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Color quality improvement of reconstructed images in color digital holography using speckle method and spectral estimation

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ABSTRACT

In this study, we report color quality improvement of reconstructed images in color digital holography using the speckle method and the spectral estimation. In this technique, an object is illuminated by a speckle field and then an object wave is produced, while a plane wave is used as a reference wave. For three wavelengths, the interference patterns of two coherent waves are recorded as digital holograms on an image sensor. Speckle fields are changed by moving a ground glass plate in an in-plane direction, and a number of holograms are acquired to average the reconstructed images. After the averaging process of images reconstructed from multiple holograms, we use the Wiener estimation method for obtaining spectral transmittance curves in reconstructed images. The color reproducibility in this method is demonstrated and evaluated using a Macbeth color chart film and staining cells of onion.

1. Introduction

Digital holography is an effective technique for the recording and reconstruction of complex amplitudes of optical fields [1–4]. In this technique, an interference pattern of two coherent wavefronts is detected and digitized by an image sensor such as a charge–coupled device (CCD) or a complementary metal–oxide semiconductor (CMOS) camera, and then digital holograms are saved into a computer. The reconstruction process of digital holograms is performed by numerical calculation in computer.

One of applications in digital holographic technique is color digital holography, which is actively researched in the area which requires color information of an object such as a three-dimensional (3D) color imaging, recognition of 3D color objects, deformation measurement and microscopy [5–10]. In color digital holography, digital holograms are typically recorded using three lasers with different wavelengths corresponding to red, green and blue (RGB), respectively. These RGB holograms are reconstructed by a computer, and then a reconstructed color image is produced by the process of color composition in colorimetry. In this technique, the main issue is that a color information of an object is obtained in a few spectral values corresponding to wavelengths of the lasers used in the recording process, not a continuous spectral curve. It is the inherent and critical issue in color digital holography while the acquisition of a continuous spectral curve is desired for applying this technique to various research areas, such as biology, medical science, food and agricultural inspection, information security and so on. For obtaining continuous spectral curves of objects from a few spectral values, the Wiener estimation method is applied to color digital holography [11,12]. Recently, Funamizu et al. reported the application of the estimation method of a spectral curve to color digital holographic microscopy using speckle illuminations [13,14]. In these reports, digital holograms are recorded using an off-axis optical system, and direct current (DC) terms and a twin image are separated from the object image and are eliminated by the spatial filtering method [15]. The digital holographic technique in the off-axis setup makes a sacrifice of the spatial resolution while it gives the higher temporal resolution.

A rational technique has been proposed for suppressing DC terms and a twin image in digital holography using speckle illuminations, which is called the speckle method [4,16,17]. In this technique, an in-line setup is used as an optical system, and an object is illuminated with speckle fields generated from a diffuser such as a ground glass plate. After recording a number of digital holograms using statistically-independent speckle fields, DC terms are suppressed by applying a high-pass filter to each hologram [18]. Object and twin images reconstructed from multiple holograms are averaged for reducing the intensity fluctuation of object images due to speckle illuminations and for eliminating a twin image. After the averaging process, intensity distributions of a twin image become a constant since it is regarded as speckle fields by

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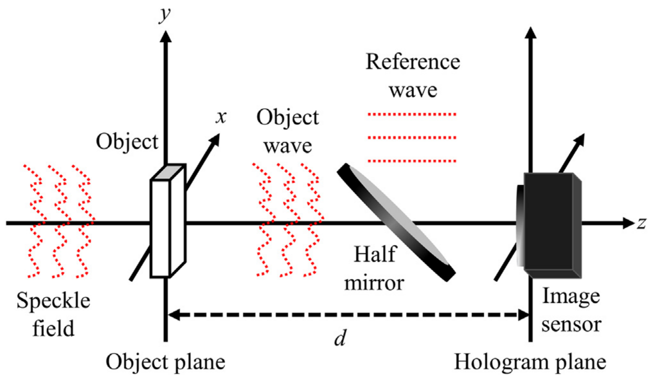

Fig. 1. Schematic diagram of optical configuration.

use of speckle illuminations. Therefore, a twin image is eliminated by subtracting the constant from the reconstructed image. In comparison with the other methods, digital holographic technique using speckle illuminations mainly has two advantages [19]. First one is that spatial resolution in the 3D space is enhanced by a random down-shifting of the higher spatial frequency components of the object using speckle illuminations. Second one is that image quality is improved by the averaging process since speckle noises due to the use of an optical source with higher coherence and inherent fixed pattern noise due to the diffraction from scatters in the optical system are reduced. However, it also has two disadvantages. One is that temporal resolution becomes lower due to the acquisition of a number of holograms, even if the off-axis setup and the spatial filtering method are used for the recording and reconstruction of holograms. Another is that phase information of reconstructed images is not directly obtained since it is randomly modulated by the complex amplitude of speckle illuminations.

In the present paper, we report color quality improvement of reconstructed images in color digital holography using the speckle method and the Wiener estimation method. In addition, we evaluate the effect of DC terms and a twin image on color quality of spectral images using these methods.

2. Recording and reconstruction of digital holography using speckle illuminations

Fig. 1 shows the schematic diagram for recording holograms. An object is placed in the x–y plane at $z = 0$, which is called the object plane. An image sensor is placed in the x–y plane at $z = d$, which is called the hologram plane. The object is illuminated by a speckle field, which is produced by illuminating a diffuser such as a ground glass plate with coherent light, and then an object wave modulated by the speckle field is generated. The object wave propagates over a distance d and is detected on an image sensor.

Now, we carry out a one-dimensional analysis of the propagation of the object wave in the z-axis direction for simplicity. The light propagation of the object wave can be denoted by [4]

$$U_{os}(z) = \mathcal{D}_z[U_{os}(0)], \tag{1}$$

where $U_{os}(z)$ is the complex amplitude of the object wave at a distance z and $\mathcal{D}_z[\cdot]$ stands for the light propagation from the object plane to an arbitrary plane at a distance z on the basis of Fresnel diffraction. The object wave in the object plane can be written as

$$U_{os}(0) = U_o(0)U_s(0), \tag{2}$$

where $U_o(0)$ and $U_s(0)$ are the complex amplitude of an object and of a speckle field incident on an object. In the recording process of digital holograms, a plane wave is used as a reference wave $U_r = 1$. The two waves interfere and a hologram is recorded on an image sensor. The intensity distribution of holograms is expressed as

$$\begin{aligned} I_H(d) &= |1 + U_{os}(d)|^2 \\ &= 1 + |U_{os}(d)|^2 + U_{os}(d) + U^*_{os}(d), \end{aligned} \tag{3}$$

where $*$ stands for the complex conjugate. In the reconstruction process of digital holograms, the inverse propagation of optical fields is calculated and is expressed as

$$\mathcal{D}_{-d}[I_H(d)] = \mathcal{D}_{-d}[1 + |U_{os}(d)|^2] + \mathcal{D}_{-d}[U_{os}(d)] + \mathcal{D}_{-d}[U^*_{os}(d)]. \tag{4}$$

Using Eqs. (1) and (2), and these expressions

$$\mathcal{D}_{-z}[U_{os}(0)] = U^*_{os}(z) \tag{5}$$

$$\mathcal{D}_{-z}\{\mathcal{D}_z[U_{os}(0)]\} = \mathcal{D}_z\{\mathcal{D}_{-z}[U_{os}(0)]\} = U_{os}(0) \tag{6}$$

$$\mathcal{D}_{-z}\{\mathcal{D}_{-z}[U_{os}(0)]\} = \mathcal{D}_{-2z}[U_{os}(0)] = U^*_{os}(2z), \tag{7}$$

Eq. (4) is rewritten as

$$\mathcal{D}_{-d}[I_H(d)] = \mathcal{D}_{-d}[1 + |U_{os}(d)|^2] + U_{os}(0) + U^*_{os}(2d). \tag{8}$$

In this equation, the first and second terms are DC terms. The third term has information about the object wave, which we will call an object image, and the fourth term is a twin image. In the case of holograms recorded by an in-line setup, all terms are reconstructed around the origin in the reconstruction plane. Therefore, the object image overlaps with DC terms and a twin image, which causes the degradation of image quality of the object image.

3. Suppression of DC terms and a twin image in digital holography using the speckle method

For suppressing DC terms of holograms recorded in an in-line setup, several high-pass filters are proposed. The properties of these filters are derived theoretically [18] and demonstrated experimentally [16]. As a preprocessing before the reconstruction process of multiple holograms, DC terms are suppressed by the numerical technique based on high-pass filtering of digital holograms in the spatial frequency region. The Fourier spectrum of digital holograms is filtered by a Gaussian filter expressed as

$$g(f_x) = \exp\left(-\frac{f_x^2}{w_f^2}\right), \tag{9}$$

where f_x is the spatial frequency coordinate of a hologram and w_f is the extent of the Gaussian filter. A smoothed hologram is produced by applying the inverse Fourier transform to the filtered Fourier spectrum. DC terms could be suppressed by subtracting the smoothed hologram from the original one, which is a role in a high-pass filtering of the original hologram.

After suppressing DC terms, Eq. (8) reduces to

$$\mathcal{D}_{-d}[I_H(d)] = U_{os}(0) + U^*_{os}(2d). \tag{10}$$

A number of holograms are acquired by illuminating the object with speckle fields which are statistically independent of each other. When the reconstructed images from the holograms are averaged on the basis of intensity, Eq. (10) becomes

$$\begin{aligned} \left\langle |\mathcal{D}_{-d}[I_H(d)]|^2 \right\rangle &= \left\langle |U_{os}(0) + U^*_{os}(2d)|^2 \right\rangle, \\ &= \left\langle |U_{os}(0)|^2 \right\rangle + \left\langle |U^*_{os}(2d)|^2 \right\rangle, \end{aligned} \tag{11}$$

where $\langle \cdot \rangle$ stands for an ensemble average. Now, it is assumed that the intensity distributions of a twin image uniformly spread over the reconstruction plane and can be regarded as speckle fields due to the use of speckle illuminations. Since the two images have the same energies and the ensemble average of speckle intensity becomes a constant [20,21], the averaged intensity of a twin image is approximately derived from

$$\left\langle |U^*_{os}(2d)|^2 \right\rangle = \frac{I_E}{2N^2}, \tag{12}$$