Unknown Arbitrary Phase Shift Retrieval and Holographic Reconstruction from Images Obtained from Self-Interference Incoherent Digital Holography

Jisoo Hong and Myung K. Kim*

Digital Holography and Microscopy Laboratory, Department of Physics, University of South Florida, Tampa, FL, US 33620
Corresponding author: mkkim@usf.edu

Abstract: The algorithm to retrieve the phase shift from the image recorded using the self-interference incoherent digital holography is proposed. Using the proposed algorithm, the complex hologram can be retrieved with unknown and arbitrary phase shift.
OCIS codes: (110.1080) Active or adaptive optics; (090.1995) Digital holography

Self-interference incoherent digital holography (SIDH) retrieves the complex hologram from the object illuminated by the incoherent light source with the optical configuration shown in Fig. 1 [1]. The basic principle of SIDH is similar to the Fresnel incoherent correlation holography proposed by Rosen [2]. By using the self-coherency of each point source at the object plane, SIDH system creates two copies of propagation from each point source and imposes different curvatures to them using the combination of curved and plane mirrors. However, for the usual object composed of many point sources, the interference patterns are added up and the fringes are washed out. Hence, SIDH adopts usually the 3 or 4 phase shift interferometry (PSI) to retrieve complex hologram from the recorded images [1, 2]. Once we obtain the complex hologram, the object image can be easily reconstructed by propagating the complex hologram. However, the PSI used in the previous works requires the phase shift values to be equally spaced known values. Sometimes, this requirement is not satisfied when the phase shift value cannot be controlled exactly. For example, the high speed imaging may not allow the phase shift to be stabilized or cover the entire 2π range. Or the calibration for the phase shift could be changed by some reason. Recently, our group presented the full-color imaging by using the 3 channel charge-coupled-device (CCD) with the usual Bayer-color-filter-array attached [3]. To deal with the different 3 wavelengths, 8 phase shifts were used to obtain equally spaced phase shift values for all different wavelengths. If we can use the arbitrary phase shift instead, the recording process will be more practically useful one.

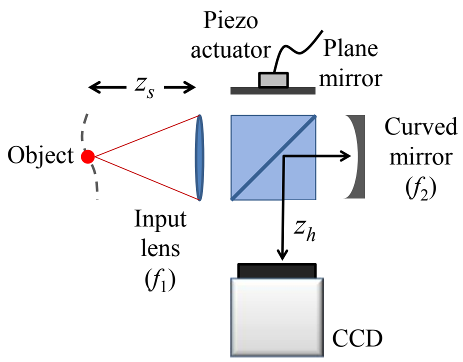

Fig. 1. Optical configuration of SIDH system

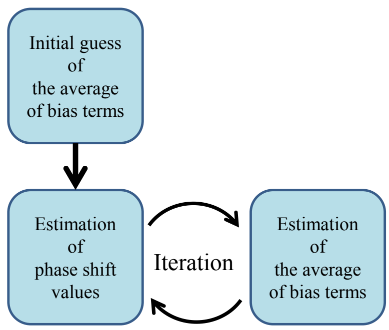

Fig. 2. Procedure of the proposed algorithm

In this work, we propose the method to retrieve the unknown and arbitrary phase shift values from the images recorded by the SIDH system. The point spread function (PSF) of the recorded image of SIDH system can be represented as the form [4],

$$u(x,y) = A(x_s, y_s)\left\{1+\cos\left[\varphi(x,y;x_s,y_s)+\theta\right]\right\}, \tag{1}$$

where (x, y) is the coordinate of the CCD plane; (x_s, y_s) the object plane; θ the phase shift value of the system. Eq. (1) can be thought to be composed of the bias term ($A(x_s, y_s)$) and the sinusoidal term ($A(x_s,y_s)\cos\left[\varphi(x,y;x_s,y_s)+\theta\right]$). Inspired by the work in [5], the proposed algorithm uses two phase shifted images instead of 3 or 4, and starts from estimating the average of the bias terms of all PSFs to retrieve the unknown phase values. The simple average of the two phase shifted images can be a good initial guess to the average of the bias terms under the condition where the area of sensor plane is sufficiently large. The initial guesses for two phase shift values are chosen as arbitrary numbers. Using those initial guesses, the recorded CCD image for a certain given phase shift value can be estimated by propagating back and forth between the CCD plane and the object plane. Then the phase shift values θ_1

and θ_2 can be estimated by minimizing the cost function defined as the mean square error (MSE) between the estimated CCD images and the actual recorded CCD images:

$$\tilde{\theta}_1 = \arg\min_{\theta_1} \sum_{x,y} \left| \tilde{I}_1(x,y) - I_1(x,y) \right|^2 , \qquad (2)$$

$$\tilde{\theta}_2 = \arg\min_{\theta_2} \sum_{x,y} \left| \tilde{I}_2(x,y) - I_2(x,y) \right|^2 , \qquad (3)$$

where $I_1(x, y)$ and $I_2(x, y)$ are the recorded phase shifted images corresponding to θ_1 and θ_2 respectively. Here, tilde represents that it is the estimated value of the symbol. Then, the average of the bias term is corrected using the estimated phase shifted values. Again, we go back to the estimation of the phase shift values using the new estimated bias value. Hence, the unknown phase shift values can be retrieved by doing iteration of two stages: the estimation of the average of the bias terms from all PSFs and the estimation of the phase shift values. The entire procedures of the proposed algorithm can be summarized as a simple diagram shown in Fig. 2.

To verify the feasibility of the proposed method, the simulation was performed for the SIDH implemented by the optical configuration presented in Fig. 1. The focal length of the input lens f_1 and the curved mirror f_2 were both 100 mm. The distances z_s and z_h were 100 mm and 200 mm respectively. The wavelength was assumed to be 600 nm. Figure 3(a) shows two recorded CCD images with the phase shift values of 0.12π and 0.32π for the object shown in Fig. 3(b). After 10 iterations of the proposed estimation scheme, the reconstructed image can be estimated as shown in the right image of Fig. 3(b) using the estimated phase shift values. Figure 3(c) shows the changes of the estimated phase shift values as the iteration proceeds.

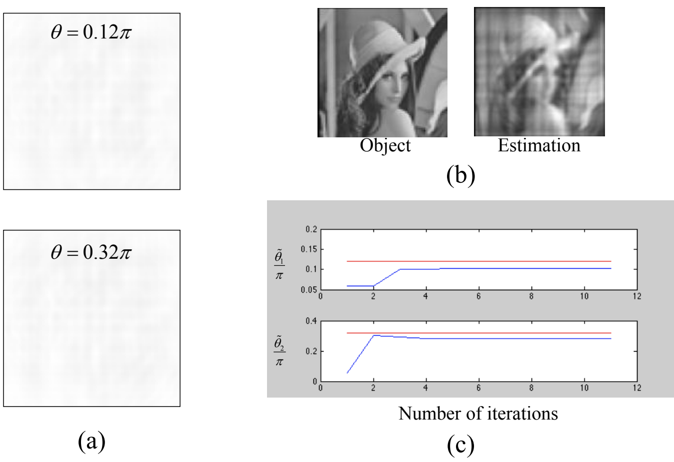

Fig. 3. Simulation results of the proposed method. (a) Recorded CCD images with the phase shifts of 0.12π and 0.32π respectively. (b) Object image and its estimation using the proposed method after 10 iterations. (c) Comparison of the actual phase shift values and their estimations as the iteration proceeds. (Red: actual phase shift value; blue: estimated phase shift value).

The proposed unknown and arbitrary phase retrieval method can be useful in applying SIDH system for the high speed imaging or the full-color natural imaging. Though the algorithm of current state can retrieve the values approaching to the solution, the performance of algorithm needs to be improved to retrieve more exact values and, accordingly, better reconstructed image. In the presentation, we will show the more improved algorithm and the experimental results obtained by applying the algorithm for the real implementation.

Acknowledgment

Research reported in this publication was supported by the National Eye Institute of the National Institutes of Health under Award Number R21EY021876. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

[1] M. K. Kim, "Incoherent digital holographic adaptive optics," Appl. Opt. **52**, A117-A130 (2013).
[2] J. Rosen and G. Brooker, "Non-scanning motionless fluorescence three-dimensional holographic microscopy," Nat. Photonics **2**, 190-195 (2008).
[3] M. K. Kim, "Full color natural light holographic camera," Opt. Express **21**, 9636-9642 (2013).
[4] G. Brooker, N. Siegel, V. Wang, and J. Rosen, "Optimal resolution in Fresnel incoherent correlation holographic fluorescence microscopy," Opt. Express **19**, 5047-5062 (2011).
[5] X. F. Xu, L. Z. Cai, Y. R. Wang, X. L. Yang, X. F. Meng, G. Y. Dong, X. X. Shen, and H. Zhang, "Generalized phase-shifting interferometry with arbitrary unknown phase shifts: direct wavefront reconstruction by blind phase shift extraction and its experimental verification," Appl. Phys. Lett. **90**, 121124 (2007).