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Optical realization for the computer-generated cylindrical hologram

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Abstract

A novel optical realization method for the computer-generated cylindrical hologram by using the high-speed display device and the spinning screen is proposed. The sub-holograms are sampled for each determined viewpoints along the horizontal direction by a given angular step after the entire computer-generated cylindrical hologram is generated. In the experiment, the laser beam reflects on the high-speed digital micromirror device and reaches on the rotating screen during the digital micromirror device displays sub-holograms according to the generated consistency. The three-dimensional holographic images are reconstructed on a rotating screen and they are tailored with each other along horizontal direction while rotating screen is synchronized with digital micromirror device. Finally, horizontally assembled entire 3D image is reconstructed in 360-degree viewing zone with perfect human depth cues that observers can see the displayed 3D image from anywhere around the display.

Introduction

The cylindrical hologram is a hologram which is recorded on the cylinder surface where the object is located inside it. In the conventional (analog) case, the laser beam is illuminated from the top of the object and object beams reflect from the object to the cylinder surface while the reference beam is directly recorded on the cylindrical hologram plate from the laser illumination source [1, 2]. The recorded cylindrical hologram includes the 3D information of the object for all viewpoints around it; in other words, the 3D image with 360-degree viewing angle can be observed when the recorded hologram is reconstructed. However, due to the laser beam is illuminated from the top, some elements of the object cannot be recorded, especially when the lower part of the object has smaller size than the upper part. And, as a well-known fact, the recording process is much complicated

Recently proposed computer-generated cylindrical hologram (CGCH) technique has a great opportunity to generate the hologram on the virtual cylindrical surface perfectly, without any optical complication [3]. Note that, the virtual object is desired as the self-illuminated object and any shaped object can be utilized in the CGCH generation. However, the generation process for the CGCH requires too long processing time, especially for large-sized object and CGCH, due to the huge and complicated calculations. Therefore, several researchers and institutes have proposed the methods which accelerating the CGCH generation process in recent years. For example, the methods using the single or double fast-Fourier transform loops for the wave propagation of the CGCH, a Taylor expansion, or wave-front recording surface which is a virtual surface locates closer to the object than original hologram surface, have been proposed recently [4-8]. However, these methods cannot reduce the processing time as fast as the other type of the light field displays, due to the limitation of the modern technology

It is almost impossible to realize the cylindrical hologram practically, therefore, usually the reconstruction process for the CGCH can be completed digitally, such that entire virtual 3D representation of the object is reconstructed through computer graphics [8], and print the single viewpoint of the digital reconstruction through the holographic printer. [5]. The digital reconstruction process requires such a huge computation, usually more the CGCH generation; so, the overall process (CGCH generation + digital reconstruction) takes a very long processing time. Note that, the CGCH is not reconstructed fully through the optical reconstruction so far.

In this report, a novel optical realization method for the CGCH by use of the high-speed projection and the spinning screen is proposed. The proposed novel holographic display system reconstructs the CGCH through real optical display entirely and reduces the overall processing time due to removes the digital reconstruction process. In the experiment, the full-parallax holographic 3D visualization of the object is reconstructed fully from the generated CGCH. Note that the main schematic configuration of the proposed system is based on the recently proposed 360-degree integral-floating display [9-12]. The 360-degree integral-floating display demonstrates the full-parallax 3D images with unlimited 360-degree viewing angle horizontally and wide vertical viewing angle. The system consists of basic integral imaging 3D display with high-speed projection, 4-f configured double floating lenses and spinning anamorphic optical mirror screen. Also, a 360-degree holographic display method has been proposed recently, but it does not provide the CGCH, and the demonstrated table-top display system has the horizontal-parallax only [13].

Optical realization for the CGCH

The basic configuration of the CGCH is shown in Fig. 1. Here, it can be seen that the calculation of CGCH depends on the radius and height of the cylindrical surface, r and y', and the angle between the reference direction and the directional line from each object point and the CGCH, azimuthal angle ϕ. Note that the calculation for the CGCH is based on the calculation of conventional Fresnel hologram and a spherical hologram [5, 14].

Basically, the light field distribution on the CGCH for each object point $P(x,y,z)$ is given by:

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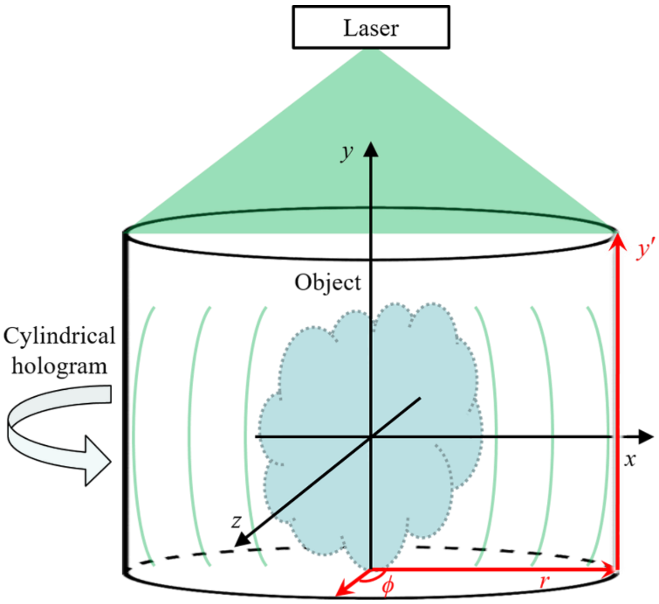

Figure 1. *The basic recording process for the CGCH*

$$U(x',y',z')=\sum_{i=1}^{N}\frac{A\exp(jkd)}{d} \quad (1)$$

where A is the complex amplitude of object beam, k is the wave number which is given by $k=2\pi/\lambda$ where λ is the wavelength of the laser beam, and d is the distance between each object point, $P(x,y,z)$, and the corresponding hologram point in the CGCH, $P'(x',y',z')$, that can be defined as:

$$d=\sqrt{(r\cos\phi-x)^2+(r\sin\phi-z)^2+(y'-y)^2} \quad (2)$$

where (x,y,z) is the coordinate information of each object point and (x',y',z') is the coordinate information of the corresponding points on the CGCH. And the complex amplitude of CGCH, A, is determined by:

$$A(x',y',z')=\sum_{i=1}^{N}\frac{\alpha}{d}\exp[j(kd+\varphi)] \quad (3)$$

where α and φ are the amplitude and phase information respectively. By use of the Eqs. (1)-(3), the complex value of the diffraction field for the CGCH is calculated by the following equation:

$$U(r,\phi,y')=\sum_{i=1}^{N}\frac{A\exp\left(jk\sqrt{(r\cos\phi-x)^2+(r\sin\phi-z)^2}\right)}{\sqrt{(r\cos\phi-x)^2+(r\sin\phi-z)^2}} \quad (4)$$

Based on the 360-degree integral-floating display and CGCH theory, we proposed the real 360-degree holographic display using a high-frame rate display device, i.e. a digital micromirror device (DMD), and spinning screen in order to realize the CGCH optically. Figure 2 shows the CGCH generation process and schematic configuration of the proposed optical realization method for CGCH. When the entire CGCH is generated from the given computer-generated virtual 3D object through the basic calculation method described above, the sub-holograms are sampled and separated one-by-one. The sub-holograms are the portions of the entire CGCH and each sub-hologram includes the 3D information of the object from the corresponding viewpoints, as shown in Fig. 2(a). When the single 3D perspectives reconstructed from the corresponding sub-holograms are combined with each other that are tailored by the rotating screen along the horizontal direction, in the reconstruction part. Note that the generation process for the sub-holograms uses the basic calculation equations of the CGCH by controlling the azimuthal angle. Obviously, the generated sub-holograms are divided into the amplitude and phase data of the object and saved as the image files respectively.

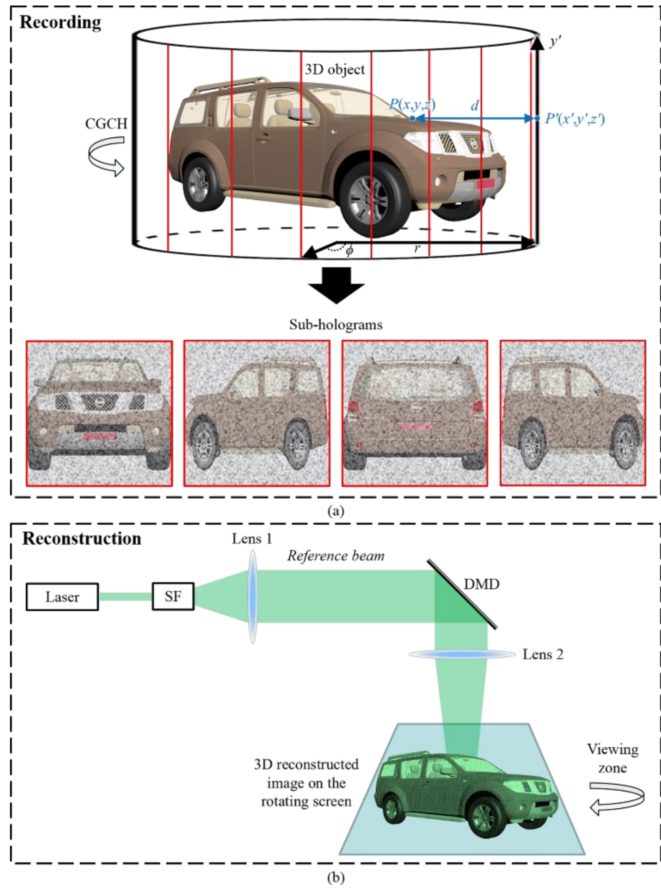

Figure 2. *The schematic configuration of the proposed 360-degree holographic display*

The general scheme of the optical reconstruction process is illustrated in the Fig. 2(b). First, the images files for sub-holograms are uploaded into the memory of the DMD and the frame rate of the DMD is set by the user. In the demonstration, the illuminated laser beam reflects on the high-speed DMD and reaches on the rotating screen during the DMD displays the sub-holograms according to the generated consistency one-by-one in high-speed. Thus, the initial 3D images are reconstructed on a rotating screen for the corresponding viewpoints and the rotation of the screen tailors them with each other along the horizontal direction while the screen rotation is synchronized with the DMD frame rate. The horizontally assembled entire 3D image creates the 360-degree viewing zone with perfect human depth cues that observers can see the displayed 3D image from anywhere around the display and CGCH can be realized successfully.

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As mentioned above, the optical realization of the entire CGCH is impossible up to now; except the digitally reconstructed 3D image viewable from a single viewpoint is printed by the holographic printers. The proposed 360-degree holographic display is an effective method to realize the CGCH through a simple way.

Another big advantage of the proposed 360-degree holographic display is that it also reduces the overall processing time of the CGCH generation and reconstruction. Because, the generation for the CGCH requires a huge computation and the digital reconstruction process of the CGCH takes much more processing time, additionally in the overall processing time. Although, the several methods, in order to reduce the long processing time, have been proposed recently, as mentioned earlier; but it still require the very long processing time due to the combination of the digital recording and reconstruction of the CGCH. In the proposed 360-degree holographic display system, the reconstruction process is run through the optical implementation; so the total processing time of the system only depends on the CGCH generation.

Experimental results

Before proceeding the experiment, we verified the proposed method through a simulation which is the numerical reconstruction for each sub-hologram. Here, a 3D point cloud model – teapot with 4658 object points and 29.2×14.2×14 mm dimensions is utilized as an object and the radius of CGCH is 500 mm where the resolution of the sub-holograms is 600×600 pixels. Figure 3 shows the object from the multiple viewpoints (Fig. 3(a)), and the corresponding amplitude and phase sub-holograms (Figs. 3(b) and 3(c)).

Here, the distance between each pixel of the sub-holograms and corresponding reconstructed point, d_{NR}, can be determined by a following equation:

$$d_{NR} = \sqrt{\left(r\sin\phi - x''\right)^2 + \left(r\cos\phi - z''\right)^2 + \left(y' - y''\right)^2} \qquad (5)$$

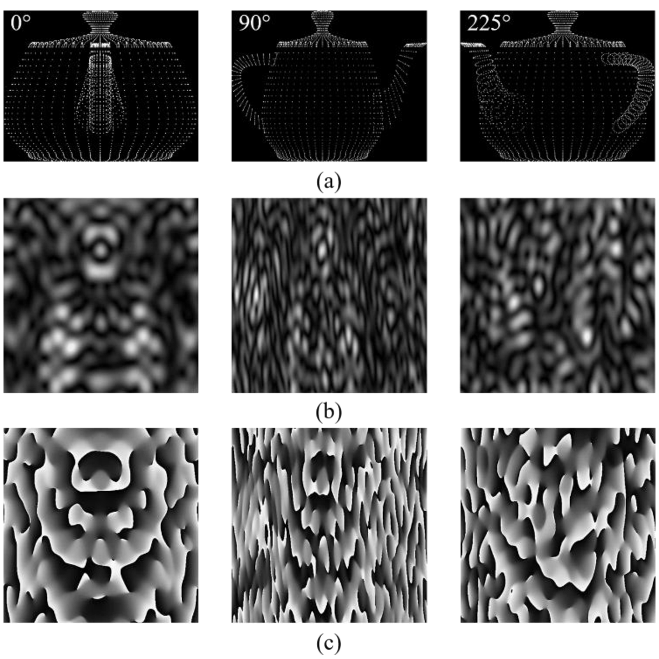

Figure 3. *(a) The multiple viewpoint of the 3D point cloud model, such that 0, 90 and 225 degrees; (b) corresponding amplitude and (c) phase sub-holograms*

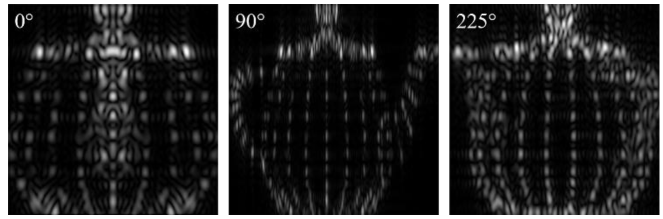

Figure 4. *The results of the numerical reconstruction for the corresponding sub-holograms*

where (x'',y'',z'') is the coordinate information of the each point in the numerical reconstruction and $y'=y''$. By use of d_{NR}, the complex value for the numerical reconstruction can be calculated by:

$$U'\left(x'',y'',z''\right) = \frac{U\left(x',y',z'\right)\exp\left(jk\sqrt{\left(r\sin\phi - x''\right)^2 + \left(r\cos\phi - z''\right)^2}\right)}{\sqrt{\left(r\sin\phi - x''\right)^2 + \left(r\cos\phi - z''\right)^2}} \qquad (6)$$

Figure 4 shows the numerical reconstruction results for corresponding sub-holograms of the Fig. 3. The resolution of the numerical reconstructions is 100×100 pixels. These results shows that the proposed method is possible to produce the 360-degree holographic 3D on the rotating screen by associating the 3D perspectives with each other, because the 360-degree integral-floating display already presented that it can be display the 360-degree 3D image by tailoring the 3D perspectives with different viewpoints along the horizontal direction.

In the optical experiment, a green laser illumination with λ=532 nm wavelength, a single DMD with 1024×768 micromirrors, a screen spinning with ~1200 rpm rotation speed, and the other basic holographic devices such as a spatial filter and the lenses are utilized. Figure 5 shows the optical setup of the proposed system.

In the experiment, first, we converted each sub-hologram into the planar hologram, due to some difficulties of the experiment. Here, the resolution of the planar hologram has to be desired, as shown in Fig. 6. The optical field of the planar hologram for each sub-hologram is defined by:

$$U\left(u,v\right) = \frac{1}{j\lambda}\sum_{u=1}^{m}\sum_{v=1}^{n}\frac{U\left(x',y',z'\right)\exp\left(jkd'\right)}{d'} \qquad (7)$$

where (u,v) is the coordinate of each point in the converted planar

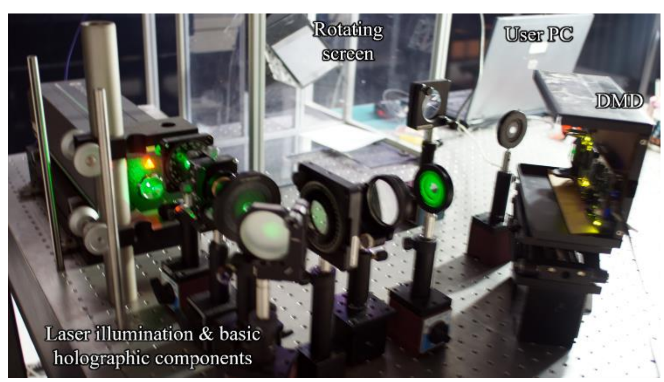

Figure 5. *The experimental setup on the optical table*

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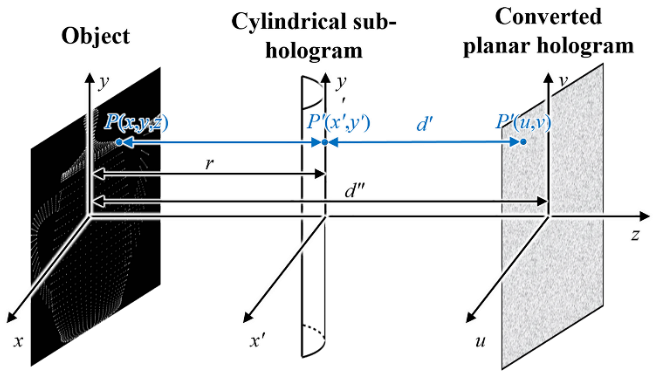

***Figure 6.** The conversion process from the cylindrical sub-holograms to a corresponding planar holograms.*

hologram, (m,n) is the resolution of the converted planar hologram, d' is the distance between each cylindrical sub-hologram point and the corresponding point on the planar hologram plane which is given by:

$$d' = \sqrt{\left(u - r\cos\phi\right)^2 + \left(d'' - r\sin\phi\right)^2 + \left(v - r\right)^2} \qquad (8)$$

where d'' is the distance between the center of the object or CGCH and the converted planar hologram. Note that the amplitude sub-holograms are used in the experiment and converted into the planar holograms.

Figure 7 shows example of the converted planar holograms and the experimental results through the proposed 360-degree holographic display. Note that the displayed 3D holographic images are reconstructed from the planar holograms converted from cylindrical sub-holograms. These experimental results certify the proposed system can display the true holographic 3D image viewable from 360-degree viewing zone by realizing the CGCH. Also, the displayed images are corresponded to the example sub-holograms which presented in Fig. 3. However, the inversed twin images occur with each of original initial 3D holographic perspectives, and duplicated during the display.

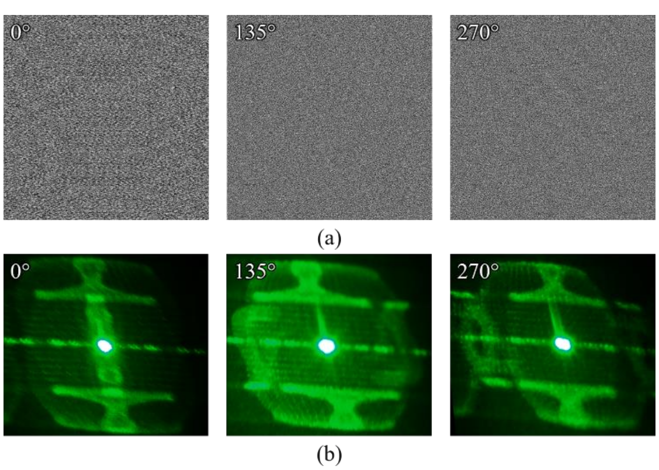

***Figure 7.** (a) Converted planar holograms for the corresponding cylindrical sub-holograms from 0°, 135° and 270° viewpoints and (b) the reconstructed 3D images on the rotating screen from the corresponding viewpoints*

Conclusion

The CGCHs are cannot demonstrated fully through the real optical demonstration up to now. So, authors suggested a novel 360-degree holographic display using a high-speed DMD and rotating screen in order to realize the CGCH entirely. After the CGCH is generated, the sub-holograms are sampled and stored separately as the image files. When these sub-holograms are uploaded into the DMD memory, the DMD displays them one-by-one in the generated order, and the initial 3D holographic images are reconstructed on the rotating screen through the based holographic display components where the screen rotation is synchronized with DMD frame rate. The entire visualization of the given CGCH is completed by tailoring the initial 3D holographic perspectives along the horizontal direction. The experimental results verify that the proposed method is possible to satisfy the main goal of authors which is a realization of CGCH. Additionally, the proposed method reduces entire processing time of the existing methods for CGCH by removing the digital reconstruction processes where the digital reconstruction requires much more computation time than the CGCH generation. Further research is focused on removing the twin images and direct reconstruction from the cylindrical sub-holograms, without converting into the planar holograms.

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