LED holographic imaging by spatial-domain diffraction computation of textured models

Ding-Chen Chen, Xiao-Ning Pang, Yi-Cong Ding, Yi-Gui Chen, and Jian-Wen Dong*
School of Physics and Engineering, and State Key Laboratory of Optoelectronic Materials and Technologies, Sun Yat-sen University, Guangzhou, China
* Corresponding author: dongjwen@mail.sysu.edu.cn

ABSTRACT

Unavoidable speckle noise on reconstructed image in laser-based holographic system has been a serious problem in holographic display, due to both temporal and spatial coherence of laser. Employing partially coherent light into optics experiment is an effective way to reduce the speckle noise and thus enhance the signal-to-noise ratio. We will show you the analysis on the coherence of input light, which will affect the quality of the reconstructed image by computer generated hologram (CGH). LED light source with band-pass filters and spatial filters is used to achieve different levels of coherence. The experimental results show high agreement with our analysis. We will also show you how to eliminate the unexpected fringes by employing fast Fourier transform, which can overcome the drawback in our previous proposal with a full analytical algorithm for encoding the CGH of polygonal model. In conclusion, we propose the LED-based holographic imaging system, in order to improve the quality of the holographic imaging.

Keywords: Speckle; Holography; Computer holography; Holographic display.

1. INTRODUCTION

Three dimensional (3D) display is now attracting more and more attention with the help of the development of the manufacturing technology. Holography is one of the promising 3D techniques that is able to provide binocular parallax. Computer generated hologram (CGH) employs quantities of computing segments to form the virtual 3D model, and the hologram is obtained by the superposition of light fields propagating from each computing unit to the hologram plane. Polygon-based encoding method uses a group of triangles to form the model, so that the number of computing units is dramatically less than the one in point-based method in which the model is constructed by millions of concrete points [1-2]. Since holography is based on the interference among light beams, laser has been used in this field due to its high temporal and spatial coherence. However, utilizing laser in holographic reconstruction leads to unavoidable speckle noise when light beams transmit through or reflect off a diffusive plane. Introducing low coherence light sources such as LED is an effective way to smooth speckle noise, with the price of unsatisfactory imaging quality. Many researchers have utilized LED in the holographic systems [3-6]. Although it is aware that introducing light sources with different levels of coherence results in remarkable variation of the reconstructed scenes, quantitative analysis of imaging quality for LED holographic display is seldom to be reported. On the other hand, we previously proposed an analytical calculation method for phase-only hologram. Extra fringes on the reconstructed model seriously debase the impression for observation. New computing method is necessary for the elimination of such unexpected mesh.

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In this paper, we will first proposed our new coding method for phase-only CGH using fast Fourier transform (FFT) instead of analytical FT. Subdivision of the polygons on the model is no longer necessary for calculation so that extra fringes inside the reconstructed scene vanish, and consequently the surface appears continuous and smooth. The analysis of the imaging quality on a target plane will be investigated by using the correlation among the imaging quality, the pixel pitch of the modulator and the coherence length of the light. Some of behaviors have been experimentally demonstrated by LED light source with band-pass filters and spatial filters. The optical results show good agreement with the analysis. In addition, multiple-image superposition and time averaging technique is utilized to reduce the speckle noise.

2. ELIMINATE UNEXPECTED FRINGES BY FAST FOURIER TRANSFORM

The calculation of optical field propagation can be accomplished by the analytical diffraction in spatial domain and it requires less computation complexity than other methods in frequency domain [1, 2]. However, the triangles on the model need to be further divided into numbers of small-enough triangles so as to guarantee constant colormap inside each polygon. This will dramatically increase the computation complexity especially for the reconstruction of a complicated scene. Furthermore, the sub-division may create some virtual frame mesh adhering on the reconstructed image as the optical energy will mainly concentrate on the edge of the polygons if the triangles are not so small. This will seriously reduce the impression for human beings [see for example Fig. 1(a)]. To eliminate such unexpected fringes, one can use the FFT instead of the analytical FT. The sub-division technique is no longer to use because FFT is directly applied to a particular triangle. The diffraction fields of all other polygons are then connected to such particular triangle by the affine transformation. Figure 1(b) illustrates the reconstructed results of an arbitrary triangle by FFT calculation. It is found that the meshes on Fig. 1(a) vanish and a smooth triangle is obtained.

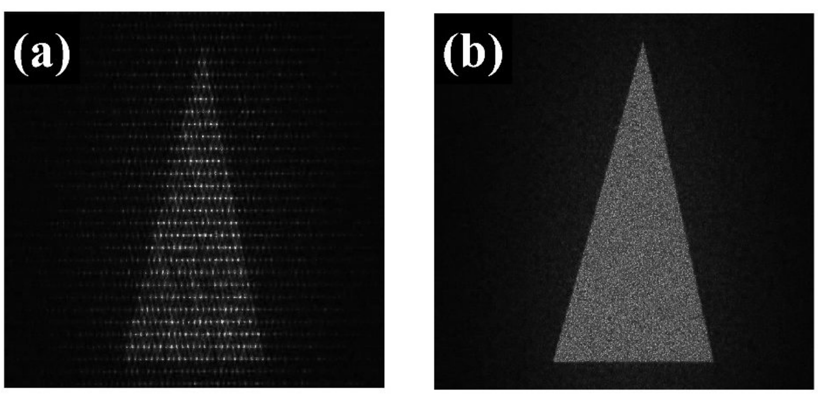

Fig. 1. Comparison of the reconstruction of a triangle using (a) analytical Fourier transform and (b) fast Fourier transform (FFT) method. Unexpected fringes can be seen in (a) due to the subdivision of the triangle. However, a smooth triangle can be obtained as the subdivision is not necessary for the FFT method.

3. INFLUENCE OF TEMPORAL COHERENCE IN LED HOLOGRAPHIC IMAGING

In this section, we will study the influence of temporal coherence in LED holographic imaging. Providing that the coherence length of the light source is $L_c = \lambda^2 / \Delta\lambda$, and ΔL is the optical path difference of any two light beams, where $\Delta\lambda$ is the bandwidth of the light source. The condition for perfect coherence imaging can be simply written as,

$$\Delta L << L_c \tag{1}$$

Eq. (1) ensures complete coherence among all beams in the optical system. In the following, we will discuss the coherence degree of the light beams between the pixels of spatial light modulator (SLM) and the image plane according to Eq. (1). We choose two outmost pixels of the modulator to calculate the optical path difference as the optical path difference between them is the maximum. Then the optical path difference can be expressed as $\Delta L = np\sin\varphi \approx npx / r$, where r is the distance between the SLM and the image plane, x is the distance between the image point and the optical axis, n is the resolution of the SLM, and p is the pixel pitch of the SLM, respectively.

The quantitative comparison between laser and LED holographic reconstruction will be illustrated below. In the experiment, we have $\lambda(\text{Laser}) = 532nm, n = 1920, p = 8\mu m, r = 800mm$. The bandwidth of the commercial LED is measured at $40nm$. Assume that the lateral size of the reconstructed scene for laser is 1 *m*, while it is 0.1 *m* for LED. The depth of the scene is fixed at $800mm$. As shown in Table 1, we find that $\Delta L(L\text{aser}) << L_c(L\text{aser})$, meaning that the perfect coherence can be achieved in a large lateral area (here it is 1*m*). However, for the LED case, we have $\Delta L(\text{LED}) >> L_c(LED)$, indicating that the perfect coherence cannot be satisfied even in a small screen (here it is 0.1*m*). The reconstructed patterns for the LED illumination will blur at the edge of the 0.1m-wide screen.

Table 1. Comparison between laser and LED holographic reconstruction

Light Source	Bandwidth (nm)	Coherence length (m)	Optical path difference (m)
Laser($x = 1\ m$)	$\Delta\lambda(L\text{aser}) = 10^{-4}$	$L_c(L\text{aser}) \approx 2.83$	$\Delta L(L\text{aser}) \approx 1.92\times10^{-2}$
LED($x = 0.1\ m$)	$\Delta\lambda(LED) = 40$	$L_c(\text{LED}) \approx 7.08\times10^{-6}$	$\Delta L(\text{LED}) \approx 1.92\times10^{-3}$

In order for quantitative analysis on the image plane, the image quality factor is defined by,

$$R = \Delta L / (10L_c) = (npx\cdot\Delta\lambda) / (10\lambda^2 \cdot \text{r}) \tag{2}$$

Eq. (2) indicates the relationship between the coherence length of light source and the optical path difference. From the calculation experience, we find the image of good enough quality occurs when $R < 1$ .When the optical path difference is larger than the coherence length of the light (e.g. the LED illuminated system), the reconstructed patterns near the center of the screen has sharp edge, while those away from the center will become blurred. Figure 2 shows the optical experimental reconstructions by LED illumination. The differences is the location of the 3D pyramid, which is nearby the 0^{th}-order diffraction light [bright spot at the bottom of Fig. 2(a)] in Fig. 2(a) and is far away from 0^{th}-order in Fig. 2(b). One can find that sharp edge of the model can be observed in the former, whereas in the latter, the image quality decreases remarkably and the clarity of the boundary becomes unsatisfactory.

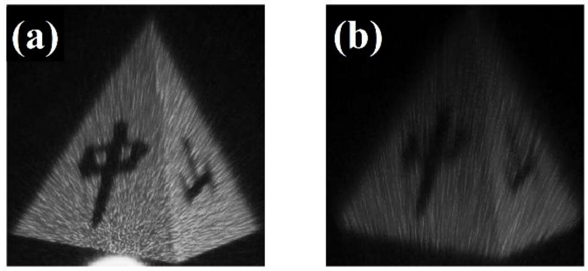

Fig. 2. Imaging quality for the same pyramid at different lateral positions. (a) The pattern can be clearly seen when it locates near the optical axis, while (b) the edge of the model becomes seriously blurred.

In Eq. (2), we notice that both the pixel pitch of the modulator and the coherence length of the light source play significant roles for the effect of reconstruction. The image quality will be enhanced when the pixel pitch reduces and the coherence length increases. To demonstrate the effect of pixel-pitch reduction, one might do the optical experiment using SLM with different pixel pitch, but it should rely on the manufacturing technique. We are waiting for the new SLM device and will do in the near future. Here, we first experimentally investigate the coherence length by adhering band-pass filters to the LED source. The first row in Fig. 3 demonstrates the reconstructed images with the total height of 15mm and the second row illustrates the corresponding spectrum after adding four kinds of band-pass filters. Sharp edges and patterns can be witnessed when using high coherence light source [e.g. laser in Fig. 3(a)], but the whole scene is filled with serious speckle. In Figs. 3(b)-3(d), the speckle noise is depressed as the spectrum bandwidth increases, while the clarity also degrades. It is obvious that a proper bandwidth tailor of the light source can balance between speckle noise and the image clarity although it is difficult to evaluate rigorously and precisely. In the studied case, such a bandwidth is about 10-18 nm.

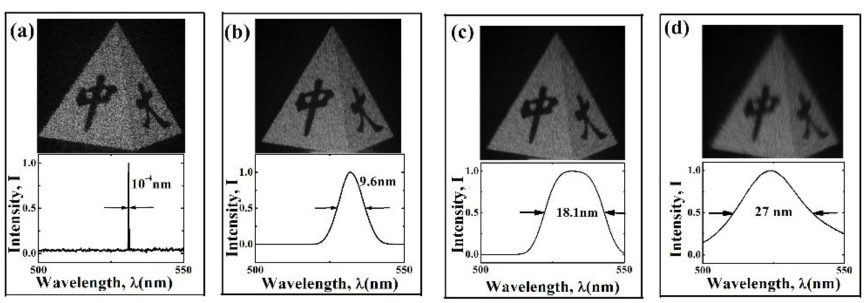

Fig. 3. Influence of the spectrum bandwidth of the light source. Experimental results illuminated by (a) laser, (b) & (c) LED with band-pass filters, and (d) naked LED are shown in the first row. The full width at half maximum for these four kinds of light sources are about to 10^{-4}, 9.6, 18.1, 27 nm, as illustrated in the second row. Longer coherence length contributes to higher clarity and greater speckle noise.

4. INFLUENCE OF SPATIAL COHERENCE IN LED HOLOGRAPHIC IMAGING

In this section, we will discuss the effect of spatial coherence in LED holographic imaging. To guarantee the perfect coherence for an extended source, a condition needs to be satisfied as $b \le S\lambda / d$. Here, b is the dimension of the pinhole adhering to the extended source, d is the width of the SLM plane and S is the propagating distance from the source to the SLM plane. In the experiment, $S = 40mm$. As the maximum and minimum of d are $d_{\max} = 8um \times 1920 = 15.36mm$ and $d_{\min} = 8um$, respectively, the pinhole is in the interval of $(1.38\mu m, 2.66mm)$. After considering the problem of power loss, the pinholes with the diameters from 10 to 150 μm are utilized in the experiment. We also calculated the speckle contrast ratio in order to evaluate the appearance of the reconstructions. The ratio is defined as,

$$C = \sigma_I / \overline{I} = \left(\frac{1}{N} \sum_{i=1}^{N} \sqrt{(p_i - \overline{I})^2} \right) / \overline{I} \tag{3}$$

where p_i is the i-th pixel value of the reconstruction, $\overline{I}$ is the average value of all pixel values, N is the total number of pixels. The ratio has a small value when the speckle goes to vanish. From Fig. 4, it can be seen that larger pinhole leads to smoother speckle noise while smaller pinhole results in higher clarity. Similar to the temporal coherence, there is a proper pinhole diameter which is able to deal with the tradeoff between speckle noise and image quality.

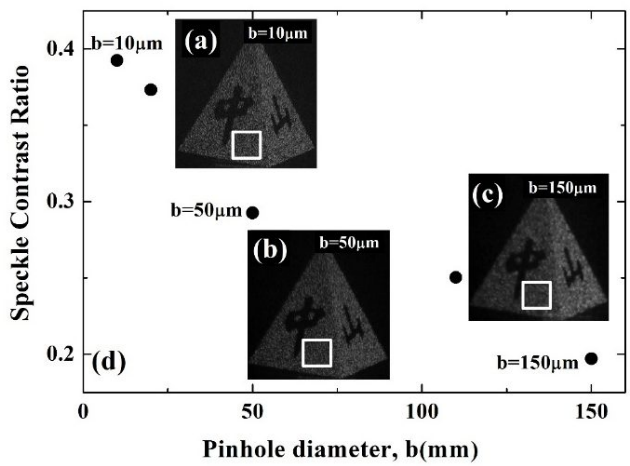

Fig. 4 Analysis on spatial coherence of the light source. (a)-(c) Reconstructed images of three kinds of light sources when different pinholes are used. The diameter of the pinhole is (a) 14, (b) 80, and (c) 140 μm, respectively. (d) Speckle contrast ratio for several kinds of pinholes by calculating the area inside the white frame.

5. USING TEMPORAL AVERAGE METHOD TO SMOOTH SPECKLE NOISE

Speckle noise in the reconstructed image of holography appears partly because we introduce random phase during computation. If we calculate a group of holograms with independent random phases, the speckle noise of the superposition of those reconstructed images will be suppressed due to the decline of phase distribution irregularity. We make different videos which all last for 1 second but with various numbers of holograms. These videos are then displayed on the SLM and camera is fixed at some position with exposure time fixed at 1 second. Speckle contrast ratio of the same area on the reconstructed image [see e.g. Figs. 5(a)-5(c)] is then computed and the result is shown in Fig. 5(d). Speckle noise is depressed as the number of images in the video rises, which shows agreement with the theoretical analysis.

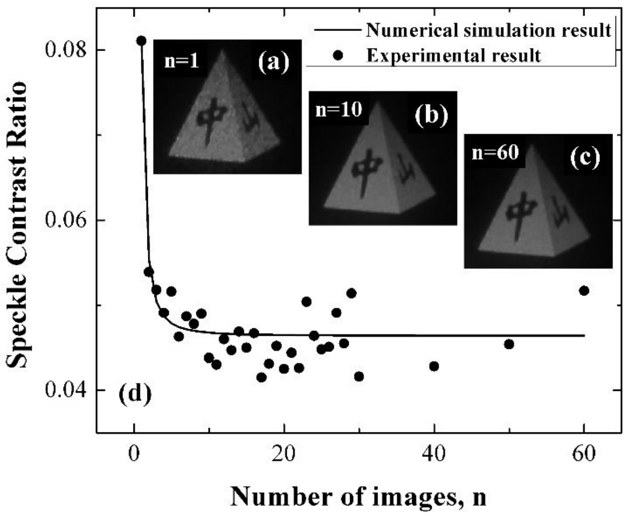

Fig. 5. Experimental results with different numbers of images n, (a) n=1, (b) n=10 and (c) n=60. Larger number indicates smoother reconstructed model. Numerical simulation on speckle contrast ratio in (d) shows that speckle reduces as the number increases.

6. CONCLUSION

We present a method for encoding phase-only CGH of polygonal model using fast Fourier transform, which is able to eliminate the unexpected fringes inside the object and improve the impression for observation. The coherence length of light source and optical path difference are investigated. By analyzing the correlation among the imaging quality, the pixel pitch of the modulator and the coherence length of the light, we carried out experiments by introducing band-pass filters and spatial filters in order to demonstrate the analysis. In addition, multiple-image superposition and time averaging is also utilized to reduce the speckle noise.

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