Improving image quality of parallel phase-shifting digital holography

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Abstract. The authors propose parallel two-step phase-shifting digital holography to improve the image quality of parallel phase-shifting digital holography. The proposed technique can increase the effective number of pixels of hologram twice in comparison to the conventional parallel four-step technique. The increase of the number of pixels makes it possible to improve the image quality of the reconstructed image of the parallel phase-shifting digital holography. Numerical simulation and preliminary experiment of the proposed technique were conducted and the effectiveness of the technique was confirmed. The proposed technique is more practical than the conventional parallel phase-shifting digital holography, because the composition of the digital holographic system based on the proposed technique is simpler.

1. Introduction
Recently, there has been a great deal of progress in image sensors such as charge-coupled devices (CCDs) and complementary metal-oxide semiconductor image sensors. Image sensors have been used in holography in place of the holographic material. Holography using image sensors is called digital holography \cite{1} and it is applied to many fields \cite{2,3}. Digital holography reconstructs the image of an object by computer, and therefore has the following attractive features: a wet-process for developing recording media is not required; quantitative evaluation is easy for three-dimensional (3-D) images of objects; and focused images of 3-D objects at desired depth can be instantaneously acquired without a mechanical focusing process.

In digital holography, a Fresnel transform is generally applied to the hologram recorded at the image sensor to reconstruct the image. Although the Fresnel transform alone is the simplest calculation scheme to reconstruct the image and it allows instantaneous measurement, the quality of the reconstructed image is not high because both the minus-first and the zeroth-order diffracted waves are superimposed on the image of the object. To obtain only the first-order diffracted wave, phase-shifting interferometry have been introduced to digital holography \cite{4}.

It is well known that in phase-shifting digital holography to retrieve the original complex amplitude of object wave at the image sensor at least three holograms are sequentially recorded using reference
waves with different phase retardations. Usually, the retardation is sequentially changed by using wave plates or a piezoelectric-transducer mirror. Although the phase-shifting technique achieves accurate images, it is useless for instantaneous measurement of moving objects. To achieve phase-shifting method for instantaneous measurement, a parallel phase-shifting digital holography and its optical implementation were proposed [5-9].

The parallel phase-shifting digital holography can carry out the phase-shifting interferometry by a single-shot recording of a digital hologram. In the technique, the phase-shifting for the reference wave is simultaneously implemented by wavefront segmentation of reference wave. Although the parallel phase-shifting digital holography previously reported has been able to carry out instantaneous phase-shifting interferometry, the device consisting array of $3 \times 1$ or $2 \times 2$ phase retarders located in the reference wave to implement parallel phase-shifting is complicated. If the number of pixels in each segment can be decreased, the effective number of the pixels composing the image can be increased in case that the number of pixels of image sensor is constant. The increase of the effective number of pixels can improve the quality of the reconstructed image. To lessen the number of pixels in each segment than three, some conditions or restrictions have to be appended as it is required in sequential two-step phase-shifting interferometry. As another example of phase-shifting digital holography, a phase-shifting method using array of $2 \times 1$-cell configuration located in front of image sensor was proposed [9]. Because the technique requires not only a hologram including information of two holograms but also intensity of object wave, the technique is not capable of measuring moving object. Only the $2 \times 1$-cell configuration reported in the paper is impossible to record the intensity of object wave and two holograms simultaneously. If the intensity of the object wave was recorded only before operating the digital holography system in advance, the technique is impossible to measure 3-D information of moving object.

In this paper, we propose parallel two-step phase-shifting digital holography, which uses two-step phase-shifting interferometry proposed by M. F. Meng et al. [10], capable of instantaneous 3-D measurement for dynamically moving object. This technique can improve the quality of the reconstructed image. To verify the effectiveness of the proposed holography, both numerical simulation and preliminary experiment are conducted.

2. Parallel phase-shifting digital holography
Parallel phase-shifting digital holography [5] is a technique that can record and reconstruct amplitude and phase distributions of the object from a single hologram. Essence of the technique is capable of carrying out the phase-shifting interferometry using wavefront segmentation of reference wave at a time. Several types of parallel phase-shifting digital holography were reported [5-9]. To explain the principle of parallel technique, we take parallel four-step phase-shifting digital holography for instance. The recording process of the technique is schematically illustrated in Fig. 1. An example of the optical implementation of the parallel four-step phase-shifting digital holography is shown in Fig. 1(a).

A phase-shifting device array is placed in the reference wave in the recording optical setup of digital holography, which uses the Fresnel transform alone in the reconstruction. The array device is a segmented array with a $2 \times 2$-cell configuration that generates the periodical four-step phase distributions, $0, \pi/2, \pi, 3\pi/2$, required for phase-shifting, as shown in Fig. 1(b). The array device is imaged onto the image sensor by an imaging system so that the phase distribution of the reference wave at the image sensor plane corresponds with the arrangement of pixels in the image sensor. The size of the imaged cells at the image sensor is the same as that of the pixels. Thus, the image sensor captures a hologram recorded with the reference wave containing the four-step phase distributions.
The processing procedure for the reconstruction of the digital holography [5,6] is as follows. The pixels containing the same phase-shift are extracted from the recorded hologram. For each phase shift, the extracted pixels are relocated in another 2-D image at the same addresses at which they were located before being extracted. The values of pixels not relocated in the 2-D image are interpolated using the neighboring pixel values. By carrying out the relocation and interpolation for the four phase-shifts, four holograms, $I_0$, $I_{\pi/2}$, $I_\pi$, $I_{3\pi/2}$, are obtained. If the amplitude and phase distributions of the object are not drastic, Eq. (1) below, which is a calculation of the complex amplitude used in the sequential phase-shifting digital holography, gives almost the same distribution as $u(x, y)$ which is the true complex amplitude of the object wave on the image sensor plane.

$$u(x, y) = \frac{[I(0) - I(\pi)] + i[I(\pi/2) + I(3\pi/2)]}{4A_r}. \tag{1}$$

Here, $A_r$ is the amplitude of the reference beam. The complex amplitude of the object $U(X, Y)$ can be reconstructed by the following Fresnel transformation of the derived complex amplitude.

$$U(X, Y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} u(x, y) \exp \left[ \frac{2\pi i}{\lambda} \left( Z + \frac{(X-x)^2 + (Y-y)^2}{2Z} \right) \right] dx dy. \tag{2}$$

Here, $\lambda$ and $Z$ are the wavelength of the laser beam and the distance from the image sensor and image reconstruction plane, respectively. Key to realize the parallel phase-shifting digital holography is improving image quality of the reconstructed image and simplifying the elements and configuration of the phase-shifting array device so as to implement the array device easily. To improve the image quality, a parallel three-step phase-shifting digital holography has been proposed based on the same concept of spatial division multiplexing of reference wave[8].

### 3. Parallel two-step phase-shifting digital holography

To improve the quality of the reconstructed image and to implement the phase-shifting array device simply, a parallel two-step phase-shifting digital holography is proposed by merging the two-step phase-shifting method reported by Meng et al. [10] with the parallel phase-shifting digital holography. Meng’s technique can calculate complete complex amplitude of object from two holograms and the amplitude of reference wave under the condition that the intensity of reference wave is greater than the maximum intensity of object wave. The amplitude of reference wave has only to be measured before operating the digital holographic system based on the technique, because the reference wave is constant during the system operation. Therefore, the technique is applicable for moving object. The intensity of the reference wave $|A_r|^2$ is measured by blocking the object wave and adjusted so as to be sufficiently greater than that of the object wave before the system operation in advance. The recording process of the proposed technique is the same as the conventional parallel technique except for the elements and configuration of the phase-shifting array device. The array device is a segmented array
with such the $2 \times 1$-cell configuration that the periodical two-step phase distributions, $0$ and $-\pi/2$, required for the two-step phase-shifting interferometry are generated, as shown in Fig. 2. As similar to the conventional parallel techniques, the array device is imaged onto the image sensor and the size of the imaged cells at the image sensor is the same as that of the pixels. Thus, the image sensor captures a single hologram recorded with the reference wave containing the phase-distributions required for the two-step phase shifting interferometry. The proposed technique can be also embodied as the same way as reported in [6] by using polarization.

The processing procedure for the reconstruction of the proposed technique is as follows. As similar to the conventional techniques, the pixel extraction, the relocation and interpolation for the two phase-shifts are carried out, then two holograms, $I(0)$, $I(-\pi/2)$, are obtained. Eq. (3) below, which is a calculation of the complex amplitude used in the case of $-\pi/2$ in phase shift of Meng’s technique [10], gives $u(x, y)$ the complex amplitude of the object wave at the image sensor plane.

$$u(x, y) = \frac{\{I(0) - a(x, y)\} - i\{I(-\pi/2) - a(x, y)\}}{2A_r}.$$  \hspace{1cm} (3)

Here, $a(x, y)$ is defined as follows.

$$a(x, y) = \frac{\{v - (v^2 - 2w)^{1/2}\}}{2},$$  \hspace{1cm} (4)

$$v = I(0) + I(-\pi/2) + 2A_r^2,$$  \hspace{1cm} (5)

$$w = I(0)^2 + I(-\pi/2)^2 + 4A_r^4.$$  \hspace{1cm} (6)

When $I(0)$, $I(-\pi/2)$ and $A_r$ are known, the complex amplitude of the object $U(X, Y)$ can be reconstructed by Eqs.(2) and (3).

**Figure 2** Schematic diagram of the parallel two-step phase-shifting digital holography. (a) An example of optical implementation system, (b) the phase-shifting array device and the distribution of the reference wave for the parallel two-step-phase-shifting digital holography.

### 4. Numerical simulation

The proposed digital holography was numerically simulated to verify its validity. The wavelength of the laser beam for illuminating the object, the pixel size of the image sensor, and the distance between the object and the image sensor were assumed to be 633 nm, 10 µm, and 7 cm, respectively. Images shown in Figs. 3(a) and 3(b) were prepared as the object. The intensity ratio of the reference wave to that of the object wave is set to be greater than four. Numerical results are shown in Figs. 3(c)-3(l).
5. Preliminary experiment

A preliminary experiment was conducted to verify the validity of the proposed technique. Figure 4 shows the experimental system. Since a phase-shifting array device has not been commercially available yet, we used an optical system employed in the sequential two-step phase-shifting technique proposed by Meng et al. [10], consisting of a piezoelectric-transducer mirror equivalently producing the hologram to be obtained, a He-Ne laser operating at 633 nm, and a CCD camera with 768(H) × 493(V) pixels of 11 mm (H) × 13 mm (V) pixel size. At the beginning of the experiment, the intensity of the reference wave was measured. The intensity ratio of the reference wave to that of the object wave was set to be greater than five. Next, two holograms, \( I(0) \) and \( I(-\pi/2) \), were optically obtained in sequence by changing the position of the piezoelectric-transducer. As shown in Fig.4(b), the object was a transparent film on which the Japanese character meaning “light” was printed, and it is located 31 cm distant from the CCD plane. A diffuser was attached on the transparent film. For the hologram recorded using each phase-retardation, the pixels corresponding to the same phase retardation by the phase-shifting device were extracted. The extracted pixels for the two holograms were relocated in a 2-D image at the same addresses at which they were located before being extracted. Thus the hologram to be recorded using the array device was equivalently generated.

Figure 4 Optical system for the preliminary experiment. (a) Recording system, (b) object.
Experimental results are shown in Fig. 5. The correlation coefficients between the reconstructed images by parallel techniques and that by sequential technique are summarized in Table 1. The reconstructed image by the proposed technique more closely resembles that by the sequential technique than that by the Fresnel transform alone.

![Figure 5](image)

*Figure 5* Reconstructed images. Sequential 4-step phase-shifting, (a) amplitude, (b) phase; 2-step phase-shifting, (c) amplitude, (d) phase; Fresnel transform alone, (e) amplitude, (f) phase.

| Table 1. Correlation coefficients between the reconstructed images by other digital holographies. |
|-------------|------------------|------------------|
|             | Amplitude        | Phase            |
| Proposed parallel (2-step) | 0.863            | 0.205            |
| Fresnel transform alone        | 0.087            | 0.040            |

6. Conclusion

We have proposed a single-shot phase-shifting digital holography that carries out the two-step phase-shifting interferometry at a time in order to improve image quality of parallel phase-shifting digital holography. Furthermore, the proposed system is more practical than the conventional parallel phase-shifting digital holography systems because the system based on the proposed technique can be constructed more simply than that of the conventional parallel phase-shifting digital holography. The results of the numerical simulation and preliminary experiment agree well with those of the sequential phase-shifting digital holography. The proposed parallel technique will contribute to accurate measurement of dynamically moving 3-D objects, such as those of interest in biology, fluid physics, particle measurement, and so on.

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