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**Abstract:** 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).

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.

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.

1. Conventional M-WRPs method

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

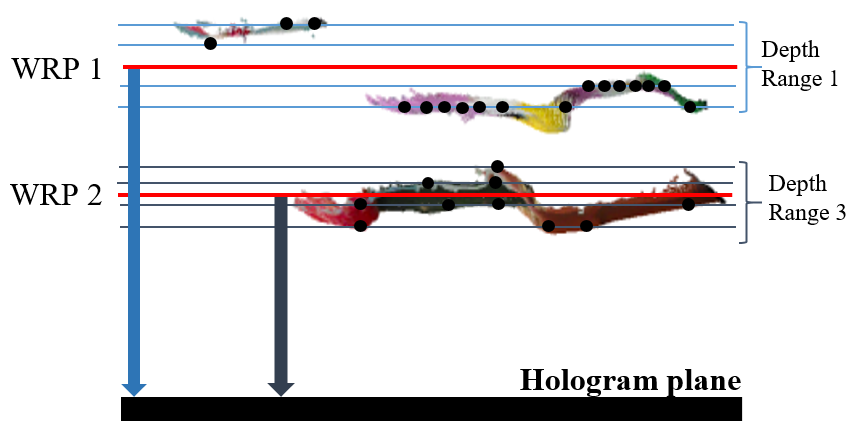


Fig. 2 Schematic diagram of conventional M-WRPs method

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

, (1)

Here is the distance between jth point and the WRP, shown by equation (2), *is* the number of object points, is the wavelength of the light, is the intensity of the jth object point, and is the coordinate of the jth point on the WRP object.

 (2)

The smaller the depth range is the shorter would be. This would reduce the calculation time for  and would also record higher intensity of light from the object points to the WRP. Thus each depth range is divided farther into smaller depth ranges until minimum calculation time or maximum PSNR is found, as shown in Fig 3.

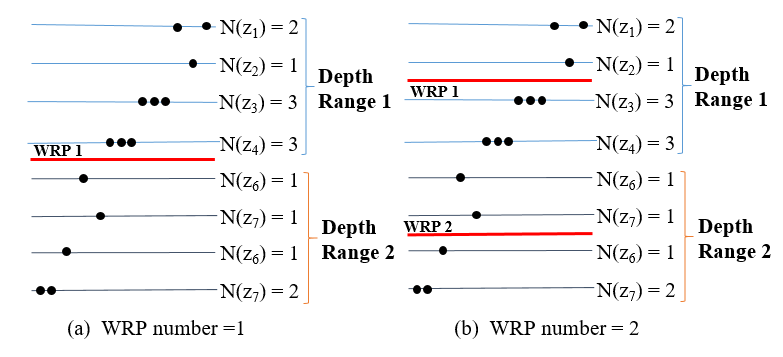


Fig. 3 Relation of WRP and depth range in conventional M-WRPs method

Next, we light propagate from the WRPs to the CGH via a diffraction calculation, as shown in equation (3). 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)

 and  are the Fourier and inverse Fourier operators, *k* is the wave number, *z* is the distance between the WRP and the hologram plane, and  is the impulse response of *P-th* WRP, shown by equation (4).

1. **Proposed Method**
   1. *Distributed M-WRPs method*

In this section methodology of DistributedM-WRPs (DM-WRPs) method is proposed. Below all steps of DM-WRPs are presented:

Step 1: Number of object point in each depth layer is computed

Step 2: Second order of difference among all values in Step 1 is calculated.

Step 3: Object is divided into depth ranges based on the change in second order of difference from Step 2.

Step 4: Within each depth range WRP is set closest to the depth layer with maximum number of object point, shown in Fig. 4

Step 5: Until minimum calculation time or maximum PSNR is achieved depth ranges with maximum number of depth layers are further divided into smaller depth ranges following from Step 1 on onwards.

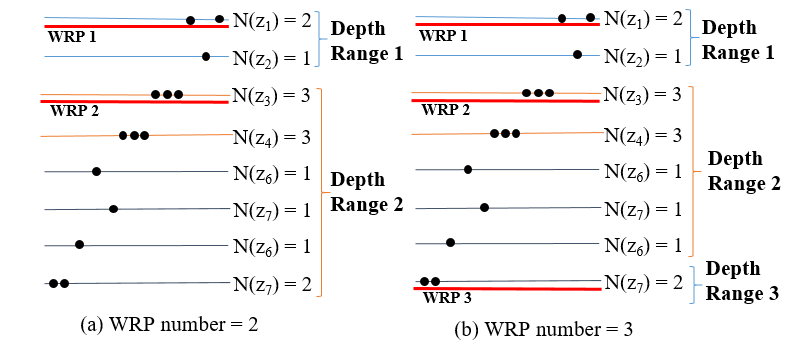


Fig. 4 Relation of WRP and depth range in DM-WRPs method

In best case, when maximum number of object point is in the depth layer positioned in the middle of the object *d* can be expressed as:

 (5)

Where d is the average distance between each object point within a depth range and the WRP and *D* is the total number of layers within the depth range. Since distance between each depth layer is equal D can be considered as the height of the depth range. In worst case, when maximum number of object point is in the depth layer positioned at the farthest end of the depth range *d*. Total propagation distance of all object points within a depth range to the WRP can be expressed as:

 (6)

So d can be expressed as:



* 1. *Reduced M-WRPs method*

In this section methodology of Reduced M-WRPs (RM-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.

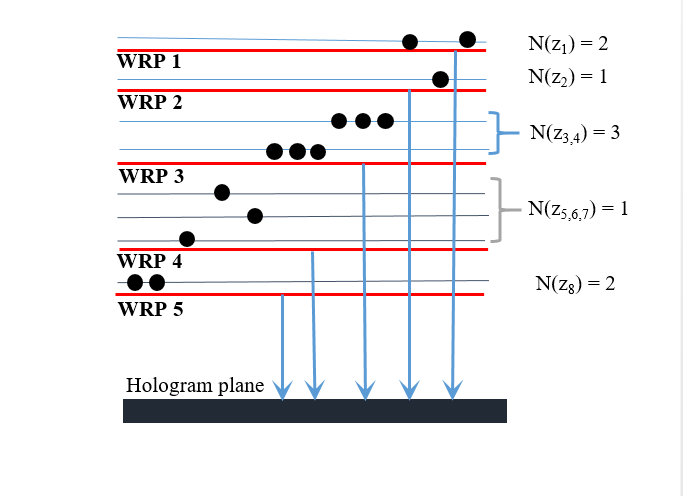


Fig. 3. Hologram generation using conventional RM-WRPs

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  is the number of object point in the *ith* depth layer.

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. In best case number of object point would be different at each and every depth layer.   
Thus but for worst case number object point can be repeated for  number of layers and the sum of distance of all object points to the WRP is same as equation (6). Here *d* can be expressed as:



Data acquisition from depth cameras or any kind of real life data acquisition. Here  is total number of layers that didn’t have same number of object points same as the previous layer. Total number of depth layers and Total number of WRPs can be expressed as follows:

 (5)

 (6)

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

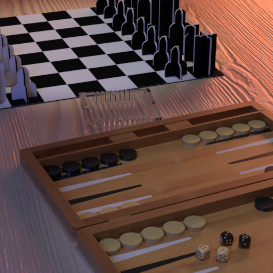
 (7)

Where  and  are total number of object points in *C* and *O* layers. All WRP diffraction calculation to hologram plane can be expressed as:

 (8)

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

EXPERIMENT RESULTS

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To verify the proposed RM-WRPs method, we have calculated CGH from RGB-D image using the conventional M-WRPs method and the proposed method. The experimental environment is Window 10 64-bit operating system, MATLAB 2018b, and Intel(R) Core(TM) i5-7500 CPU @3.40GHz. The parameters for calculation are as follows: the wavelength of Red, Green, and Blue is 633nm, 532nm, and 473nm, respectively. For optical experiment SLM with 7.4µm was chosen. The size of all RGB-D image and hologram is 520ⅹ520 pixels, and the pixel pitch is 7.4µm.and the distance between object and hologram plane is 0.5m,

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

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3.4 Abstract

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Fig. 1. Sample caption (Ref. [4], Fig. 2).

Table 2. Optical Constants of Thin Films of Materials*a*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | 83.4 nm | |  | 121.6 nm | |
| Material | n | K |  | n | k |
| Ir | 1.182 | 0.865 |  | 1.450 | 1.040 |
| MgF2 | 1.584 | 0.487 |  | 1.682 | 0.0627 |
| Al | 0.09874 | 0.1915 |  | 0.0424 | 1.137 |
| Mo | 0.98 | 1.08 |  | 0.78 | 1.03 |
| C | 1.16 | 1.29 |  | 1.85 | 1.10 |

*a*From Appl. Opt. **40**, 1128 (2001).

1. Funding, acknowledgments, and disclosures

5.1 Funding

Funding information should be listed in a separate block preceding any acknowledgments. The section title should not follow the numbering scheme of the body of the paper. List just the funding agencies and any associated grants or project numbers, as shown in the example below:

National Science Foundation (NSF) (1253236, 0868895, 1222301); Program 973 (2014AA014402); Natural National Science Foundation of China (NSFC) (123456).

5.2 Acknowledgments

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[1–4].

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1. Summary

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| --- | --- | --- | --- | --- |
| Standard Page Text Area: 5.25 x 8.5 in.; Margins: 1.3 in. top and bottom, 1.625 in. left and right | | | | |
| **Type of Text** | **Font** | **Font Size (Points)** | **Alignment** | **Notes** |
| Title | Arial | 16 | Left | **Bold**  Spacing expanded by 0.5 pts.  Kerning 16 pts |
| Author Name | Arial | 12 | Left | **Bold**  Use Small caps  Use journal color |
| Affiliation & Email | Times New Roman | 9 | Left | *Italic* |
| Abstract | Times New Roman | 10 | Justified | Bold “**Abstract:**” header |
| Copyright | Times New Roman | 8 | Left |  |
| Main Text  First paragraph  Subsequent paragraphs | Times New Roman | 10 | Justified | The first paragraph of a section or subsection is not indented. The first line of subsequent paragraphs is indented 0.2 in. |
| Section & Subsection Headings | Arial | 10 | Left | Insert 6-pt. space above and below each heading.  Section headers: **Bold**  Subsection headers: *Italic* |
| Equations |  | 10 | Center | Eq. Number: right tab to end of last line of Eq., in parentheses. |
| Figures |  |  | Center |  |
| Figure Captions | Times New Roman | 8 | Justified | Long captions: indent 0.5 in. left/right. |
| Tables | Times New Roman | 8 | Center | **Table 1. Bold table captions** |
| Table Heads | Times New Roman | 8 | Center | Long heads follow table margins. |
| Funding | Times New Roman | 10 | Justified | Bold “**Funding**” section header |
| Acknowledgments | Times New Roman | 10 | Justified | Bold “**Acknowledgments**” section header |
| Disclosures | Times New Roman | 10 | Justified | Bold “**Disclosures**” section header |
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