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Numerical study for the calculation of computer-generated hologram in color holographic 3D projection enabled by modified wavefront recording plane method

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ABSTRACT

A method of calculating computer-generated hologram (CGH) for color holographic 3D projection is proposed. A color 3D object is decomposed into red, green and blue components. For each color component, a virtual wavefront recording plane (WRP) is established which is nonuniformly sampled according to the depth map of the 3D object. The hologram of each color component is calculated from the nonuniform sampled WRP using the shifted Fresnel diffraction algorithm. Finally three holograms of RGB components are encoded into one single CGH based on the multiplexing encoding method. The computational cost of CGH generation is reduced by converting diffraction calculation from huge 3D voxels to three 2D planar images. Numerical experimental results show that the CGH generated by our method is capable to project zoomable color 3D object with clear quality.

1. Introduction

Laser based holographic projection from a computer-generated hologram (CGH) can provide high brightness, high contrast and wide color gamut images. Moreover, since holographic technique has potential for reconstructing all the three-dimensional (3D) information of an object in space, holographic projection is also considered to be the most potential technique to achieve true 3D display without any wearable devices. However, the huge amount of three dimensional information results in long calculation time in CGH generation for projection 3D object. Many methods have been proposed in order to accelerate the calculation of CGH. For example, the point based method with look-up tables is an effective method in which the wavefront of point light source is pre-calculated and saved in a look-up table (LUT) [1–3], however, it requires large memories for the storage of LUT. Other popular methods include the layer-based methods [4–6] and the polygon-based methods [7–9]. In these methods, the basic idea is to model the 3D object into numerous 2D planes, either parallel planes or tilted planes, and the calculation of CGH can be converted from 3D information to 2D planes in which the fast Fourier transform (FFT) algorithm could be employed for further accelerating. Nevertheless, the total calculation time of CGH is proportional to the numbers of the modeled planes. While this number is always large (sometimes more than ten thousands planes) in order to accurate sample a 3D object, these methods are still remains cumbersome. Recently, a simple method of CGH calculation based on the nonuniform sampled wavefront recording plane (WRP) method is proposed [10], which is derived from the well-known WRP methods invented by Shimobaba [11,12]. This method allows calculating CGH only from 2D intensity map of a 3D object by establishing a virtual plane close to the object, therefore the calculation can be accelerated by using the nonuniform fast Fourier transform (NUFFT) algorithm.

Another important field of holographic projection is color projection. Holographic color projection can generally be realized by: time division [13,14], depth division [15,16] and space division [17,18]. In time division method, three sub-holograms of red, green and blue component of color object are calculated and displayed on the SLM in sequence, in which we need to control each laser source and sub-hologram synchronously. In addition, this method requires very high frame rate devices to display sub-holograms for the effect to be seen by a human eye. Another kind of method use only one SLM to achieve color projection, Makowski proposed a method by dividing one SLM into three regions with each region loaded one component hologram [17], but the resolution is lost by taking advantage of only one third of

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the whole SLM for one color component. More effective method is to use multiplexing by encoding three color components into one SLM with whole area [18]. However, most of these methods only consider the projection of two dimensional color images. For dynamic holographic 3D projection, Gaolei Xue proposed a method to reconstruct full color 3D object by modeling its complex amplitude [19]. In this method, the CGH of each color component is calculated using polygon-based methods and three CGHs are synthesized into one CGH by multiplexing encoding method. However, the calculation time of the CGH will be proportional to the numbers of the modeled polygons.

In this paper we propose a method to simply calculate CGH for color holographic 3D projection, based on the combination of the nonuniform sampled WRP method and the multiplexing encoding technique. The CGH calculation is simple and fast, the calculation time is independent on the number of object points. The CGH is capable to reconstruct zoomable color 3D object in holographic projection system.

2. Method of CGH generation in color holographic 3D projection

2.1. CGH calculation from 3D object using nonuniform sampled WRP

The nonuniform sampled WRP (NS-WRP) based method [10] presents the effectiveness to simply and fast calculate a CGH that can project 3D object with perceptive depth and zoomable function. The schematic diagram of this method of calculating CGH from a monochrome 3D object is shown in Fig. 1(a). First, a virtual wavefront recording plane (WRP) which is sufficiently close to the 3D object is established. The 3D object is represented by a 2D intensity map $I(u, v)$ and a depth map $d(u, v)$. The intensity map $I(u, v)$ is located at distance d_{min} from the WRP where d_{min} is the minimum value of $d(u, v)$. Both of the intensity map and the WRP is sampled in the same way and their sampling pitch is given according to the depth map as:

$$dW(u, v) = \sqrt{d_{min}/d(u, v)} \cdot du \quad (1)$$

Where du is the transversal pixel pitch of the 3D object. In this way, the different depth value $d(u, v)$ of each object point give rise to the nonuniform sampled (NS) WRP and the intensity map. Next, the calculation of the NS-WRP from the NS intensity map is performed by using the nonuniform fast Fourier transform (NUFFT) based angular spectrum method expressed as:

$$W(xw, yw) = NUFFT2\{NUFFT1[I(u, v)] \cdot T(f_x, f_y)\} \quad (2)$$

Where $W(xw, yw)$ is the light field of the WRP and $T(f_x, f_y)$ is the transfer function of the angular spectrum method. NUFFT1 and NUFFT2 denote the first and second type of the NUFFT respectively. The detailed explanation of NUFFT can be found in Ref. [20–22]. After that the calculated WRP $W(xw, yw)$ is forcely re-sampled to an uniform sampled WRP $W(xw', yw')$ with the samping pitch of du. In the last step of the method, the hologram is obtained by calculating the diffraction from the $W(xw', yw')$ employing the ARSS –Fresnel diffraction algorithm [23]. The calculation of the hologram $H(x, y)$ is given by:

$$H(x, y) = FFT^{-1}\{FFT[W(xw, yw) \cdot \exp(i\varphi_1)] \cdot FFT[\exp(i\varphi_2) \cdot \mathrm{Re}\,ct]\} \quad (3)$$

Where f_1 and f_2 are the quadratic phase term and *Rect* is a rectangular function that reduces aliasing noise. Their detailed expression can be found in Ref. [23].

Fig. 1(b) shows the reconstruction of the hologram calculated by the above described NS-WRP based method. Due to the resampling operation from nonuniform sampled WRP to uniform sampled WRP in the calculation step, each object point of the intensity map will be reconstructed to a new position at its original depth distance according to the relations between the reconstruction distance and the sampling pitch change [10]. Consequently the whole monochrome 3D object with inherent depth cue can be reconstructed.

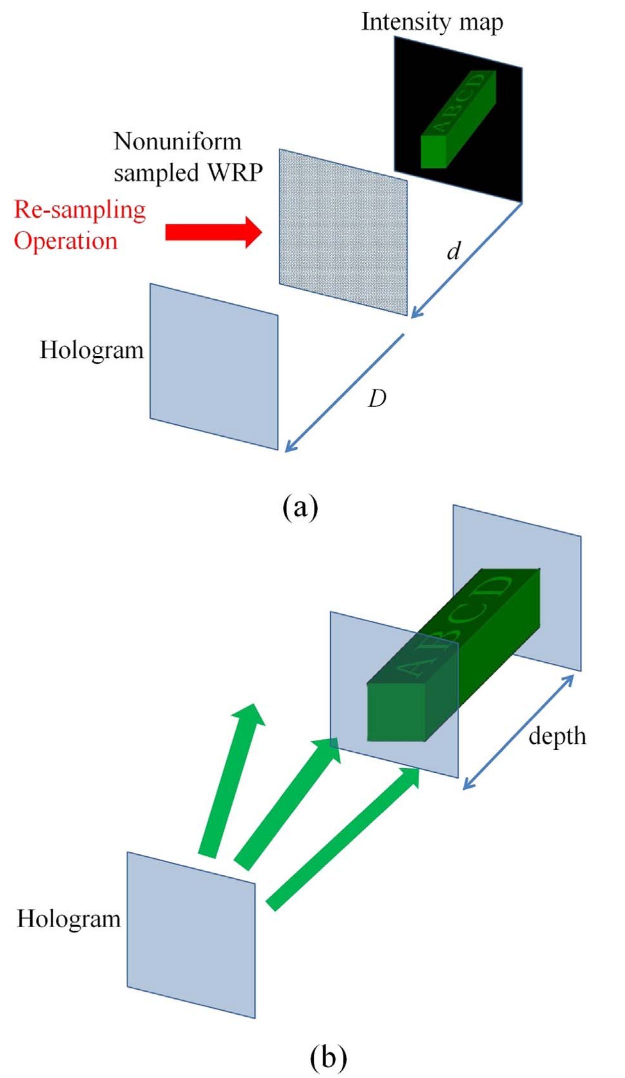

Fig. 1. (a) Hologram calculation by the NS-WRP based method. (b) Reconstruction of the hologram..

2.2. CGH synthesize from color 3D object by multiplexing technique

The calculation process of the CGH from a color 3D object is shown in Fig. 2. The color 3D object can be divided into RGB component. Each divided component is represented by a 2D intensity map and distributed transversely in space as shown in Fig. 2. Then the intensity map of each color component is propagated toward to the three NS-WRPs directly and separately, using the NUFFT based angular spectrum method. After resampling three NS-WRPs to nonuniform sampled WRPs according to the depth map of the object, we calculate the sub-hologram of RGB component from each re-sampled WRP. Here the propagation from each WRP to the hologram is off-axis diffraction, hence we employ the ARSS- Fresnel diffraction algorithm [23] to calculate the off-axis diffraction and generate three complex sub-holograms of RGB component. Finally we superimpose the three complex sub-holograms of RGB component in order to synthesize one final CGH.

The reconstruction process of the CGH is shown in Fig. 3. In the reconstruction, the CGH is illuminated simultaneously by three reference lights of RGB colors with different angles. By properly adjusting the angle θ of the three illumination lights, the RGB component of the target object can be reconstructed at the desired