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2015

Wang, Z., Qu, W., Yang, F., Wen, Y., & Anand, A. (2015). A new autofocus method based on angular spectrum method in digital holography. Proceedings of SPIE - The International Conference on Photonics and Optical Engineering (icPOE 2014), 9449, 94492H-. doi:10.1117/12.2076853

<https://hdl.handle.net/10356/88187>

<https://doi.org/10.1117/12.2076853>

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A New Autofocus Method Based on Angular Spectrum Method in Digital Holography

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Abstract: The determination of numerical reconstruction distance is key to recover the wavefront at focal plane in digital holography. In this paper, we propose a new autofocus method based on angular spectrum method (ASM). The proposed method takes successive Fourier transform after 1st order spectrum selection, and then calculates the summation. It saves operations compared to classic autofocus functions. When an exhaustive z-axis search is performed, the proposed method obtains unimodality coincided with the results from four classic autofocus functions. Moreover, the proposed method is more time-effective, which is the optimal one for ASM.

Key words: Digital holography Angular spectrum method Autofocus

1. Introduction

Digital holography (DH) permits quantitative phase analysis for high-resolution technical surfaces in nondestructive measurements[1]. This quantitative analysis feature requires accurate the phase map to represent real surface. In DH, the optical field can be accessed along optical axis. When numerical reconstruction is performed, the amplitude and phase of the optical field at different reconstruction distance could be obtained accordingly. The ideal situation for numerical reconstruction is to reconstruct the optical field at focal plane. Hence, an autofocus function that enables an automated evaluation of imaging plane is required. The main criteria for the evaluation of the different autofocus functions are unimodality as well as time efficiency.

2. Methodology

Angular Spectrum Method (ASM) expands a complex wave field into a summation of infinite number of plane waves[2]. When it applies in numerical reconstruction in DH, the objective field $E(x, y, d)$ at reconstruction distance d is calculated as follows

$$E(x, y, d) = \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ E_R' I_H \exp \left[i \frac{2\pi}{\lambda} d \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] \right\} [f_x, f_y] \right\} [x, y] \quad (1)$$

Where I_H is intensity of the hologram. E_R' is reference wavefront. λ is wavelength. (x, y) and (f_x, f_y) represent coordinate in spatial and spectral domain. $\mathcal{F}$ and $\mathcal{F}^{-1}$ represent Fourier transform and its invers.

When autofocusing is performed based on ASM, there are two distributions for evaluation: intensity or spectrum of the objective field. To illustrate the evaluations, a reconstruction flow chart is shown in Figure 1. According to the flow chart, if the evaluation is based on amplitude distribution (step 6 in flow chart), it will take place after numerical reconstruction is completed; otherwise, no evaluation object is available. If the evaluation is based on spectral distribution, the process will need to perform Fourier transform based step 5 in the flow chart.

Fig. 1 Numerical reconstruction flow chart of ASM

Table 1 tabulates four most used autofocus functions along with their definition and references[3, 4]. In this table the evaluated object $g_{i,j} = |E(x, y, d)|$, where i and j are the spatial coordinates, N_x and N_y are pixel numbers along x and y axes. When performed with an exhaustive z -axis search, the autofocus functions in the table will calculate the whole numerical reconstruction at every reconstruction distance iteratively. This will lead the process occupy a lot of computer's resource. As a result, the process will be time consuming.

Table 1 Autofocus functions	
Autofocus function	Description
$F_1 = \sum_{i,j} (s_x^2 + s_y^2)$ <p>where $s_x = g_{i+1,j-1} + g_{i+1,j+1} - g_{i-1,j-1} + g_{i-1,j+1} + 2g_{i+1,j} + 2g_{i-1,j}$ $s_y = g_{i-1,j+1} + g_{i+1,j+1} - g_{i-1,j-1} + g_{i+1,j-1} + 2g_{i,j+1} + 2g_{i,j-1}$</p>	Sobel
$F_2 = \sum_{i,j} (g_{i,j}g_{i+1,j} - g_{i,j}g_{i+2,j})$	Autocorrelation (CORR)
$F_3 = \sum_{i,j} (g_{i,j} - \bar{g})^2 \text{ where } \bar{g} = \frac{\sum g_{i,j}}{N_x N_y}$	Variance (VAR)
$F_4 = \sum_{u,v} \log \{1 + [\mathcal{F}(g_{i,j})](u, v)\}$	Weighted spectrum (SPEC)

To identify a robust and time-effective autofocus for ASM, we take successive Fourier transform after 1st order spectrum selection (step 4 in figure 1), and then calculates the summation. The autofocus functions for AMS is written as follows

$$F_5 = \sum \left| \mathcal{F} \left\{ \mathcal{F}_{filtered} \left\{ E_R' I_H \exp \left[i \frac{2\pi}{\lambda} d \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} \right] \right\} \right\} \right| \quad (2)$$

Where $\mathcal{F}_{filtered}$ means selected spectrum, $\mathcal{F}$ means Fourier transform of the spectral data.

The proposed function evaluates optimal reconstruction distance at step (4) in ASM. The evaluations save 2 steps or more compared to conventional evaluation methods. Furthermore, a Fourier transform and summation of a sagittal line consume less time.

3. Experiment

Figure 2 presents a typical transmission configuration of digital holographic microscopy (DHM) setup. A 632.8nm laser is used as light source. Beam from the light source is split into two beams, after collimating, one goes through to the specimen, and then gets magnified by 40X Olympus microscope objective lens as objective wavefront; and the other one as reference wavefront. The objective and reference beam meets at beam splitter and interferes. A CCD camera captures and digitalizes the image as 1280×960 pixels hologram with pixel resolution 4.65 um×4.65um.

Fig. 2 Transmission DHM setup

For a comparison of the proposed method and conventional methods, an investigation of a USAF target was carried out with the digital holographic microscopy setup

depicted in Fig. 2. For each method, focus value functions were determined in the propagation range 0 mm to 100 mm with a step incremental of 1 mm.

Figure 3 shows the results of investigations of the USAF target. In Figure 3, the x axis represents the numerical propagation direction, and y axis represents the normalized values of different autofocus functions along the propagation direction. We can see the all the unimodality are coincide with each other except variance method. This demonstrates that the proposed method works and can draw correct result.

Fig. 3 Autofocus values of different methods

Figure 4 shows the difference of defocused and focused amplitude and phase. Amplitude and phase are easier to recognize than defocused amplitude and phase.

Fig. 4 Comparison of (a), (b) defocused and (c), (d) focused reconstructed amplitude and unwrapped phase distribution

To characterize the computation times for each autofocus method, 100 times iteration in z-axis searching were carried out. The applied computer system during this investigation is Window7 64bit operation system with processor of Intel(R) Xeon(R) CPU E5-2650 v2. The results obtained are presented in Table 2. We can see the proposed method spent least time.

Table 2 Computation time comparison

Method	Search time (s)
Sobel	49.12
CORR	3.14
VAR	2.63
SPEC	4.03
Proposed method	2.33

4. Conclusion

We have demonstrated a novel approach for autofocusing in DH. The method has been tested with hologram of a USAF target and compared to other autofocus methods developed in the past. The results show that the proposed method is able to find a single focus-value with less searching time.

Acknowledgement

This study is supported by Translational Research & Development grant MOE2012-TIF-1-T-003 from the Singapore National Research Foundation and Innovation Fund grant MOE2013-TIF-2-G-012 from the Singapore Ministry of Education.

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