A Fast Hologram Calculation Method Based on the Light Field Rendering

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ABSTRACT

We propose a new method based on ray-sampling (RS) algorithm to reconstruct the holographic light field. Different from the previous method, we accumulate elemental images in the space domain without any Fourier transform. The results demonstrate that the proposed method successfully reconstructs the 3D scene with accurate depth cues.

1 INTRODUCTION

Holographic display is considered to be the ideal technology for three-dimensional (3D) display since it can reconstruct the whole optical wave field of a 3D scene and can provide all the depth cues that can be perceived by human eyes [1,2]. The traditional method of obtaining holograms is to use recording materials to record the optical holograms, such as photorefractive polymers, and so on, which are reproduced as static images. However, this method can only be applicable to real objects [3]. With the development of the computer technology, both real and virtual objects can be reconstructed by computer-generated holograms (CGHs) as long as their mathematical descriptions of the 3D scenes are provided. There have been many attempts to synthesize CGH, and different algorithms can lead different effects to the optical performance and the computational efficiency.

Point-source and polygon-based methods, are commonly used in CGH calculations by simulating the wave propagation process from the 3D scene to the hologram. According to these methods, the 3D scenes are often divided into multiple points or polygons [4,5]. The wavefront is generated based on the physical model of diffraction, so both accurate depth information and continuing motion parallax can be retrieved. However, calculating point-source or polygon-based holograms requires an enormous number of points or polygons, which results in a heavy computational load. Moreover, point-source or polygon-based algorithms are difficult to provide correct occlusion effect because the handlings of different primitives are independent.

As an alternative approach, layer based algorithms can be used to improve the computational efficiency [7]. When we apply this method, the 3D scenes are often sliced into multiple parallel layers under depth information. The wave propagation between parallel planes is calculated through Fast Fourier transform(FFT) based Fresnel diffraction or angular spectrum. If there are too many layers, it will affect 3D perception. In addition, artifacts would be reconstructed with a large viewing angle due to the orthographic projection based slicing strategy.

The holographic-stereogram(HS)-based method is another algorithm to generate CGHs. During calculating HS-based CGH, the hologram is spatially segmented into multiple hologram elements(hogels), and each hogels are captured by perspective projections from the corresponding viewpoints. Moreover, the light-field(LF) can be reconstructed with the increasing of the number of viewpoints and full-parallax is implemented. This case can also be called ray-based CGH[8]. Thanks to the advanced techniques of 3D computer graphics(3DCG) and image-based rendering, calculating holograms with light rays promises expression of realistic appearance and occlusion. Group of Shunsuke Igarashi from Tokyo Institute of Technology have proposed an efficient algorithm for calculating holograms using an RS plane with orthographic projection images [9]. Recently, group of Hao Zhang from Tsinghua University have proposed an efficient algorithm for calculating photorealistic three-dimensional(3D) computer-generated hologram with Fourier domain segmentation [10].

When apply CGHs, the electro-holographic display systems always employ electro-optics devices, such as liquid crystal modulators; liquid crystal on silicon modulators; optically addressed modulators; mirror-based modulators; and holographic polymer-dispersed modulators, acoustic-optic devices, and so on, to reconstruct the 3D image dynamically or in real-time. Generally, liquid crystal on silicon (LCOS) spatial light modulators (SLM) are used to load CGHs to obtain the wave front of the objects. However, restricted by existing conditions, the SLM can only modulate amplitude or phase of a hologram, and we always choose phase only LCOS SLM due to its higher diffraction efficiency.

To calculate the phase only holograms, we usually have two effective methods. One method is the traditional Gerchberg–Saxton (G-S) iterative algorithms with random phase. And the other is complex amplitude modulation (CAM) with constant phase by specific encoding method, such as double-phase hologram (DPH) [11,12]. There is no denying that both these two methods have their own advantages and disadvantages and it is difficult to combine these advantages. When we operate G-S algorithms, random phase can result in more accurate depth cues for observer. However, it can also lead to serious speckle noise which cannot be ignored. Different with G-S algorithms, constant phase can promise us a better quality of the reconstructed image when we apply DPH. But at the same time, the depth cues are not obvious, so we can find the reconstructed images are always clear just like Maxwellian display. The paradox is that we want to obtain good imaging quality and accurate depth cues together.

In this paper, we propose an efficient algorithm for calculating complex amplitude hologram with HS-based method. Firstly, we capture perspective projection images of the 3D scene with RS-plane. Secondly, we multiple each image with a slant plane corresponding to its angle information. Thirdly, we add each image to obtain the complex amplitude hologram. Finally, we apply double-phase encoding method to the complex amplitude hologram to finish 3D display. At the same time, this method can promise us good image quality and accurate depth cues. Moreover, the calculation process is more concise than the previous RS-plane method. Numerical simulations and optical experiments demonstrate that the proposed method can reconstruct photorealistic 3D images with accurate depth cues.

2 METHOD

As mentioned above, in the traditional G-S algorithms, speckle noise exists in the reconstruction of the CGH due to the uncontrolled phase distribution, like the image shown in Fig.1(a). Differently, in the traditional CAM, the image quality has been improved apparently due to the uniform initial phase. However, the diffraction angle of the images with uniform phase is small, so the phase vector couldn't diverge within a certain distance of propagation. Therefore, observers cannot feel accurate depth cues in the reconstructed scenes. This means the reconstructed images are always clear in a long distance range without the effect of natural blur, as shown in Fig.1(b).

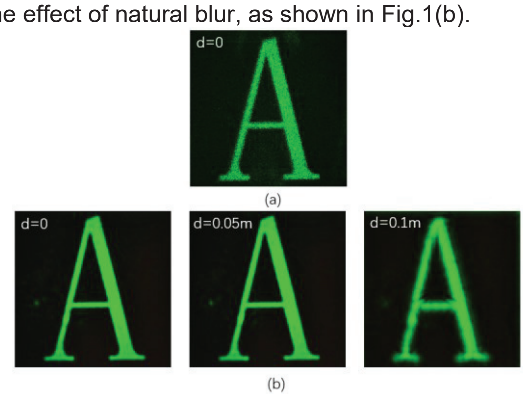

Fig.1 (a) The reconstructed image in the traditional G-S algorithm. (b) The reconstructed images in the traditional CAM algorithm.

Here, d is the distance from the reconstructed plane. The above two situations represent large depth of field and small depth of field, but what we want to do is reconstructing the real light field. So, we need to optimize the amplitude and phase for the real light field. For the sake of achieving good image quality and accurate depth cues at the same time, we combine the idea of light field on the basis of complex amplitude modulation.

Fig.2 shows the scheme of the hologram calculation using a ray-sampling(RS) plane. In this approach, a RS plane is defined near the object and the LF of an object passing through the RS plane is densely sampled as perspective elemental images at different angles. The captured LF is converted into the wavefront via Fourier transformation and the obtained wavefront is numerically propagated to the hologram plane using diffraction theory. Therefore, the information of angle and depth is already included in captured rays.

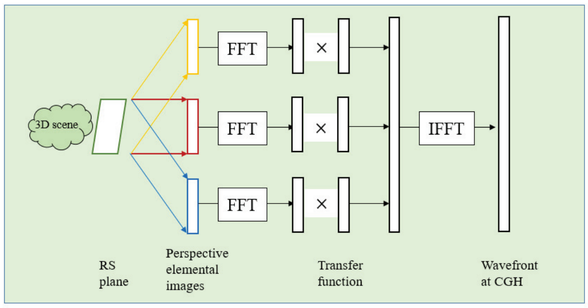

Fig.2 Scheme of the CGH calculation using the RS plane.

The propagation from the RS plane to the hologram plane can be written as a convolution as follows:

$$\begin{aligned} w_h(x) &= F^{-1}[F[w_{RS}(x)] \cdot H(f_x; z)] \\ &= F^{-1}[W_{RS}(f_x) \cdot H(f_x; z)]. \end{aligned} \tag{1}$$

Here, $w_h(x)$ and $w_{RS}(x)$ are the wave front at the hologram and RS plane, respectively. $W_{RS}(f_x)$ is the Fourier transform of $w_{RS}(x)$. $H(f_x; z)$ is the transfer function determined by the propagation distance, z, such as Fresnel diffraction or angular-spectrum propagation.

Based on this calculation method, we consider that when z is equal to 0, the formula becomes:

$$\begin{aligned} w_h(x) &= F^{-1}[F[w_{RS}(x)] \cdot H(f_x; z)] \\ &= F^{-1}\big[F[w_{RS}(x)]\big] = w_{RS}(x). \end{aligned} \tag{2}$$

In this situation, the wavefront at the hologram and RS plane are the same essentially. Hence, we multiply the obtained perspective projection images with the corresponding slanted phases and add them in the spatial domain. The flow chart of our method is shown in Fig.3.

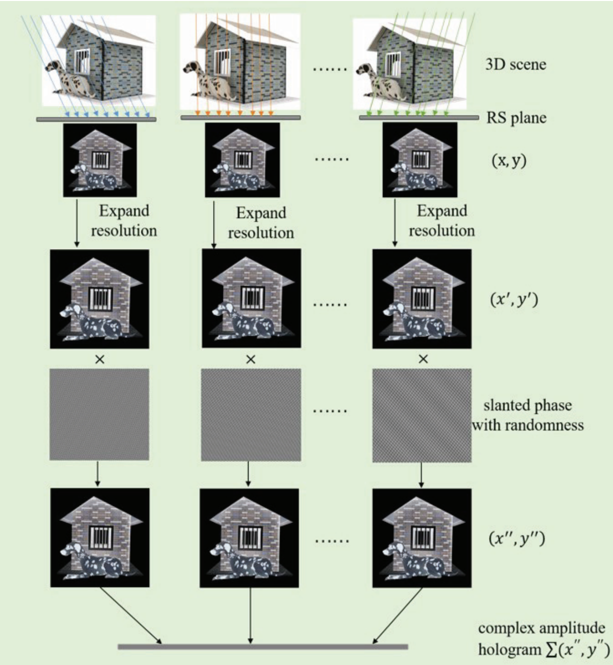

Fig.3 Flowchart of the proposed method.

In the proposed method, we first capture $n \times n$ perspective elemental images, (x, y), at many angles by RS plane. In order to avoid the unexpected images quality due to the loss of the spectrum information when we add these perspective elemental images, we expand the image resolution with n times before adding to get the images, (x', y'). And the expansion factor is determined by the number of perspective projection images. Then, we multiply (x', y') with the corresponding slanted phases, and the results are (x'', y''). Finally, we add these perspective elemental images in space domain directly and achieve the complex amplitude hologram $\sum(x'', y'')$.

Our method is similar to the RS algorithm, we need a RS plane and capture a sufficient number of perspective elemental images at the beginning of the method. However, the difference lies in that we add the elemental images in the space domain. This means that there is no Fourier transform and inverse Fourier transform involved in our method. Therefore, the calculation process is more simplified and the calculation speed is improved. The difference between the angles of each perspective elemental images is very small. So, our method is equivalent to continuous phase addition when we add these element images with their slanted phase.

It is worth noting that we introduce randomness in the slanted phases during the calculation for better images quality. When we add the perspective elemental images with the corresponding slanted phases, just like we add oblique plane waves in multiple directions. This step could result in a plaid on the final images due to the plane wave interference. The introduction of randomness means that some pixel value of the slanted phase is zero, and the others is their original value. Hence, some pixels of the perspective elemental image are multiplied with the slanted phase, and the others are their original phase. We could find that phase randomness can reduce the plaid of the reconstructed image and the effect is different owing to the different random ratios. As the proportion of zeros pixels in the random matrix increases, the image quality is getting better and better. In this paper, we make the proportion of zero pixels account for 10% after the comparison.

After we obtain the complex amplitude hologram, we can use double-phase encoding method to get pure phase hologram to suitable for phase-only SLM. Since the random phase is not introduced into the CAM, the final reconstructed image quality is perfect. Moreover, since the complex amplitude hologram we obtained contains accurate angle and depth information, the observer can obtain accurate depth cues in the reconstructed scene. In other words, the image is only clear at the reconstruction position and becomes blurred once it leaves the reconstruction position and this is similar to the real light field what we always see.

3 RESULTS

In this section, we perform the result of computer simulations and optical experiments to demonstrate the performance of the proposed algorithm. Each perspective elemental images are rendered by the 3DMAX software, and the pixel count of the image is 256×256. We totally captured the images from 9×9 different viewing angles and the distance from the RS plane to the object is set to be 100mm. Also, the distance between each elemental images in the horizontal or vertical direction is 0.5mm. The wavelength used in the calculation is 532nm. The sampling number of the hologram is 2304×2304 with the pixel pitch 8μm.

Figure 4 illustrates the optical setup of the optical experiments. In the system, we employ a phase-only SLM (Holoeye pluto) with the resolution of 1920×1080 and the pixel pitch of $8\mu m$. The polarizer is employed just after the Laser before the beam splitter (BS) to ensure the polarization directions of laser beams match that of SLM. The contrast of the results reaches its maximum when we set the polarizer. The focal length of two lens in the 4-f system are both 300mm. The results are recorded directly by the CMOS of the camera (Nikon D3100) at different positions to capture the images from different distances relative to the reconstructed plane.

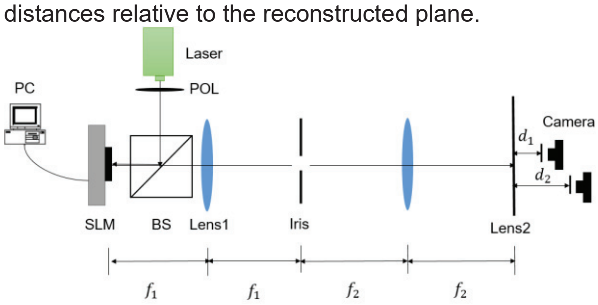

Fig. 4 The optical setup of the proposed method.

We use a 3D model made up of a dog and a wall to confirm the proposed method. Figure 5(a) shows three examples of the perspective elemental images. They were selected from 9×9 different viewing angles. The reconstructed results at different depths are shown in Figure 5(b)-(e). Figure 5(b)-(c) are the numerical reconstructed results and Figure 5(d)-(e) are the optical reconstructed results that the reconstructed plane is placed in clear positions of dog and wall, respectively. The results clearly demonstrate the effective accommodation cue provided by the proposed algorithm. As we can see that when the dog is clear, the wall is blurred, and when the wall is clear, the dog is blurred. From these results, we confirmed that the proposed method successfully reconstructs the 3D model with accurate depth cues.

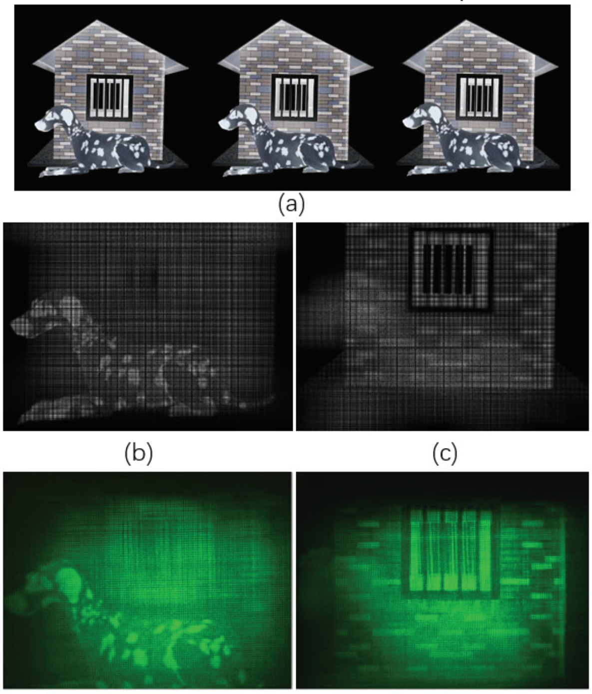

Fig. 5 Experiment results of the 3D image reproduction. (a) Three examples of rendered perspective elemental images. (b) Numerical reconstructed results at different depths. (c) Optical reconstructed results at different depths.

4 CONCLUSIONS

In this paper, we propose a new method based on RS algorithm to reconstruct the real light field. Different from the previous method, we add the elemental images in the space domain without any Fourier transform and inverse Fourier transform. In our method, after capturing perspective elemental images, we extend the image resolution firstly to avoid the unexpected images quality due to the loss of the spectrum information when we add these perspective elemental images. Then, we calculate the slanted phase for each viewpoint based on the position of each viewpoint and introduce randomness in the slanted phases to reduce the plaid on the reconstructed caused by the plane wave interference. Next, we multiply each perspective elemental images with their corresponding slanted phases and add them to the final complex amplitude hologram. Finally, we use double-phase encoding method to get pure hologram for phase-only SLM. Numerical and optical experiments indicates the proposed method can effectively achieve good image quality and accurate depth cues at the same time.

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