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Fast calculation method of computer-generated hologram using a depth camera with point cloud gridding

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ABSTRACT

We propose a fast calculation method for a computer-generated hologram (CGH) of real objects that uses a point cloud gridding method. The depth 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 CGH. The computational complexity is reduced dramatically in comparison with conventional methods. The feasibility of the proposed method was confirmed by numerical and optical experiments.

1. Introduction

The term holography refers to the recording of both the intensity and phase of an object, as compared to traditional photography that only records the intensity information of the object. With the continuous development of computer technology over the past few decades, optical holographs can be captured using digital processing methods: Brown and Lohmann introduced the computer-generated hologram (CGH) in the mid-1960s [1]. CGH is an approach to digitally generate holographic interference patterns from a three-dimensional (3D) object, where an object image is reconstructed using optical techniques. CGH has significant benefits [2] including that a hologram of a physical object can be created quickly. Many techniques have been developed for generating CGHs of real objects [3–6]. The depth and color information of the real scene can be acquired using a depth camera, and a point cloud model can be reconstructed virtually with a spatial light modulator (SLM) [7].

The point cloud method has the advantages of being simple, flexible, accurate, and suitable for obtaining 3D object models with depth cameras or laser scanning. It takes a long time to make a hologram based on the point cloud method, as it must calculate a sub-hologram from each individual point of the point cloud, which requires a huge amount of computation. Many methods [8–16] have been proposed to reduce the computational complexity of the point cloud method. The original intention with the mesh method was to reduce the amount of computation by building up a plane with vertexes (i.e. points of the point cloud). The wavefront recording plane (WRP) [8–11] is another 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. A look-up table (LUT) that has pre-computed distributions of the complex amplitude [12,13] can be used in combination with the WRP method to rapidly generate CGHs [14–16]. Remarkably, the combination of WRPs and LUTs can enable the speed for real time hologram generation. 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. Therefore, fast real object based CGH calculation algorithms are significantly required. Thus, in this paper, a fast calculation method for real objects by using point cloud gridding is proposed. The hologram

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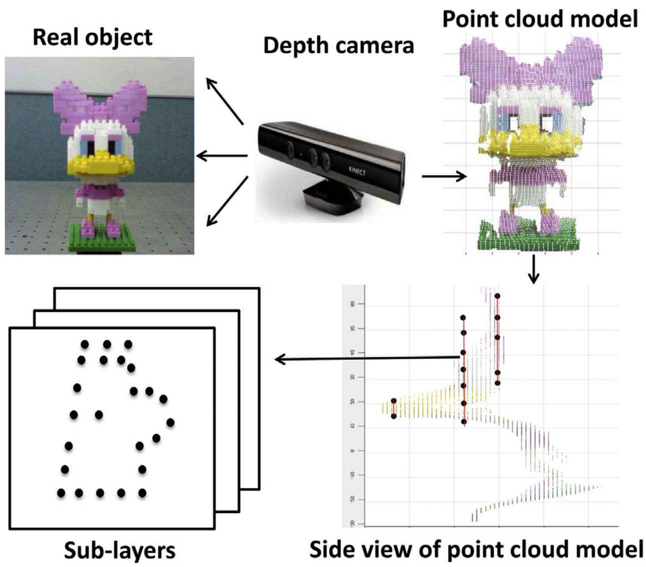

Fig. 1. Depth information acquisition with a depth camera.

Table 1
Characteristics of the depth camera.

Resolution of color stream		1920 × 1080/30 fps
Resolution of depth stream		512 × 424/30 fps
Range of detection		0.5–4.5 m
Angle of depth	Horizontal	70°
	Vertical	60°

generated with our proposed method is 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 improve the computational speed of CGH. The simulation results are discussed, which demonstrate the effectiveness of the proposed method.

2. Proposed method

Regarding the hologram generation process of real object using a depth camera, our proposed method consists of three steps. In the first step, the point cloud produced by a depth camera usually has a lot of depth information, as shown in Fig. 1(a). However, there is a finite value of the depth information in point cloud that is captured by depth cameras. Thus, the point cloud can be considered as sub-layers. The sampling of the depth information is uniform within a given depth layer. The depth camera includes red, green, and blue (RGB) sensors to detect colors and an infrared (IR) sensor to measure the depth data. Latter it is used to generate a virtual 3D visualization of the object. The experimental point cloud was captured with a Microsoft Kinect 2.0 device and the processing was performed on a PC server. Table 1 shows the specifications of the Kinect depth camera.

The second step is to classify each point into sub-layers according to depth information, as shown in Fig. 2(a). 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, as shown in Fig. 2(b), where the depth grid nodes match every point with the same depth. As a 512 × 512 depth grid has more than 260,000 node coordinates and a 1024 × 1024 grid has up to 100 million, the depth grid is sufficient for a point cloud with a few million points. 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.

In order to produces smoother reconstructed images, bicubic interpolation has been used in our research. Bicubic interpolation solves for the

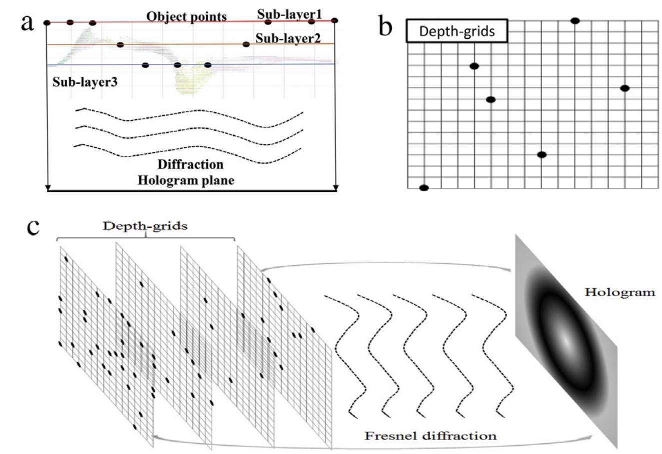

Fig. 2. (a) Plane structure for the classification of points in the proposed point cloud gridding method. (b) Depth grids and (c) spatial structure of the hologram generation using the point cloud gridding method.

value at a new point by analyzing the nearby (4×4) 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:

$$U_i[x, y] = \sum_{i=0}^{3} \sum_{j=0}^{3} a_{ij} P_{ij} \tag{1}$$

there are 16 coefficients a_{ij} that should be determined in order to compute the function in Eq. (1). 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 obtain a CGH by executing the diffraction calculation on the multi-layers using FFT techniques. The point cloud is a collection of points with 3D coordinate information. Eliminating the depth information of object points results in an accurate match between the points and 2D coordinates, referred to as a grid of oversampling. 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.

As the second step requires a point cloud gridding model to be obtained, a sub-hologram is generated for each grid using the Fresnel diffraction [20]. To generate each of the sub-holograms, each grid is processed as follows:

(1) The depth-grid is discretized as a 2D optical field, and a 2D FFT is performed:

$$U_i(f_x, f_y) = \mathcal{F}[U_i[x, y]]. \tag{2}$$

(2) An FFT is applied to the impulse response of the Fresnel diffraction, and a Fresnel diffraction transfer function is obtained:

$$H(f_X, f_Y) = e^{jkz} \exp[-j\pi\lambda z(f_X^2 + f_Y^2)] \tag{3}$$

where z is the distance between the depth grids and the hologram plane.

(3) A sub-hologram of the depth grid is generated rapidly and accurately by performing a 2D FFT on the product of Eqs. (2) and (3):

$$u(x, y) = \mathcal{F}^{-1}[U_f(f_x, f_y) H(f_X, f_Y)]. \tag{4}$$

The full hologram of the 3D object is then generated by summing the sub-holograms of each depth grid, as depicted in Fig. 2(c).

3. Verification and results

To demonstrate the acceleration efficiency of the proposed point cloud gridding method, numerical simulations and optical experiments