q_N]^T (X - X_m) \quad (6)$$

where $\Psi = [\Psi_1, \Psi_2, \dots, \Psi_N]$ 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 -1 st diffraction order I_L and $+1$ st diffraction order I_R can be extracted from the image set in each direction through the Hilbert transformation. The two orders can be estimated as

$$FT(I_L) = FT(I_s) - iFT(I_c) \quad \text{and} \quad FT(I_R) = FT(I_s) + iFT(I_c) \quad (7)$$

where FT denotes the Fourier transform and $i = \sqrt{-1}$. The next step is to assemble the -1 st and $+1$ st diffraction order in frequency domain in each direction. Thus the synthesized image can contain sub-resolution information and overcome the resolution limit. In this experiment, we only use three images in horizontal direction and three images in vertical direction. The information of Frequency domain in Fig.1(b) is consist of four diffraction order and the red square in Fig.1(b) is zoomed to show two interference patterns. The normal microscopy image is shown in Fig.1(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.1(a) and Fig.1(b) are plotted in Fig.1(c). It's clear that the resolution reaches 575Lp/mm with PCA method and it shows 78% resolution improvement in experiment.

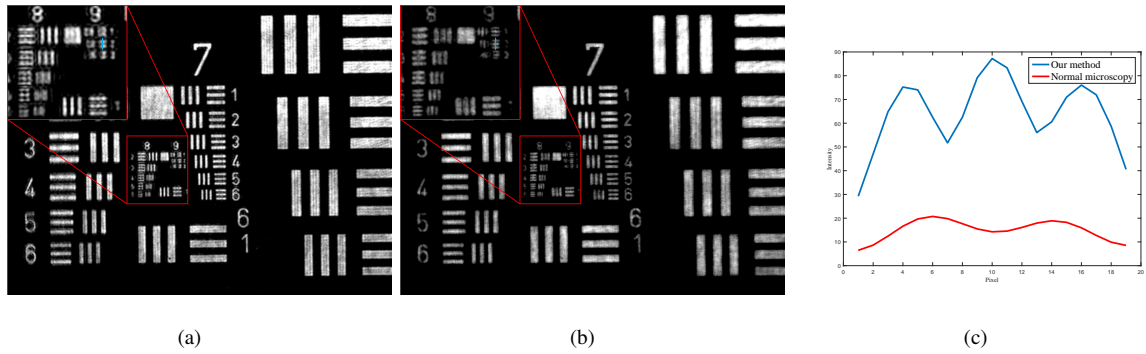


Fig. 1. Normal microscopy image (a), synthesized image (b), plots along the blue line of (a) and (b)

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

This work is supported by the National Natural Science Foundation of China (NSFC) (61775097, 61605080).

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