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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.

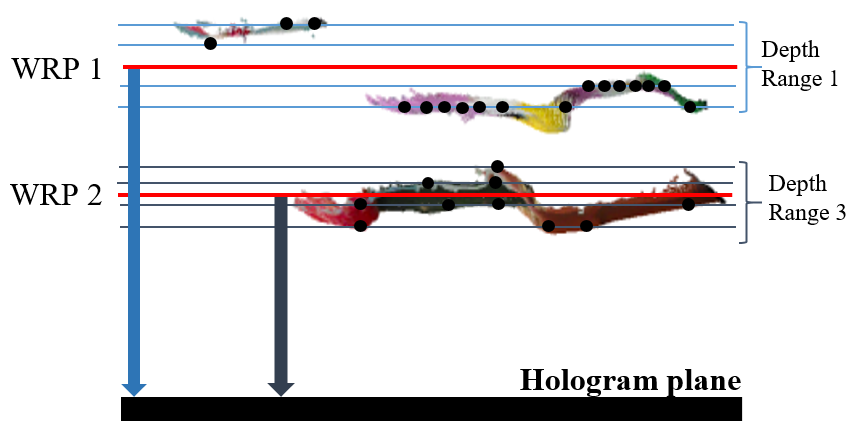


Fig. 2 Schematic diagram of conventional M-WRPs method

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.

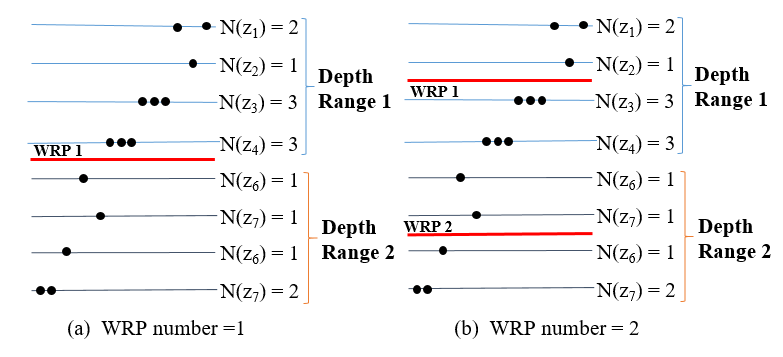


Fig. 3 Relation of WRP and depth range in conventional M-WRPs method

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.

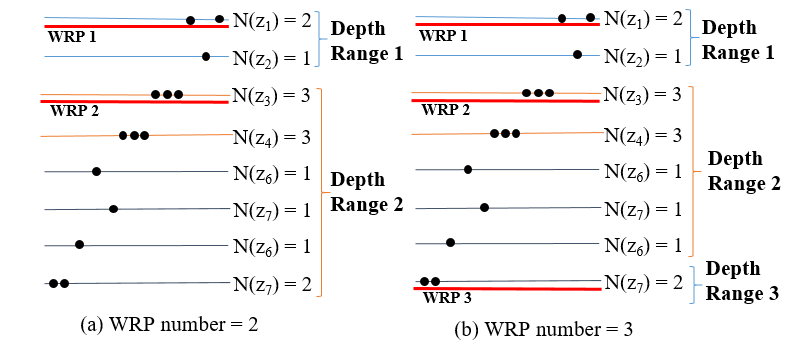


Fig. 4 Relation of WRP and depth range in DM-WRPs method

The height of the object can be expressed as:

 (5)

*D* is the average number of depth layers in a depth range. Since distance between each depth layer is equal *D* can be considered as the total distance of the depth range. *C* is the total number of depth ranges in the object. 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:

 (6)

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

 (7)

So *d* can be expressed as:

 (8)

* 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.

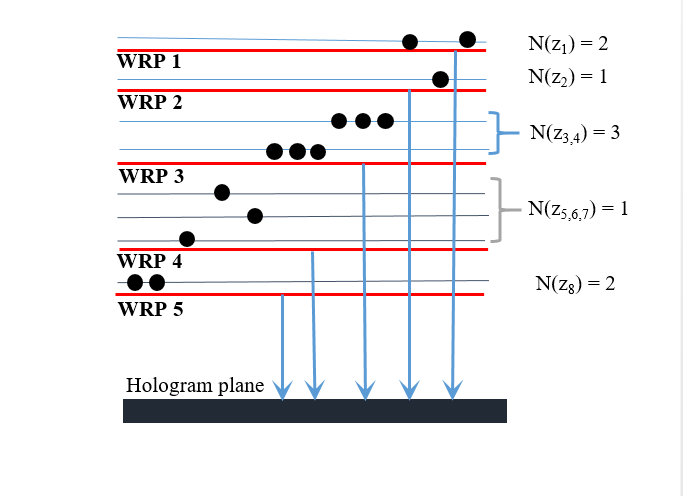


Fig. 3. Hologram generation using conventional RM-WRPs

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. Total height of the object can be expressed as:

 (9)

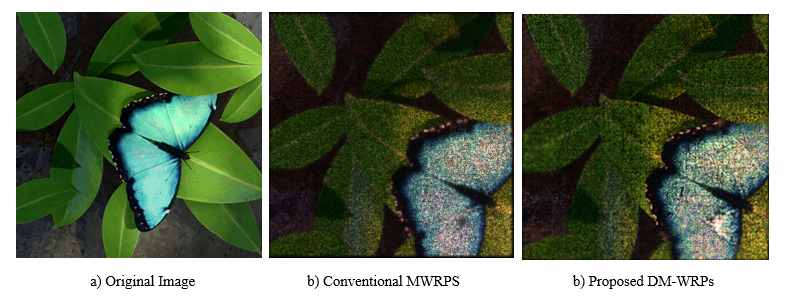
Hereis the number of depth layers with equal number of object points and  is total number of layers that have unequal number of object points with neighboring depth layers. In best case number of object point would be different at each and every depth layer. Thus *d* would be approximately 0but for worst case number object point can be same for all depth layers. Moreover data acquisition from depth cameras or any kind of real life data acquisition number of number of object points in a depth layer and its neighboring layers are hardly same, .Thus and *d* can be expressed as:

 (10)

1. **EXPERIMENT RESULTS**

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,

|  |  |  |  |
| --- | --- | --- | --- |
| Papilon | No. of WRPs | Calculation Time | |
| Conventional  M-WRPs | Proposed  DM-WRPs |
| 2 WRPs | 1587.1.1 | - |
| 4 WRPs | **1574.3** | - |
| 8 WRPs | 1600.1 | 644.75 |
| 10 WRPs | - | **636.24** |
| 16 WRPs | 1624.0 | 641.85 |
| 32 WRPs | 1668.2 | 659.69 |
| Three\_Objects | 2 WRPs | **463.4** | - |
| 4 WRPs | 465.2 | 159.34 |
| 5 WRPs | - | **156.94** |
| 8 WRPs | 469.1 | 161.42 |
| 16 WRPs | 483.0 | 170.23 |
| 32 WRPs | 483.0 | 179.27 |



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Conventional  M-WRPS | | Proposed  RM-WRPS | |
| Time | PSNR | Time | PSNR |
| Papilon | 1574.3 |  | 694.58 |  |
| Three\_object | 463.4 |  | 180.2489 |  |

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