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Super-resolution imaging in digital holography by using dynamic grating with a spatial light modulator

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ABSTRACT

A super-resolution imaging method using dynamic grating based on liquid-crystal spatial light modulator (SLM) is developed to improve the resolution of a digital holographic system. The one-dimensional amplitude cosine grating is loaded on the SLM, which is placed between the object and hologram plane in order to collect more high-frequency components towards CCD plane. The point spread function of the system is given to confirm the separation condition of reconstructed images for multiple diffraction orders. The simulation and experiments are carried out for a standard resolution test target as a sample, which confirms that the imaging resolution is improved from 55.7 μm to 31.3 μm compared with traditional lensless Fourier transform digital holography. The unique advantage of the proposed method is that the period of the grating can be programmably adjusted according to the separation condition.

1. Introduction

In digital holography (DH), the hologram is recorded by a CCD or a CMOS camera instead of the traditional photosensitive materials, and the reconstruction is performed numerically. DH has growing applications in biological cell imaging, microstructure detection, particle field analysis, and temperature field measurement etc. [1–6]. The resolution of a digital holographic system is directly related to the numerical aperture (NA) of the recording device and the wavelength used in the recording. Because of the finite aperture of the imaging system, only the low-frequency parts of the object spectrum are recorded by the CCD. As a result, the corresponding reconstructed images are band-limited in the frequency domain. Therefore the improvement of the resolution in digital holography is the main research focus [7–18].

To improve the resolution, researchers have lately introduced super-resolution techniques into digital holographic imaging. Alexandrov et al. rotated the sample and recorded a digital hologram for each position to enhance the resolution [7]. Massing et al. recorded nine holograms by translating CCD to different positions to improve the resolution [8]. Mico et al. utilized the tilted illumination and common-path interferometric recording to enhance the resolution of the imaging system [12]. These methods need to record multiple digital holograms by moving optical elements manually, and the object position must be fixed during the recording. Therefore, the high stability of the system is demanded. However it is not easy to meet this rigid demand in a practical environment. Fortunately, grating technology only needs to record one hologram, which is reconstructed by subsequent numerical processing in order to get more information on the object wave, and the experimental set-up is simple and stable. Liu et al. demonstrated that placing a grating in front of the specimen means high frequency diffracted object waves can reach the CCD to improve the resolution [16]. Paturzo et al. specially designed an electro-optical two-dimensional grating in their lab to improve the resolution [18], but their grating is not available commercially. At present, the diffraction propagation theory using grating for super-resolution imaging need to be further studied and the separation conditions of numerical reconstructed images for multiple diffraction orders of the object wave have not been quantitatively analyzed. The key to super-resolution imaging with grating technology is to optimize the experimental parameters in the configuration system. If a fixed grating is used for the super-resolution imaging, the adjustment of experimental parameters is often more complicated and the field of view of the imaging system cannot be adjusted flexibly.

In this paper, we analyze the point spread function of the system and confirm the separation condition of reconstructed images for multiple diffraction orders. Then the SLM is applied to realize the periodic amplitude grating which can be dynamically adjusted by

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computer. The effectiveness of the super-resolution imaging method is verified by the simulation and experimental results.

2. Theoretical analysis of super-resolution imaging in digital holography

2.1. Recording principle of digital hologram

The recording process of the hologram based on one-dimensional grating in digital holography is shown in Fig. 1, where (x_0, y_0), (x', y') and (x, y) are the coordinates on the object, grating and hologram planes, d_1 is the distance between the object and the grating planes, d_2 is the distance between the grating and the hologram plane, and $d_1+d_2=d$ represents the recording distance.

A collimated plane beam illuminates the object, and it is scattered by the micro-structure of the object to form the diffraction beams O_0, O_1, O_{-1}, O_2, O_{-2}, …. The beams with high diffraction angles carry the higher frequency information of the object. Because of the limited aperture of the CCD, only part of the total light scattered by the object can be collected by the CCD in conventional holography. The cosine gray grating loaded on the SLM is placed between the object and the CCD, which collects the higher frequency information of the object towards CCD. Next we will analyze the diffraction propagation of the object wave from the object plane to the hologram plane. For simplification, one-dimensional distribution is assumed in the following analysis.

Assuming a point object is located at the object plane $x_o=0$, it is represented by $\delta(x_0)$. According to the Fresnel diffraction formula, ignoring the constant factors, the complex amplitude distribution of the object beam after the grating is

$$U(x')=\exp\left[\frac{jk}{2d_1}(x')^2\right]\times t(x'), \tag{1a}$$

where k is the wave vector, and

$$t(x')=\frac{1}{2}+\frac{m}{2}\cos\left(\frac{2\pi}{p}x'\right), \tag{1b}$$

denotes the transmittance function of the diffraction grating, and m and p describe the parameters of the modulation and the period of the grating, respectively. The transmittance function of the grating diffracts the object beam into three diffraction orders such as: 0 order, $+1$ order, and -1 order. That is why the recorded optical field distributions on the CCD are $U_0(x)$, $U_{+1}(x)$ and $U_{-1}(x)$, respectively, and can be written as follows

$$U(x)=\int_{-\infty}^{\infty}U(x')\times\exp\left[\frac{jk}{2d_2}(x-x')^2\right]dx'=U_0(x)+U_{+1}(x)+U_{-1}(x) \tag{2}$$

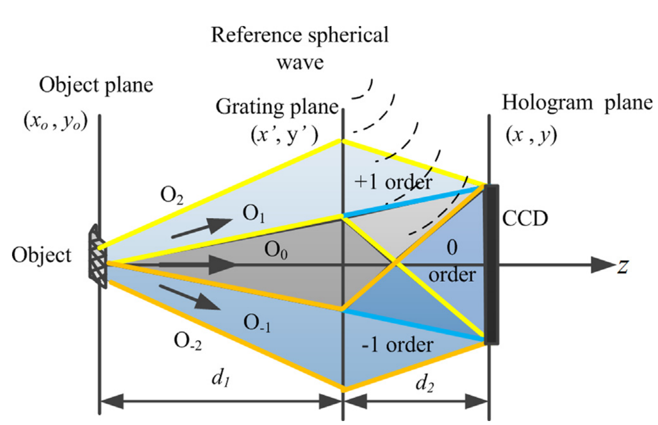

Fig. 1. Schematic diagram of recording process in super-resolution digital holographic imaging based on the grating system.

The optical field distributions of the three diffraction orders waves on the CCD are

$$U_0(x)=\exp\left(\frac{jk}{2d}x^2\right), \tag{3a}$$

$$U_{+1}(x)=\frac{m}{2}\exp\left(-\frac{j\lambda\pi d_1 d_2}{p^2 d}\right)\exp\left(\frac{jk}{2d}x^2\right)\exp\left(-\frac{j2\pi d_1 x}{pd}\right), \tag{3b}$$

and

$$U_{-1}(x)=\frac{m}{2}\exp\left(-\frac{j\lambda\pi d_1 d_2}{p^2 d}\right)\exp\left(\frac{jk}{2d}x^2\right)\exp\left(\frac{j2\pi d_1 x}{pd}\right). \tag{3c}$$

The spherical wave from the point source of light (x_r, y_r) located at distance equivalent to the object plane from the CCD plane is used as a reference beam. It is a typical lensless Fourier transform digital holographic system if the grating is removed [19].

The spherical reference beam on the CCD is given by

$$R(x)=\exp\left[\frac{jk}{2d}(x-x_r)^2\right]. \tag{4}$$

The intensity of the recorded hologram is

$$H(x)=\left|U_0(x)+U_{+1}(x)+U_{-1}(x)+R(x)\right|^2\times\mathrm{rect}\left(\frac{x}{L}\right), \tag{5}$$

where L is the size of the CCD. In order to obtain the object information in the digital hologram, only the terms related to the real image are considered, and then $H'(x)$ can be expressed as [21]

$$\begin{aligned}H'(x)&=\left[U_0(x)R^*(x)+U_{+1}(x)R^*(x)+U_{-1}(x)R^*(x)\right]\times\mathrm{rect}\left(\frac{x}{N\Delta x}\right)\\&=H_0(x)+H_{+1}(x)+H_{-1}(x)\end{aligned} \tag{6}$$

It can be seen that the hologram is the superposition of the sub-holograms which are caused by the interference between the three diffraction orders waves and the reference beam on the CCD.

2.2. Separation condition of reconstructed images for multiple diffraction orders

Assuming that the reconstruction illumination beam is $C(x)=\exp(jkx^2/2d)$, we multiply $H'(x)$ by $C(x)$ and then back propagate the optical field to the original input plane [20]. The distribution of the optical field on the object plane can be obtained as the point spread function (PSF) of the holographic imaging system. After derivation, it can be expressed as

$$\begin{aligned}PSF(x_0)=\exp\left[-\frac{jk}{2d}x_0^2\right]\Bigg\{&\mathrm{sinc}\left[N\Delta x\left(\frac{x_r}{\lambda d}+\frac{x_0}{\lambda d}\right)\right]\\&+\frac{m}{2}\times\exp\left[-\frac{j\lambda d_1 d_2\pi}{p^2 d}\right]\mathrm{sinc}\left[N\Delta x\left(\frac{x_r}{\lambda d}+\frac{x_0}{\lambda d}+\frac{d_1}{pd}\right)\right]\\&+\frac{m}{2}\times\exp\left[-\frac{j\lambda d_1 d_2\pi}{p^2 d}\right]\mathrm{sinc}\left[N\Delta x\left(\frac{x_r}{\lambda d}+\frac{x_0}{\lambda d}-\frac{d_1}{pd}\right)\right]\Bigg\}\end{aligned} \tag{7}$$

The point spread function is composed of three parts modulated by Sinc Functions in different central positions. They are the complex amplitude distribution of the reconstruction of 0, $+1$, and -1 order diffraction waves. According to Eq. (7), the distances are $\lambda d_1/p$ between 0 order and ±1 order and to prevent aliasing among the three diffraction orders, the size of the imaging object should satisfy the following equation

$$X\le\frac{\lambda d_1}{p}, \tag{8}$$

where X denotes the size of the imaging object. Meanwhile, in order to satisfy the sampling theorem and the separation condition of reconstruction, the offset x_r of the reference point source should satisfy [19]

$$\frac{3}{2}X\le x_r\le\frac{\lambda d}{2\Delta x}-\frac{X}{2}. \tag{9}$$