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Digital Off-axis Holography with Angular Multiplexing and Synthetic Aperture

Wang Zhaomin^{*ab}, Qu Weijuan^a, Yang Fang^a, Wen Yongfu^a, Anand Asundi^b

^aCentre for Applied Photonics and Laser Technology, Ngee Ann Polytechnic, 535 Clementi Road, 599489 Singapore; ^bSchool of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore

ABSTRACT

This paper discusses conventional synthetic-aperture method combined angular multiplexing in digital holography to increase the resolution and to enlarge the field of view at the same time. A structured illumination is used to realize angular multiplexing. A camera is moved by a motorized x-y stage, and scanning is performed at imaging plane. In this way we extend the band-pass for single hologram recording as well as obtain a greater sensor area resulting in a larger numerical aperture (NA). A larger NA enables a more detailed reconstruction combined with a smaller depth of field. Moreover, a phase map of the object is experimentally presented.

Keywords: Synthetic aperture, digital holography, angular multiplexing

1. INTRODUCTION

Digital holography microscopy (DHM) is an imaging technique which can access to amplitude-contrast and phase-contrast images of specimen by numerical reconstruction of digital hologram[1]. It has been successfully applied in many fields, such as the imaging of MEMS, micro-optics, and biological cells [2-5]. The resolution of DHM is equal to that of its microscopic imaging system and is given by $0.61\lambda/\text{NA}$, where NA is the numerical aperture and λ is the wavelength of the light source[6]. High resolution can be obtained by choosing a large NA microscope objective. However, a large NA Microscope Objective (MO) is associated with a small field of view and a short working distance and focus depth. These limitations restrict the application of DHM. In many situations, DHM with high resolution as well as large field of view is desired.

Angular multiplexing technique is being widely used in imaging to obtain phase and amplitude contrast super-resolution images[7]. It utilizes structured angular illumination and records the low frequency information and high frequency information of object in one frame. Through fusion processing, the resolution of the fused image can be greatly improved.

The field of view of DHM is limited to the comparatively low number of pixels of Charge Coupled Device (CCD) cameras. The pixel number is roughly 1 million with pixel size $4.65\mu\text{m} \times 4.65\mu\text{m}$ and thus the sensing size of CCD camera is $3\text{mm} \times 4\text{mm}$ accordingly. The size is still small in comparison to image on imaging plane. A dramatic improvement can in principle be obtained by use of synthetic apertures[8]. The basic idea is to combine images recorded at different camera positions to give a large image.

In this paper, a recording based on angular multiplexing is performed firstly in which multiple simultaneous interferences between the object and the reference beams are recorded on the CCD plane and then reconstruction is performed on different angle 1st spectrum. These reconstructed amplitude-contrast images are fused into a complete one. A scanning is finished by a motorized x-y stage at imaging plane. Different fused images at planed position are captured in sequence. Finally a stitched amplitude-contrast image is presented.

2. METHOD

The proposed microscopic digital holographic recording system is a modified Mach-Zehnder interferometer, as shown in Fig. 1. A collimated and expanded plane beam is divided into two beams by the beam splitter BS1. One of the beams serves as reference, and the other as object beam. Both of them are further divided to generate structure illumination and its reference. The object beam is divided into two by BS2. One passes BS3 and serves as on-axis illumination beam. The other beam is reflected by mirror M1 and M2 twice, and then it passes BS3 and serves as off-axis illumination beam. Both beams go to MO and meet reference beams at BS8. The reference beam is divided by BS4 into two beams. One of them passes BS5 and is reflected by BS6 to BS7. The other beam goes to BS7 directly. These two beams pass BS7 and

*wzh3@np.edu.sg; phone 65 6460 7715; fax 65 6467 1730

serve as reference beams, and then inference with object beams at BS8. The interferogram is finally recorded by CCD camera.

Figure 1. A modified Mach-Zehnder interferometer.

The light source used is a He-Ne laser with the wavelength 633 nm. The compound digital hologram is recorded by a CCD with 960×1280 pixels; the pixel size is $4.65 \mu\text{m} \times 4.65 \mu\text{m}$. A $10\times$ MO with NA 0.25 is used to image the object onto the recording plane. With these parameters, the resolution of the system is $0.61 \lambda / \text{NA} = 1.54 \mu\text{m}$. The camera was mounted upon a motorized X-Y stage, which was operated automatically. In a series of digital hologram exposures the camera was moved to 36 positions in a rectangular raster. The scanning route is demonstrated in Fig. 2. The steps are 6 in both the vertical and the horizontal, and the step lengths for both directions are 0.6mm. Neighboring digital holograms overlapped.

Figure 2. Scanning route.

3. EXPERIMENT

A USAF target is used for testing. A compound hologram recorded with our setup is shown in Fig. 3(a). The Fourier transformation of the hologram is shown in Fig. 3(b). From this figure, it can be seen that 1st order spectrum of the low and high frequencies, as well as the corresponding conjugated wavefronts, are separated. After frequency filtering and subsequent inverse Fourier transform, the reconstructed images containing the low and high frequencies are specified by red and green boxes are shown in Figs. 4(a) and 4(b), respectively. Fig. 4(c) is fused image from Figs. 4(a) and 4(b). Through observation, we can see that Figs. 4(a) and 4(b) are poor image quality because of the lack of low or high frequency. On the other hand, the fused image has better resolution for containing both low and high frequency information.

Figure 3. (a)Compound digital hologram, and its (b) Fourier spectrum.

Figure 4. (a) Low frequency amplitude, (b) high frequency amplitude, (c) fused amplitude.

To demonstrate the resolution improvement more clearly, we draw 3 plots at 400th row over above three amplitude images. Fig. 5(a)-(c) show the difference among them. We can see the baseline exist in low frequency amplitude image in Fig. 4(a), and more detail information is in Fig. 4(b) which contains more high frequency information. In Fig. 5(c), we can judge that it contains both low and high frequency information, and leads to better resolution.

Figure 5. Plots at 400th row over (a) Fig.4 (a), (b) Fig.4 (b), (c) Fig.4 (c).

The synthetic aperture was achieved by scanning in the following way. The positions of the section holograms are accurately known from the setting of motorized stage. The scanning route is a zigzag. A direct alignment is employed for stitching. A mask without any specimen is used to compensate for system errors[9]. The stitched digital hologram and its reconstructed amplitude distribution are shown in Fig. 6.

Figure 6. (a) Stitched digital holograms, and its (b) reconstructed amplitude.

4. CONCLUSION

In summary, a method of off-axis digital holography with angular multiplexing and synthetic aperture is introduced, which can be used to effectively get high resolution image as well as enlarge the field of view. More quantitative calibration work is needed in future.

5. ACKNOWLEDGEMENT

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