Wavefront 3D Reconstruction and Measurement for Natural 3D Display System

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Abstract

Three-dimensional (3D) display systems based on wavefront reconstruction are presented. To obtain the wavefront of 3D objects, we present holographic recording using temporally or spatially phase-shifting interferometer. In the 3D display systems, phase-only reconstruction using a spatial light modulator and an approach to increase the reconstructed power are presented.

1. Introduction

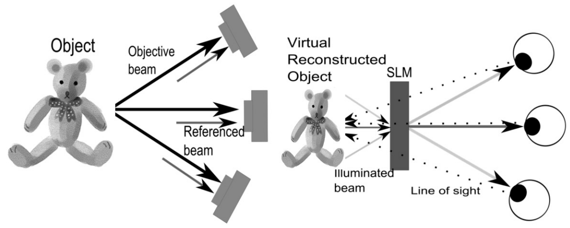
It is well known that wavefront reconstruction such as holography is an ideal method for three-dimensional (3D) display[1]. In an ideal wavefront reconstruction of 3D object, the complex amplitude distribution of the 3D object is required to avoid other unwanted reconstruction. The key issues to implement the wavefront reconstruction of 3D object are how to measure and display the complex amplitude of 3D object.

In the 3D object recording system, phase-shifting interferometer is used to obtain the complex amplitude of 3D objects. This technique is used in digital holography that can obtain the hologram as digital format and numerical reconstruction of 3D objects[2-10]. The phase-shifting interferometer can obtain only the complex amplitude of 3D object by using three or four interference patterns with appropriate phase retardation in the reference arm. To apply the phase-shifting interferometer to moving 3D object, we have been developing a spatially coded phase shifting interferometer[3,4]. We have also trying to develop multi-camera system to obtain 3D object information of 3D object[11]. In a large observation field, multi-camera system is useful to obtain the 3D object information.

In the 3D object reconstruction, spatial light modulators (SLMs) are used to display the complex amplitude distribution. Rapid recent advance of SLM enables us to modulate the amplitude or the phase with 4000 x 2000 pixels. However, the pixel size is about 10μm. This results in the small diffraction angle. 0th and 1st order reconstruction overlaps each other when the pixel size of SLM is about ten micromerter in hologram reconstruction. Another problem in the reconstruction is the low power in the 3D object for wide viewing zone. There is the limited illumination power to avoid the damage in SLM. We have been developing a coherent amplification system of optical wave of 3D object generated by SLM. A polymer dye is used as a coherent amplifier. The preliminary experiments are presented.

2. 3D display system by wavefront recording and reconstruction system

Figure 1 shows a concept of a proposed system based on wavefront recording and reconstruction of 3D objects with wide viewing angle. In the



(a) (b)

Fig. 1. Concept of a system of (a) wavefront recording and (b) wavefront reconstruction of three-dimensional objects with wide angle.

recording system, an array of spatially coded phase-shifting interferometers is used for measuring simultaneously the wavefront of moving 3D objects. In the reconstruction, time-sharing reconstruction is used to realize wide angle reconstruction by titled illumination[12].

2. 3D display system by wavefront recording and reconstruction system

In the recording system, it is required to record the wavefront of 3D objects even when they are moving. First we briefly introduce phase shiting interferometer. Here $o(x,y)$ and $r(x,y)$ are an object and a reference wave in the image sensor plane. The interference pattern, $I_n(x,y)$ is described by

$$I_n(x,y) = \left| o(x,y) + r(x,y)\exp\left(i\frac{\pi}{2}n\right)\right|^2, \quad (1)$$

where n is 0, 1, 2, or 3. In Eq. (1), the phase delay in the reference wave is changed by 0, $\pi/2$, π, or $3\pi/2$. From the four equations, we can calculate the amplitude and the phase of the object wave by

$$|o(x,y)| = \frac{\sqrt{(I_0 - I_2)^2 + (I_1 - I_3)^2}}{2|r(x,y)|} \quad (2)$$

and

$$\arg(o(x,y)) = \tan^{-1}\left(\frac{I_1 - I_3}{I_0 - I_2}\right) + \arg(r(x,y)). \quad (3)$$

In the 3D display system, complex amplitude of 3D object is useful to avoid other reconstructed terms as seen in hologram. Therefore, the phase shift interferometer is used to obtain the complex amplitude of 3D object. However, the temporal phase retardation to obtain four holograms cannot be applied to record moving 3D objects. We have been developing an array of spatially coded phase-shifting interferometer[3,4]. To realize this system, we use a phase-mode SLM to modulate the phase distribution in the reference arm. Another advantage of using a phase-mode SLM can compensate the distortion in optical elements.

We first show a temporal phase-shifting interferometer by using a phase-mode SLM. Figure 2 shows an experimental setup. A reflection-type SLM (LCOS) is used. A number of pixels in the SLM is 1920 x 1080. An image sensor has 512 x 512 pixels with 10-bit intensity resolution. The phase distortion caused by the imaging lens is reduced by phase-modulation of the SLM. A beam passing through a PBS(Polarization beam splitter) is used as an object beam. A transparency of two-dimensional image character is used as input data. The transparency is put in the object arm between the mirror and the beamsplitter(BS). The input data is located at 1500mm from the image sensor. Phase retardation required in four-step phase shift interferometer is operated by the SLM. Figure 3 shows the reconstructed result. The character is clearly reconstructed. This result indicates that the SLM can be used as a phase retarder with phase compensation of distortion in optical system.

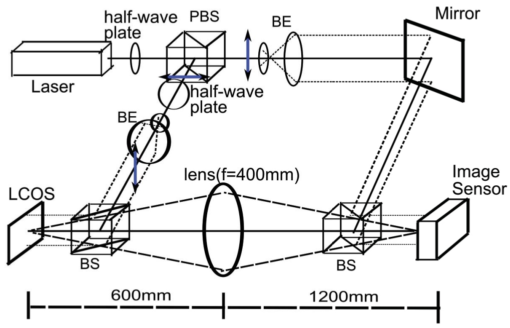


Fig. 2. Experimental setup for compensation of phase distortion caused by optical elements in imaging system.

Fig. 3. Reconstructed image at 1500mm from the image sensor.

3. Display system of wavefront of 3D object

In the 3D display system, we discussed two issues. One is the phase-only reconstruction. The other is the coherent amplification to increase the reconstructed power. Figure 4 shows a schematic of wavefront reconstruction of 3D object by using a SLM. A coherent amplifier is located after the reconstruction of wavefront by the SLM. Complex amplitude distribution is displayed on a SLM and then the modulated wave is amplified coherently by an amplifier. At appropriate propagation distance, a 3D object can be reconstructed. In the system, a virtual or a real 3D object can be reconstructed. The key component is a coherent amplifier.

Unfortunately, there is no commercially available SLM to modulate simultaneously both amplitude and phase distribution. Therefore, one solution is to use the phase distribution in the reconstruction[7]. Figure 5 shows the reconstruction of a screw when the complex amplitude distribution and the phase-only

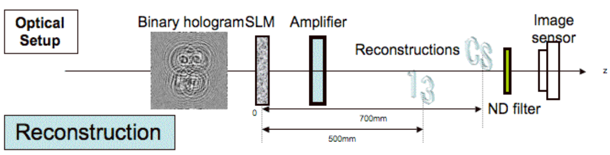
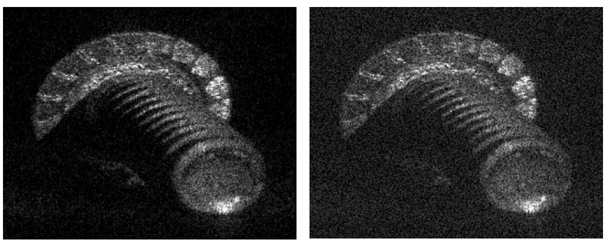


Fig. 4. Optical setup for coherent amplification in wavefront reconstruction.



(a) (b)

Fig. 5. Numerically reconstructed 3D objects of screw from (a) fully complex field and (b) phase-only information.

distribution are used. The screw is located at 390mm from the image sensor. This result shows that the phase-only reconstruction is successful. This is because the amplitude at the image sensor is estimated to be statistically uniform when the scattering at 3D object is strong enough.

Next, we describe the coherent amplification of wavefront to increase the reconstructed power of 3D object. Here we show the optical pumping by a polymer dye that shows high gain coefficient in visible wavelength range.

A polymer dye with a thickness of 8mm is used as shown in Fig. 6. The polymer dye consists of Rohdamin 6G in PMMA. We experimentally evaluate the amplification characteristics of the polymer dye by end pumping geometry. Small signal gain of 3.4 cm^{-1} and saturation fluence of 642 $\mu J/cm^2$ are obtained in the used polymer dye when pump fluence is 43 mJ/cm^2 and a wavelength of probe light is 555nm. Due to the large absorption of the polymer at 532nm, the gain is not large. In the used polymer with a thickness of 8mm, amplification rate of 15 is expected. Two

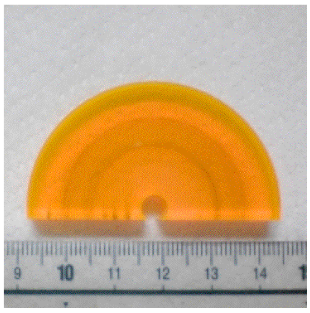


Fig. 6. Picture of polymer dye used in the experiments.

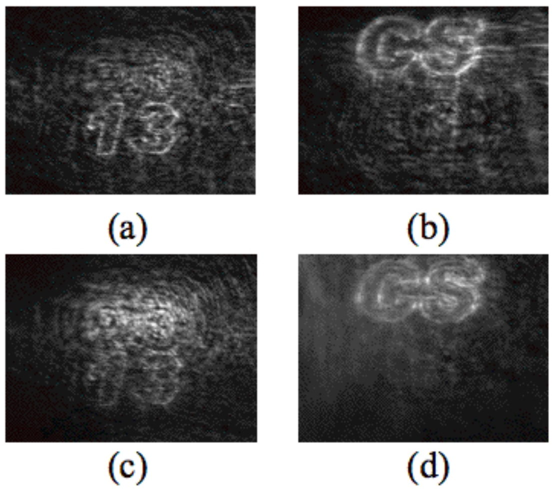


Fig. 7. Reconstructed images at distances of (a) 500mm and (b) 700mm without amplification and of (c) 500mm and (d) 700mm with amplification.

character images at different propagation distances are reconstructed. Edge of the character image is enhanced. We use a SLM with a pixel size of 16 x 16 μm. to reconstruct both characters. Figure 7 shows the reconstructed images by displaying binary hologram. Figures 7(a) and (c) are reconstructed images located at 500mm from the SLM. Figures 7(b) and (d) are the images located at 700mm from the SLM. Two characters can be seen. The amplification rate between Figs. 7(c) and (a) is 15. To obtain much amplification rate, side pumping is a possible way.

4. Summary

In this paper, we have described a 3D display system based on wavefront recording and reconstruction. In the wavefront recording systems, instantaneous recording of 3D objects can be achieved by an array of spatially coded phase-shifting interferometers. We have presented preliminary experiments to use a phase-mode SLM to generate the spatial pattern of phase retardation used in the spatially coded phase-shifting interferometers. In the 3D object reconstruction, we have discussed two issues. One is the phase-only reconstruction and the other is optical power amplification using a coherent amplifier. We have presented two methods to solve the above two issues.

5. References

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