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Space-bandwidth extension in single-shot off-axis digital holography using dual-wavelength phase unwrapping

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1. Introduction

Digital holography[1] is a technique for recording a wavefront of an object wave using an image sensor and then reconstructing a three-dimensional (3D) image of an object using a computer. High-accuracy 3D shape measurement can be achieved by utilizing a phase unwrapping procedure[2] to solve 2π ambiguity even if the height of an object is more than wavelength of the light source. However, accuracy is decreased by the superposition of the unwanted images, which are the 0th-order wave and the conjugate image, on the object image. This is caused by a poor space-bandwidth of an image sensor.

In this presentation, we propose a method for extending the space-bandwidth available for single-shot recording object waves required for dual-wavelength phase unwrapping and its effectiveness is numerically investigated.

2. Principle

Figure 1 shows a schematic of the proposed method. The concept is based on SPACE digital holography[4]. In each wavelength λ_1 or λ_2, aliasing is intentionally set by introducing a reference wave with a large angle against to the optical axis of an object wave. By the setting, an object wave in each wavelength is easily separated from the unwanted images in the spatial frequency domain, as shown in Fig. 2. The space-bandwidth f_{SPACE} is given by the following expression. Here, d is the pixel pitch.

$$f_{\text{SPACE}} = 1/(4\sqrt{2}\,d) \tag{1}$$

This means the space-bandwidth is extended 1.56 times in radius, 2.43 times in area. When the angular distribution of an object wave is a rectangle-shape in each wavelength as shown in Fig. 2, the optimal angles of the reference waves are $\theta_{x(\lambda_1)}=\pm\sin^{-1}(\lambda_1/4d)$, $\theta_{y(\lambda_1)}=\pm\sin^{-1}(\lambda_1/2d)$, $\theta_{x(\lambda_2)}=\pm\sin^{-1}(\lambda_2/2d)$, and $\theta_{y(\lambda_2)}=\pm\sin^{-1}(\lambda_2/4d)$, respectively.

3. Numerical simulation

The proposed method was numerically simulated to verify its effectiveness. Figure 3 shows the 3D shape of a measured object and numerical results obtained by an off-axis configuration without aliasing and the proposed method. Though a 3D shape of the object was reconstructed by each digital holography, accuracy was decreased in a conventional off-axis configuration by artifacts due to the superposition of the 0th-order wave. In contrast, artifact was not seen and then less root-mean-square error (RMSE) was calculated by the proposed method. Thus, the effectiveness of the proposed method was numerically verified.

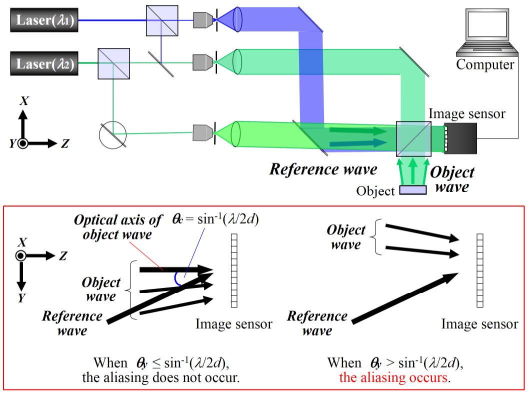

Fig. 1 Schematic of a method for extending the space-bandwidth in single-shot off-axis dual-wavelength phase unwrapping.

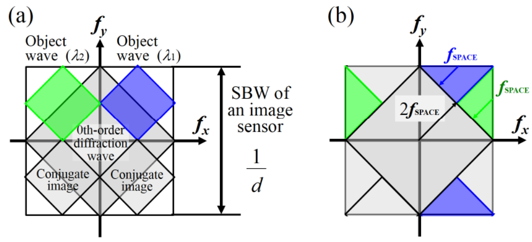

Fig. 2 Space-bandwidths in (a) a conventional off-axis configuration and (b) the proposed method, respectively.

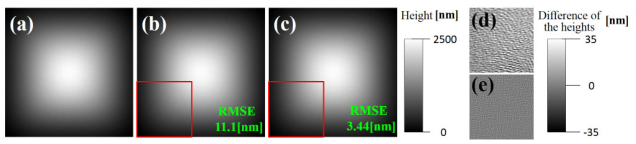

Fig. 3. (a) Object and numerical results by (b) conventional off-axis and (c) the proposed methods. (d) and (e) show the differences between the object and reconstructed images of the rectangle areas in (b) and (c). λ_1 = 488nm, λ_2 = 532nm.

4. Conclusion

We proposed, and numerically and quantitatively verified a method for measuring single-shot 3D shape with high accuracy. This method has a potential of high-speed, high-accuracy, 3D motion-picture shape imaging of dynamically moving 3D objects.

References

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