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Acquisition of information-rich images using synthetic-aperture digital holography

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Abstract: A synthetic-aperture technique is applied to the acquisition of information-rich images in phase-shifting digital holography. Since the images have a large viewing zone, diverse reconstructions can be obtained in various manners.

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1. Introduction

Rich images of objects, accompanied with phase information, can be captured by digital holography, especially using the phase-shifting [1] technique. Such information-rich images will find many applications in the future. However, generally, there are severe limitations on the size and position of objects in current digital holography due to the low resolution of current image sensors. For example, if the dimension of an object is several centimeters, it must be placed several meters from the image sensor. Since object size *w* is larger, the distance from image sensor *d* must be longer (Fig. 1). Although almost all information on the object light can be recorded as a complex-valued image, almost all recorded light comes from the same direction. In this situation, utilizing the rich information contained in the image is difficult. Therefore, increasing the angle of visual field θ is a significant problem in digital holography for display purposes. To increase angle θ, distance *d* must be reduced, which directly leads to increasing the angle of viewing zone Ω. As a result, reduction of distance *d* increases information contained in the captured images, such as object shapes observed from various angles.

Constraints on size *w* and distance *d* are relaxed in the lensless Fourier setup [2] because spatial frequency on the sensor in the setup is low compared with the Fresnel scheme. Therefore, we adopt a lensless-Fourier phase-shifting setup. We also theoretically analyzed the maximum spatial frequency of the interference fringes on the sensor and represent the maximum frequency as functions of *w* and distance *d*. As a result, the area the object can occupy is defined, i.e., if an object is placed within the area, numerical reconstruction can be obtained without aliasing error. Therefore, we refer to this as the "alias-free area". Information-rich images with largest angle θ are recorded using the alias-free area.

A lensless-Fourier setup causes another big advantage. In this setup, maximum spatial frequency on the sensor does not depend on sensor size *D*. Enlarging sensor size also directly leads to increasing angle Ω. Therefore, we introduced a synthetic aperture technique [3] into a lensless-Fourier phase-shifting setup to equivalently yield large sensor size.

In this report, we present the details of adopted techniques introduced to acquire images including rich three-dimensional information with a wide viewing zone and visual field. We also demonstrate numerical reconstructions of an object with a smooth change of visual points to prove extension of the viewing zone. Furthermore we demonstrate numerical reconstruction in the tilted plane by rotational transformation [4, 5].

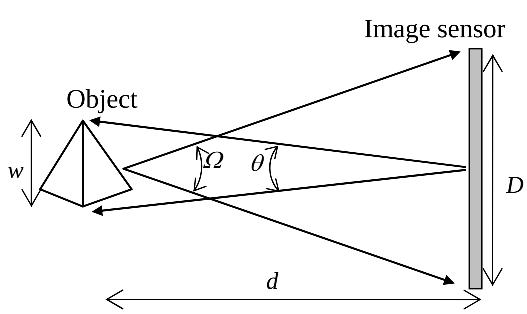

Fig. 1 Definition of visual field and viewing zone zone.

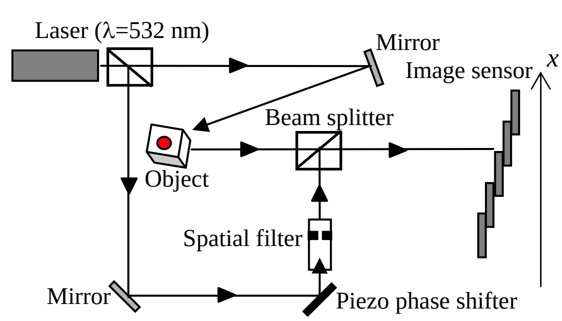

Fig. 2 Experimental setup

2. Experimental setup for synthetic-aperture digital holography

A setup for synthetic-aperture digital holography is shown in Fig. 2. The output beam of a single-mode DPSS laser is split into two arms, and a Piezo phase shifter is inserted in the reference arm. The number of pixels of the image sensor (Toshiba Terry Corp. CSB4000CL-10A) is 2000×2000 [pixel] and its sampling pitch is 6.0×6.0 [μm]. The sensor is put on a linear stage to move it in the *x*-axis direction. Fringe patterns are captured three or four times with different reference phases for each sensor position. A complex-valued image is composed of these captured fringe patterns based on the principle of phase-shifting digital holography. The sensor is moved within a distance smaller than sensor size to generate overlap between adjacent images. The exact relative position between adjacent images is provided using a correlation function between them.

3. Alias-free area and recording big objects

In the lensless-Fourier setup, the reference light is a spherical wave emitted from a point source of light. Assume that the point source and an object point are placed at distance d from the image sensor and the point source is placed on the optical axis while the object point is placed at distance w from the optical axis. The maximum spatial frequency of the interference fringe on the image sensor is given as

$$f = \frac{w/2}{\lambda\sqrt{d^2 + (w/4)^2}}, \qquad (1)$$

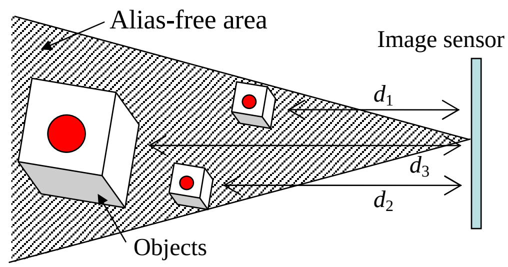

Fig. 3 Alias-free area in object space

where λ is the wavelength. When the sensor pitch is δ, this maximum frequency must satisfy Nyquist's theorem $2f \le \delta^{-1}$. When the position of all object points fulfills this relation, a captured image has an alias-free property. This alias-free area forms a pyramid in the object space, and its apex is adjacent to the image sensor, as shown in Fig. 2. Any object placed inside the alias-free area is reconstructed without aliasing errors.

The numerical reconstruction of a comparatively big object, a model of a penguin 3.0×4.5 [cm], is shown in Fig. 4. The object is placed 60 cm from the image sensor. Fig. 4 is simply the Fourier transform of the complex image calculated from four fringe patterns captured at the same sensor position (synthetic-aperture technique is not used in this case).

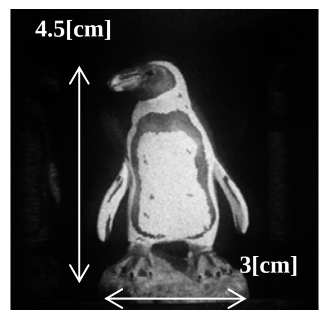

Fig. 4 Numerical reconstruction of big object

4. Numerical reconstruction from different angles

The light emitted from objects, as arranged and shown on the left side of Fig. 5, is captured as a merged complex image $g(x, y)$, composed of five images using the synthetic-aperture technique. In a lensless-Fourier setup, distribution of complex amplitude $f(x, y)$ of the object light is obtained by inverse Fourier transform of $g(x, y)$, as shown in Fig. 5. $f(x, y)$ is given on a plane at distance d_R from the sensor, where d_R is the distance between the reference point source and the image sensor. We numerically propagate $f(x, y)$ forward for distance $d \approx d_R$ and calculate complex amplitude distribution $f_d(x, y)$ near the sensor to change the point of view.

On distribution $f_d(x, y)$, a rectangle pupil whose size and position is given by (p_x, p_y) and $(x_e, 0)$, respectively, is defined as shown in Fig. 6. $f'_d(x, y)$ is a new distribution made by clipping $f_d(x, y)$ inside and padding zero outside the pupil. Finally, we again propagate $f'_d(x, y)$ backward near the object and calculate its amplitude distribution.

Examples of the numerical reconstruction of a merged complex image $g(x, y)$ recorded at distance d_R = 20 [cm] are shown in Fig. 7. The number of pixels of $g(x, y)$ is 7344×2011, and its dimension is 44.1 × 12.1 mm. Numerical reconstruction from the left and right points of

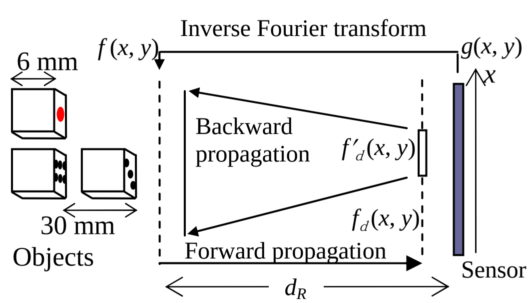

Fig. 5 Procedure for numerical reconstruction from different points of view

view is shown in (a) and (b), respectively. The pip of "6" on a die is hiding behind another die in (a), while it clearly appears in (b).

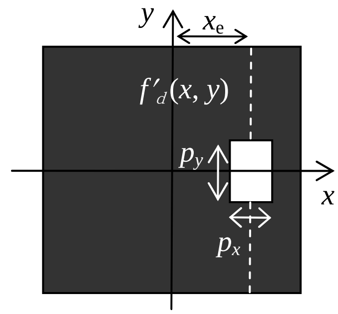

Fig. 6 Definition of pupil

5. Numerical reconstruction on a tilted plane

As shown in Fig. 8, planar objects A and B are arranged on the same plane slanted approximately 70[º] to the sensor. The merged complex image is composed of 5 individual images captured in d_R = 19.5 [cm]. We numerically propagated the merged image to an intermediated position between A and B, as shown in Fig. 9(a), and then calculated the numerical reconstruction on the tilted plane by performing rotational transformation at 69[º], as shown in Fig. 9(b).

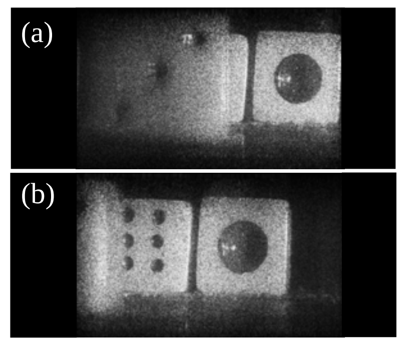

Fig. 7 Numerical reconstructions from different angles: (p_x, p_y) = (1.7, 3.5) [mm], (a) x_e = −9.83 [mm], (b) x_e = 9.83 [mm]

6. Conclusion

In this study, the expansion of a visual field was made by utilizing the alias-free area in lensless-Fourier phase-shifting digital holography. Furthermore, the viewing zone is successfully expanded by using the synthetic-aperture technique. As a result, information-rich images were acquired that allowed numerical reconstructions to be obtained from arbitrary points of view and on an arbitrary tilted plane.

7. References

[1] I.Yamaguchi and T. Zhang, "Phase-shifting digital holography," Opt. Lett. **22**, 1268-1270 (1997).

[2] C.Wagner, S. Seebacher, W. Osten, and W. Juptner, "Digital recording and numerical reconstruction of lensless Fourier holograms in optical metrology," Appl. Opt. **38**, 4812-4820 (1999).

[3] R. Binet, J. Colineau, and J. Lehureau, "Short-range synthetic aperture imaging at 633 nm by digital holography," Appl. Opt. **41**, 4489-4496 (2002).

[4] K. Matsushima, H. Schimmel, and F. Wyrowski, "Fast calculation method for optical diffraction on tilted planes by use of the angular spectrum of plane waves," J. Opt. Soc. Am. **A20**, 1755-1762 (2003).

[5] K. Matsushima, "Rotational transformation for reconstruction of digital holography and creation of CGH," to be presented at the conference on *Digital Holography and Three-Dimensional Imaging*.

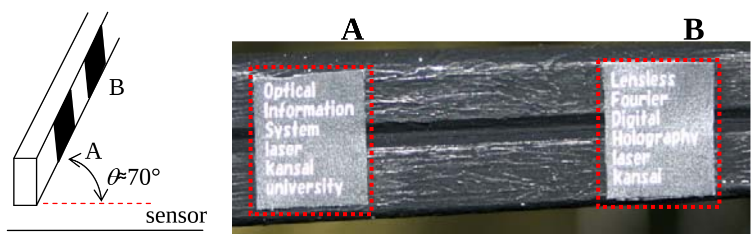

Fig. 8 Planar objects on tilted plane

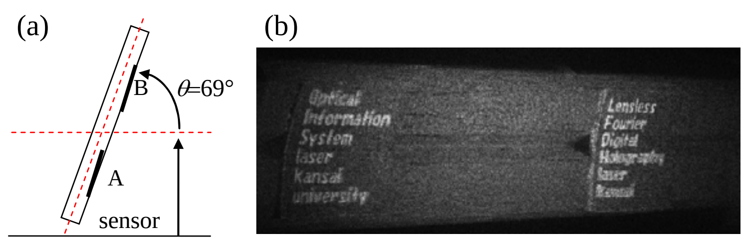

Fig. 9 Numerical reconstruction of planar objects on tilted plane (b) and its procedure (a)