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For a three-dimensional display using computer-generated holograms (CGHs), fast CGH calculations are required but calculation time can be reduced by introducing wavefront recording planes (WRPs). However the conventional multiple wavefront recording planes (M-WRPs) based full-color computer-generated hologram (CGH) have color uniformity problem caused by intensity distribution and high computation time due to the big distance between object points in the depth range and the WRPs. This paper proposes a method that creates WRPs based on the number of object’s point at each depth layer thus reducing the calculation time and also having higher intensity reconstructed images. The proposed method is confirmed by numerical and optical reconstruction.

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1. Introduction

In recent years, advancement of hardware and technologies have created more demands for 3D television, AR, VR and many more 3D display technologies. Among all holography is the most prominent technique for reconstruction of all three dimensional (3D) information of an object in space and holographic projection can also achieve true 3D scene without wearable devices. In this technique, an object’s light field is recorded as interference fringes in the form of a so-called hologram. The physical process of light propagation in holography can also be simulated on a computer, called computer generated holograms (CGHs). However, an object consists of huge amount of three dimensional information; thus CGH generation is computationally costly.

To accelerate the generation of hologram many methods have been introduced so far. To reduce computational cost of holographic calculation Zhao et al. introduced a fast calculation method for point cloud gridding (PCG) method [1] where sub holograms are generated for each individual depths of the object and finally accumulated the sub holograms to form a complete hologram. Look-up table method [7-9] are used to store pre-computed calculation and use them later for faster generation of hologram but unfortunately, these methods require large memory for data storage.

Shimobaba et al. introduced wavefront recording plane (WRP) where a virtual plane, WRP, is placed close to the object point and parallel to the hologram plane [2-3]. Instead of direct calculation of the optical field from a 3D object to the hologram plane, the optical field only calculate the active area of the WRP, as shown in Fig. 1, and then propagate to the hologram plane by the Fast Fourier Transform (FFT).

Rj

WRP

Hologram

Active Area

P1(x,y)

Fig. 1. Hologram generation using WRP

However, for long depth objects, due to large distance between the object points and WRP the active area size would also be large; thus computation time would still be high. Anh-Hoang et al proposed double WRP to reduce the calculation further [4] where they introduced two WRPS at two different distances from object. The usage of GPU and lesser distance between object and the WRPS lowered the calculation time. Arai et al. proposed acceleration of CGH generation using tilted WRP which uses “Least Square Tilted WRP method” and “RANSAC Multi-Tilted WRP method.” to maintain the minimum distance between the WRP and curved sides of the object [5]. Later, Hasegawa et al proposed a multiple WRP (M-WRPs) method to optimize the number of WRPs and their arrangements automatically [6]. Recently, Piao et al proposed a method for image quality enhancement for M-WRPs [11]. In this method WRP is set at each layer using fixed active area size. However, fixed activation area might over-estimate or under-estimate the color uniformity.

Unfortunately, for each depth range, higher the distance between the object points in the farther depth and the WRP the higher will be calculation time for CGH generation.

In this paper, a fast and efficient method is proposed for arrangement of WRPs position for point-cloud of objects with non-uniform distribution of object points. The proposed method creates WRP based on the number of object points in each depth layer. Due to prioritizing depth layers with higher number of object points and optimum distance between the objects points and WRP faster calculation with higher reconstructed image can be achieved.

2. Conventional M-WRPs method

In conventional M-WRPs object is divided into several parts based on fixed depth range and a WRP is set in the middle of each depth range, as shown in Fig. 2.

Depth

Range k

Hologram

Fig. 2. Hologram generation using conventional M-WRPs

Depth

Range 1

WRP k

WRP 1

**Point cloud object**

The light field of each pixel of the WRP is calculated by summing the contribution of each point of the object according to equation (1),

, (1)

Here *Rj* is the distance between *j*th point and the WRP, shown by equation (2), *N is* the number of object points, *λ* is the wavelength of the light and *Aj* is the intensity of the *j*th object point, (*xj, y j, z j*) is the coordinate of the jth point and (*x, y,z*) is the coordinate on the WRP object

 (2)

Next, we calculate the light propagation from the WRP to the CGH via a diffraction calculation. Because the amplitude and phase information of the object points are recorded in the WRP, the diffraction calculation from the WRP to the CGH is the same as that from the object points directly to the CGH.

 (3)

 (4)

where, F and F-1 are the Fourier and inverse Fourier operators, *k* is the wave number, *z* is the distance between

the WRP and the hologram plane, and *h*(*x*,*y*) is the impulse response of *k*-th WRP..

2. Proposed Reduced M-WRPs method

In this section methodology of Reduced M-WRPs is explained in details. In RM-WRPs method, point cloud object is considered as sub-layers based on the each depth plane and WRP is set based on the number of object points in each depth plane, as shown in Fig. 3. Firstly, WRP is set closer to one end of the object. Onwards each depth layer is iterated and number of object points is counted. A new WRP is set, if and only if, the next layer has more number of object points than the previous layer,** otherwise wavefront of all object points from the current depth layer is propagated to the previous WRP. Here Nk is the number of object point in the kth layer.

Fig. 3. Hologram generation using object with non-uniform distribution of object points

**Point cloud object**

N5, 6 = 6

N4 = 2

N3 = 4

N1, 2 = 2

WRP 4

WRP 3

WRP 2

WRP 1

Change in number of object points in next depth layer are caused by change in shape of the object. Typically, change in object points in any new depth layers due to starting of a new object or curves and edges of the object. If WRP position is too far from the starting of the new object the color intensity of the object would be less and thus finally would produce a low quality reconstruction image. Since WRPs are created for each changes in number of object points, each WRP is created for smaller depth range, sometime for each individual depth layer too.

Total number of depth layer can be expressed as follows:

 (4)

Where A is the batches of depth layers with equal number of object points, C is total number of consecutive layers within a batch of depth and O is the number of rest of the layers with unequal number of object points. Thus total time required to propagate all object points to all WRPS can be expressed as:

 (5)

Where N(C) and N(O) are total number of object points in C and O layers. All WRP diffraction calculation to hologram plane:

 (6)

Total time for all WRPs diffractions to the hologram plane, ty is the calculation time for one WRP’s diffraction to hologram plane.

**3. EXPERIMENT RESULTS**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Object** | **No. of object points** | **Number of depth layer** | **Conventional M-WRPs method** | | **RM-WRPS method** | |
| **Calculation time** | **PSNR** | **Calculation time** | **PSNR** |
|  |  |  |  |  |  |  |
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References

1. Y. Zhao, C.-X. Shi, K.-C. Kwon, Y. L. Piao, M.-L. Piao, N. Kim, “Fast calculation method of computer-generated hologram using a depth camera with point cloud gridding,” Optics Comm. 411. 166–169 (2018)
2. T. Shimobaba, N. Masuda, and T. Ito, “Simple and fast calculation algorithm for computer-generated hologram with wavefront recording plane,” Opt. Lett. 34, 3133–3135 (2009).
3. N. Okada, T. Shimobaba, Y. Ichihashi, R. Oi, K. Yamamoto, T. Kakue, and T. Ito, “Fast calculation of computer-generated hologram for RGB and depth images using wavefront recording plane method,” Photo. Lett. Poland 6, 90-92 (2014)
4. A. H. Phan, M. L. Piao, S. K. Gil, N. Kim, “Generation speed and reconstructed image quality enhancement of a long-depth object using double wavefront recording planes and a GPU,” Appl. Opt 53, 4817-4824 (2014).
5. D. Arai, T. Shimobaba, K. Murano, Y. Endo, R. Hirayama, D. Hiyama, T. Kakue, and Tomoyoshi Ito, "Acceleration of computer-generated holograms using tilted wavefront recording plane method," Opt. Express 23, 1740-1747 (2015)
6. Naotaka Hasegawa, Tomoyoshi Shimobaba, Takashi Kakue, and Tomoyoshi Ito, "Acceleration of hologram generation by optimizing the arrangement of wavefront recording planes," Appl. Opt.56, A97-A103 (2017)
7. Lucente, M., “interactive computation of holograms using a look-up table,” Journal of Electronic Imaging 2(1) (091995).
8. Yoshikawa, H., Yamaguchi, T., and Kitayama, R., “Real-time generation of full color image hologram with compact distance look-up table,” in [Advances in Imaging], Advances in Imaging, DWC4, Optical Society of America (2009).
9. Zi Wang, Guoqiang Lv, Qibin Feng, Anting Wang, and Hai Ming, "Highly efficient calculation method for computer-generated holographic stereogram using a lookup table," Appl. Opt. 58, A41-A47 (2019)
10. Yan-Ling Piao, Yu Zhao, Hui-Ying Wu, Anar Khuderchuluun, Erkhembaatar Dashdavaa, Jong-Rea Jeong, Nam Kim, "Image quality enhancement for digital holographic display using multiple wavefront recording planes method," Proc. SPIE 10944, Practical Holography XXXIII: Displays, Materials, and Applications, 1094416 (1 March 2019);
11. S. Wanner, S. Meister, and B. Goldluecke. Datasets and benchmarks for densely sampled 4d light fields. In VMV, pages 225–226. Citeseer, 2013.
12. Honauer K., Johannsen O., Kondermann D., Goldluecke B. (2017) A Dataset and Evaluation Methodology for Depth Estimation on 4D Light Fields. In: Lai SH., Lepetit V., Nishino K., Sato Y. (eds) Computer Vision – ACCV 2016. ACCV 2016. Lecture Notes in Computer Science, vol 10113. Springer, Cham