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Fast calculation method for full-color computer-generated hologram with real objects captured by a depth camera

Yu Zhao[1], Shahinur Alam[1], Seok-Hee Jeon[2], and Nam Kim[1];
[1]School of Information and Communication Engineering, Chungbuk National University, Cheongju, Chungbuk 361-763, Korea
[2]Department of Electronics Engineering, Incheon National University, 119 Academic-ro, Yeonsu-gu, Incheon 22012, Korea

*Corresponding author: **namkim@chungbuk.ac.kr***

Abstract

A fast calculation method for full-color holographic system with real objects captured by a depth camera is proposed. In this research, the depth and color information of the scene is acquired using a depth camera and the point cloud model is reconstructed virtually. Because each point of the point cloud is distributed precisely to the exact coordinates of each layer, each point of the point cloud can be classified into grids according to its depth. A diffraction calculation is performed on the grids using a fast Fourier transform (FFT) to obtain a computer-generated hologram (CGH). The computational complexity is reduced dramatically in comparison with conventional methods. The numerical simulation results confirm that our proposed method is able to improve full-color CGH computational speed.

Introduction

Recently, three-dimensional (3D) display technology has developed rapidly. Many types of 3D displays are starting to be commercialized, such as head-mounted display, volumetric display, light field display, integral imaging, and so on. Holography is a unique technology that can express 3D information almost perfectly because it can record and reproduce all the 3D information, such as motion parallax, convergence, occlusions, and accommodations. Therefore, it is possible to reconstruct a 3D object that comes very close to reality.

With the development of computing technologies over the past decades, optical holography can be totally through a digital processing method; consequently, Brown et al. introduced the computer-generated hologram (CGH) in the mid-1960s [1]. CGH has significant benefits [2] including that a hologram of a physical object can be created quickly. Over the past decade, a lot of research based on the CGH technique has been proposed, among them, real object-based methods are very popular [3-6]. The depth and color information of the real scene is acquired through a depth camera, and a point cloud model can be reconstructed virtually with a spatial light modulator (SLM) .In these studies, a depth camera acquires depth and color information from the physical object, and then holograms are generated from the object information acquired. However, their holographic systems were limited to monochrome. Chang et al. introduced a 360-degree color holographic system for real 3-D Object; however, the heavy computation load is one of the issues. To overcome those problems, research has produced many strategies. Some studies applied a graphics-processing unit (GPU) to enhance the calculation speed [7-9]. Each pixel in the hologram plane captures the light field independently. By contrast, each pixel from the object emits light independently. Thus, a GPU can be used to capture the light field at the hologram or to emit the light from the object in a parallel process where one thread controls the calculation for one pixel or one point. In addition to using a GPU, the researcher can apply a look-up table (LUT) to reduce the calculation time; however, this requires a large amount of memory [10,11]. The wavefront recording plane (WRP) [12-16] is a method proposed to overcome the drawbacks of the point cloud method. The WRP is considered to be a small virtual window placed between the object plane and the hologram plane, but it is much closer to the object plane. By calculating the complex amplitude of a small region on the WRP, rather than the entire holographic plane, the computation time to generate a CGH can be reduced dramatically. However, because the characteristics of advanced WRP require pre-computation of the optical field from the point cloud, it is much more difficult to realize real-time holographic display using these methods. Zhang et al. [17] adopted the angular-spectrum layer-oriented method to generate CGHs of versatile formats of 3-D scenes. Angular spectra from each layer are synthesized as a layer-corresponded sub-hologram based on the fast Fourier transform without paraxial approximation. Continuously, they proposed an improved time-division multiplexing method [18]. In their research, a three-dimensional (3-D) scene has been divided into multiple layers at different depths, but these hologram 3D displays methods are limited to displaying computer-synthesized images of virtual 3D objects. Recently, we previously reported an algorithm using point cloud gridding method to accelerate a monochrome CGH of a real-existing object [7].

Therefore, fast CGH calculation algorithms for full-color CGH are significantly required. Thus, in this paper, we propose a chromatic point cloud gridding method to accelerate the calculation of CGH for full-color holographic system with a GPU. The depth and color data of the real scene was simultaneously acquired through the depth camera, and a color point cloud model was extracted from the depth data. Then each point on the depth-layers can be classified into grids according to its depth, a diffraction calculation is performed on the grids using a fast Fourier transform (FFT) to obtain three CGHs in red, green and blue channels. The holograms generated with our proposed method are capable of preserving the depth information of a real object, as presented in the following sections. The experimental results show that our method is able to enhance the speed of hologram generation and the quality of the reconstructed objects is acceptable. The efficiency of the proposed method is confirmed by comparing the computational time with the previous method. The experimental results are discussed, which demonstrate the effectiveness of the proposed method.

Proposed method

In this paper, we propose a full-color holographic system for real 3D objects captured by a depth camera, as shown in Fig. 1. Regarding the full-color hologram generation process, our proposed method consists of three steps. In the first step, the point cloud produce by a depth camera usually has a lot of depth information, as shown in the acquisition part of Fig. 1. The depth and color data of the real scene are acquired simultaneously through a depth camera connected with a personal computer (PC), where the depth camera consists of a red-green-blue (RGB) sensor that detects the color, and an infra-red (IR) sensor to detect depth data. The latter is used to generate a virtual 3D visualization of the object. The experimental point cloud was captured with a Intel Real Sense 3D depth camera. Table 1 shows the specifications of the Intel Real Sense 3D depth camera.

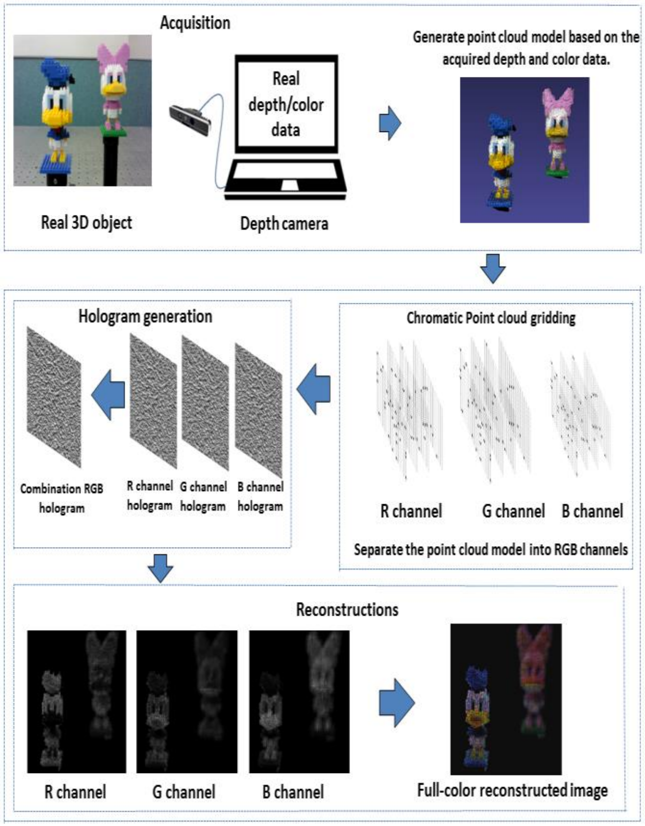


Figure 1. Entire schematic configuration of the proposed system.

After obtaining the point cloud model RGB channels, the region of interest (ROI) of the point cloud model was identified, which can be expressed as follows:

$$N = ROI\left(\sum_{i=1}^{T} U_j\right). \tag{1}$$

where U_j is the pixel value of the depth map, and N is the ROI value in the depth map. T is the number of points in the cloud. Fig. 2 shows the outline of the acquisition step.

Table. 1. Characteristics of the depth camera.

Resolution of the color stream		1920×1080/30fps
Resolution of the depth stream		640×480/30fps
Range of detection		0.2 ~ 1.5m
Angle of depth	Horizontal	70°
	Vertical	60°

The second step is to classify each point into sub-layers according to depth information, as shown in Fig. 2. After classifying the point cloud, the depth layers of the point cloud models are resampled and rasterized into depth grids. Each depth grid contains all of the points that are at the same depth, where the depth grid nodes match every point with the same depth. Here, the grids of the multi-depth layers can be considered as two-dimensional (2D) images and the points of each depth layer can be perceived effectively as pixels.

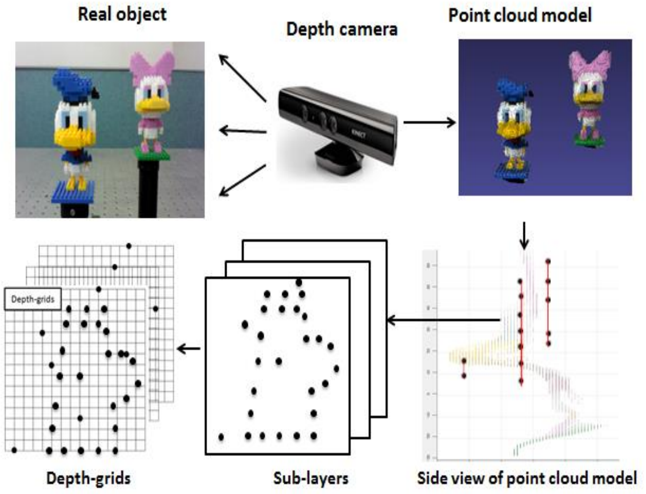


Figure 2. Outline of the proposed chromatic point cloud gridding method.

In order to produces smoother reconstructed images, bicubic interpolation has been used in our research. Bicubic interpolation solves for the value at a new point by analyzing the nearby(4x4) value of neighboring points on the depth-grids. When using the bicubic interpolation, the intensity $U_i[x,y]$ of the depth grids can be defined as:

$$U_i[x,y]=\sum_{i=0}^{3}\sum_{j=0}^{3} a_{ij}P_{ij} \tag{2}$$

there are 16 coefficients a_{ij} that should be determined in order to compute the function in Eq. (2). P_{ij} is the neighboring matrix [19].

In the third step, each point of the point cloud can be distributed accurately according to the exact coordinates of each layer in a generated grid, and we separate the depth grids into RGB channels and obtain a chromatic CGH by executing the diffraction calculation on the depth grids using FFT techniques. As 2D multi-depth grids are used to calculate the CGH, rather than every individual point of the 3D point cloud, the overall calculation time is reduced.

In the hologram generation process, each sub-hologram can be generated from each layer by using a hybrid algorithm of angular spectrum method (ASM) [20].

The sub-layer is discretized as a 2D optical field, and a 2D FFT is performed:

$$U_o(f_x, f_y) = \mathcal{F}[U_o[x, y]]. \tag{3}$$

We apply fast fourier transform (FFT) to the impulse response of Fresnel diffraction as follows:

$$H(f_X, f_Y) = e^{jkz} \exp[-j\pi\lambda z(f_X^2 + f_Y^2)]. \tag{4}$$

where λ is the wavelength. z is the distance between the object point and the hologram point. $H(f_X, f_Y)$ denotes the angular spectrum. Multiply the two equations above, and perform 2D FFT, as in Eq. (3), so a sub-hologram of a sub-layer can be generated rapidly and accurately:

$$u(x, y) = \mathcal{F}^{-1}[U_f(f_x, f_y)H(f_X, f_Y)]. \tag{5}$$

where u(x, y) denotes the sub-holograms from RGB channels, the combination hologram is combined from these RGB holograms.

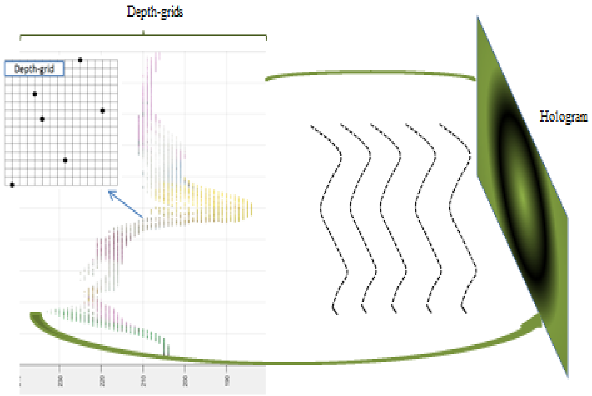
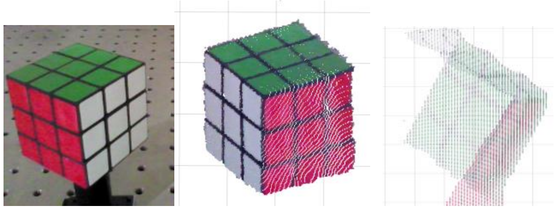


Figure 3. Spatial structure of the hologram generation using the chromatic point cloud gridding method.

Verification and results

1. Numerical simulations

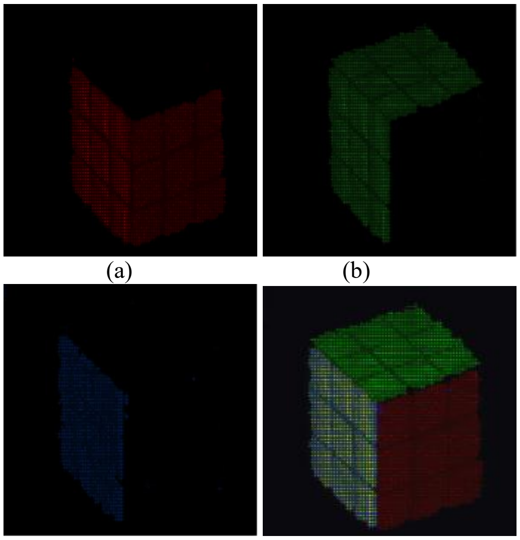
Firstly we employed numerical simulation to evaluate the performance of the proposed method. The experimental point cloud was captured by with an Intel real sense 3D depth camera. The size of the object is limited in a range from −15 to 15 mm on each x, y, and z axis, as show in Figs. 3(a), (b) and (c). After acquisition processing, the point model of a magic cube presented here contains 15033 points.



(a) (b) (c)

Figure 4. (a) Real 3D object of a magic cube, (b) point cloud model with 15033 points and (c) depth layers of point cloud model.

We used a hologram resolution of 1080 × 1080 with a pixel size of 7.4µm. Figs. 3(a), (b) and (c) show red, green, and blue components of the reconstructed results with different wavelengths from RGB channels. Fig. 3(d) is the full-color reconstructed image with the central position located at 300 mm.



(a) (b)

(c) (d)

Figure 5. Numerical reconstructed images of a magic cube with different wavelengths of (a) 633nm, (b) 532nm and (c) 473nm. (d) Full-color reconstructed image of a real magic cube.

Other simulations of our method are presented in this section. The constructed 3D models are composed of 18813 and 44624 points, respectively. The size of the object is limited in a range from −20 to 20 mm on each x, y, and z axis, as show in Figs. 5. The parameters are the same as those used for the previous simulation. To demonstrate the acceleration efficiency of the proposed point cloud gridding method, numerical simulations and optical experiments were conducted. In this section, we compare the computational performance of the conventional Rayleigh Sommerfeld (RS) method, WRP method and proposed point cloud gridding method. The simulations were conducted on a Windows 7 32-bit Operating system, MATLAB R2017b, Intel Xeon W3670 3.20GHz CPU and an NVIDIA GTX 960 GPU. The sampling distance is 7.4µm and the number of the samplings is 1024.

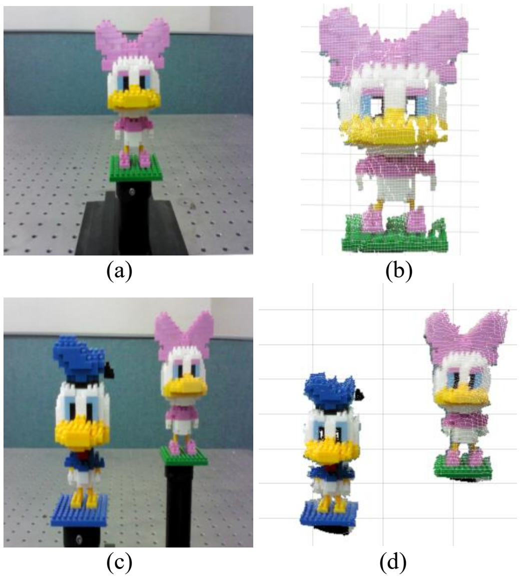

(a) (b)
(c) (d)

Figure .6 (a) Real 3D object of a toy and (b) point cloud model with 18813 points and 50 depth grids ;(c) Real 3D object of two toys and (d) point cloud model 44624 points and 107depth grids.

Figs. 7 (a), (b) and (c) show red, green, and blue components of the reconstructed results with different wavelengths from RGB channels. Fig. 6(d) is the full-color reconstructed image. Figs 6(e) and (f) are the full-color reconstructed images of two toys with the central positions are located at 300 mm and 380 mm.

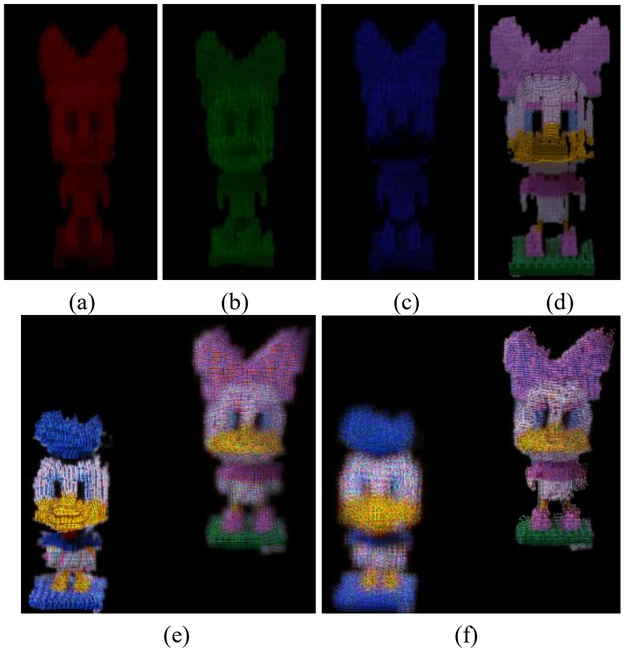

(a) (b) (c) (d)
(e) (f)

Figure 7. (a) Numerical reconstructed images with different wavelengths of 633nm, (b) 532nm and (c) 473nm. Full-color reconstructed images with central positions located at (d) 300mm and Full-color reconstructed images of two toys with central positions located at (e) 300mm and (f) 380mm

In addition, experimental data from real objects of a person is shown in Fig.7 (a) and (b). A numerical simulation of two toys is presented in Figs. 7(e) and 4(f), which shows the focal cue in the reconstructions. Other simulations of our method are presented in Fig .8. The size of the real object is limited in a range from −30 to 30 mm on each x, y, and z axis, as show in Fig. 8 (a). The constructed 3D models are composed of 71221 points and 359 depth grids. The full-color reconstructed images of person with a cactus are presented in Figs. 8 (c) and (d), which show the focal cue in the reconstructions, respectively. Fig. 8(e) and (f) are the similar experimental results, with 56876 points and 158 depth grids. PSNR of the reconstructed image Fig.8(f) is 25.7dB. The reference image is the point cloud model with intensity information. Thus, we can see that the proposed method successfully reconstructed the 3D real objects.

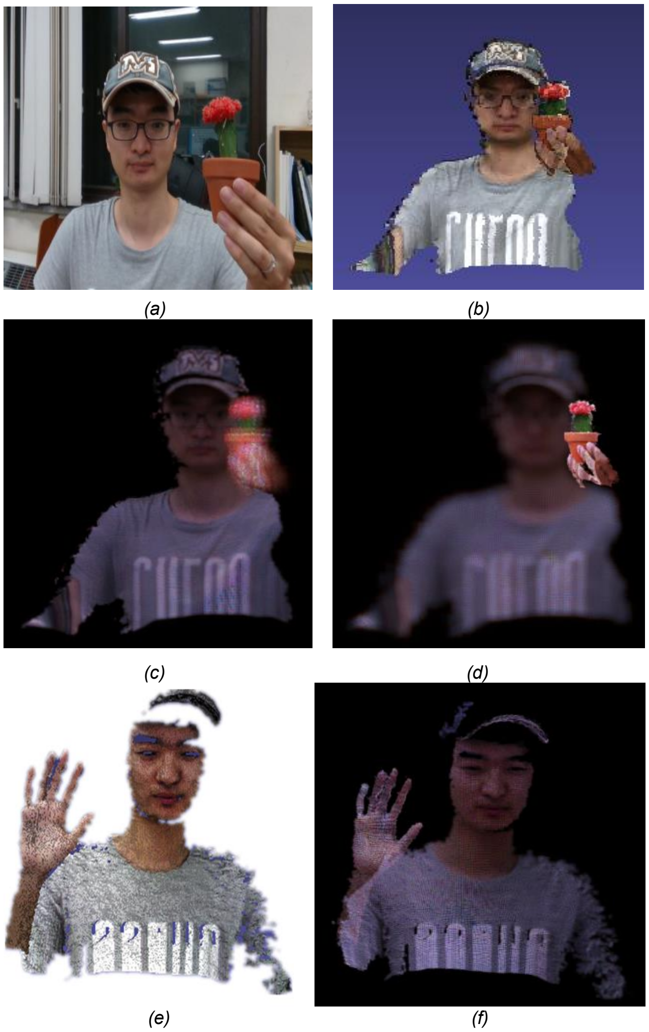

(a) *(b)*
(c) *(d)*
(e) *(f)*

Figure 8. (a) Real 3D object of a person and (b) point cloud model 71221 points and 349 depth grids. Numerical reconstructed images with central positions located at (c) 200 mm and (d) 300 mm (e) point cloud model from a real sense 56876 points and 158 depth grids (f) Full-color reconstructed images with central positions located at 200mm.

As shown in Table 2 the calculation time using proposed method was considerably reduced compared with the direct integration method. The generation time is dramatically reduced when the CPU is used, where the hologram generation speed is enhanced 123.68~198.24-fold in comparison with conventional method. In addition, the calculation time required for the proposed method is 68.70~107.69 times faster than the WRP method. The GPU calculated hologram generation speed is enhanced 2.85~5.41-fold when comparing the proposed method with the single WRP method. Our proposed method can calculate the CGHs from 20000 object points at approximately 7 frames per second (fps) using the GPU.

Table 2. Generation time for 1,024 × 1,024 holograms (seconds)

	Conventional algorithm (CPU)	WRP (CPU)	Proposed method (CPU)	WRP (GPU)	Proposed method (GPU)
One cube	813.035	451.335	6.569	1.480	0.133
One Toy	1917.068	829.268	9.638	1.770	0.143
Two toys	2843.851	1543.851	14.336	2.755	0.570
Person with cactus	4498.347	2296.443	28.017	7.590	2.663
Person	3298.347	1751.335	16.638	5.754	1.063

2. Optical experiment

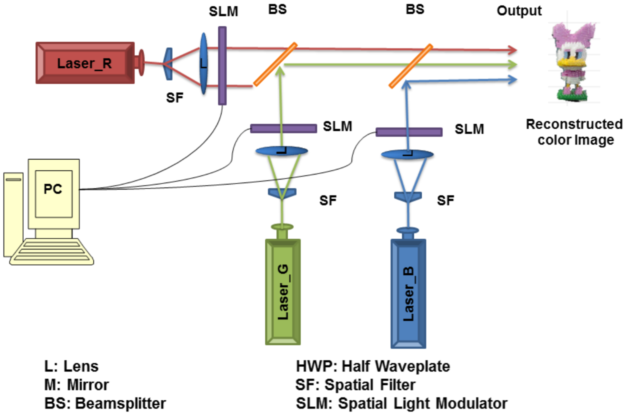
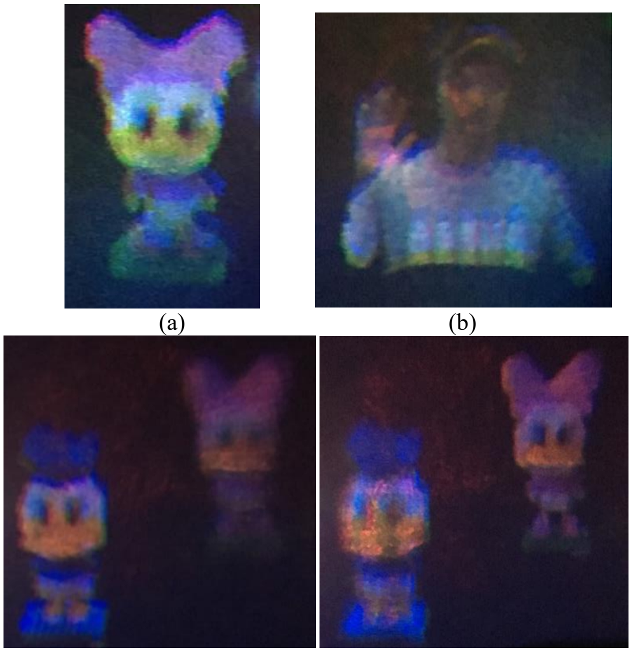


Figure 9. Optical experiment setup of proposed method

For optical reconstruction, we used a liquid crystal display HD kit 1920 × 1080 (7.4μm) transmission-type spatial light modulator (SLM) and RGB lasers. The SLM used for the experiments had a dynamic range of 255 intensity levels. Three lasers were used as the reference beams, with wavelength and output power as follows: red laser, 633 nm and 75mW; green laser, 532 nm and 100mW; and blue laser, 473 nm and 50mW. To equalize powers of the RGB components in the experimental setup, the optimal proportion of the powers of the RGB lasers can be set as 1:1:1.1. The optical setup for full-color reconstruction is shown in Fig. 9. The reconstructed images were captured using a charge-coupled device (CCD) camera connected to a computer, and Figs. 10(a) and (b) show the reconstructed results of the hologram from a magic cube and a toy, respectively. Figs. 10(c) and (d) show reconstructed images of two toys recorded at distances of 200 mm and 380 mm from the rear focus of the 3-D scene, respectively. We used a hologram resolution of 1080 × 1080 with a pixel size of 7.4μm. The experimental results indicate that the real 3-D objects can be reconstructed clearly.


(a) (b)

(c) (d)

Figure 10. Optical full-color reconstructed images of (a) mickey mouse toy and (b) person. Reconstructed images of two toys with central positions located at (c) 200 mm and (d) 380 mm captured by a charge-coupled device camera.

Conclusion

In this paper, we propose a method that uses chromatic point cloud gridding method to accelerate the full-color holographic system. The depth data of the real scene were simultaneously acquired through the depth camera, and a point cloud model was extracted from the depth data. Real 3D object can be easily encoded into CGHs with the proposed algorithm. The numerical and experimental results both indicate that real 3D objects can be reconstructed clearly. Compared with conventional WRP method the acceleration efficiency of our proposed method is excellent. The authors believe that this method will be useful for creating CGHs for a real-time full-color holographic display.

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Author Biography

Yu Zhao was received the B. E degree in Electronic and Information Engineering from YanTai University(China) in 2011 and his M.E degree in Computer and Communication Engineering from Chungbuk National University (Korea) in 2014. He is now a Ph.D. student of Chungbuk National University. His research interest includes the computer generated hologram, image processing, holographic optical element and 3D Display.