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An Efficient Hologram Generation Method via Multi-Layer WRPs and Optimal Segmentation

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Abstract

In this paper, an efficient hologram generation method via multi-layer WRPs and optimal segmentation is proposed. The method consists of four steps: First, the 3D object is discretized into point clouds and classified into depth-based groups, with each group assigned an independent WRP. Then, the sub-holograms for each point on its corresponding WRP are calculated using Fresnel diffraction theory. Third, by analyzing the viewing area, the sub-holograms are optimally segmented to obtain optimal diffraction regions (ODRs). Moreover, these ODRs are coherently superimposed to obtain the complex amplitude distribution. Finally, the complex amplitude distribution is propagated onto the holographic plane to obtain the final hologram. Experimental results demonstrate an 82.4% reduction in calculation time compared to traditional NLUT methods, while numerical and optical experiments confirm high-fidelity color reconstruction. By leveraging multi-layer WRPs and optimized segmentation, this method achieves substantial calculational efficiency improvements without compromising display quality, offering a promising solution for real-time holographic display applications.

Keywords: computer-generated hologram; Fresnel diffraction; wavefront recording plane; optimized segmentation



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1. Introduction

Holographic 3D display technology is capable of fully recording and reconstructing the wavefront information of 3D objects, making it one of the most advanced 3D display technologies for use in military, medical, educational, and entertainment applications [1–3]. Computer-generated holography has gained significant attention with the rapid advancement of optical field modulation devices and computer technology. Computer-generated holography uses computers to simulate the interference between a virtual object's light wave and a reference wave. The 3D scene is then reconstructed by loading the calculated interference patterns onto a spatial light modulator (SLM) [4–7]. The technology overcomes the limitations of traditional optical holography, which requires the recording of optical paths, while offering advantages such as high repeatability, flexible creation, and the ability to reconstruct virtual scenes. However, computer-generated holography faces challenges such as small hologram sizes, significant scattering noise, slow calculation speeds, and noticeable color differences, all of which hinder the widespread adoption and applicability of holographic 3D display technology [8,9].

The point source methods of computer-generated holograms (CGHs) hold significant potential due to their straightforward principle, ease of operation, ability to represent object surface characteristics, and high-quality reconstruction. These methods work by discretizing a 3D object into independent ideal point sources, calculating the sub-hologram for each point source, and then coherently superimposing these distributions to generate the CGH of the 3D object. The look-up table (LUT) method is a traditional point source method that improves efficiency by utilizing pre-stored sub-holograms of point sources. Building on this foundation, the LUT-based methods have focused on optimizing memory usage and computational performance. To address the issue of storing large numbers of sub-holograms, researchers introduce the novel look-up table (NLUT) method [10], which stores just the sub-holograms of the depth slice center points and generates the holograms through translation and superposition operations. The split look-up table method [11] further enhances the calculation speed by modulating the x and y directions separately. Additionally, the compressed look-up table method [12] reduces storage requirements and data retrieval cycles by introducing a modulation factor.

The wavefront recording plane (WRP) method employs a two-stage calculational process: initially computing the complex amplitude distribution on a virtual plane adjacent to the object space, followed by diffraction propagation to the holographic plane using Fresnel diffraction principles [13]. This method effectively decouples near-field wavefront calculations from free-space propagation operations, enabling efficient hologram generation through reduced calculational complexity. Many optimization methods based on WRP have been developed to improve the calculation speed, memory usage, and image quality, achieving promising results [14–18]. To overcome the limitations of the WRP method in recording 3D objects exceeding hologram dimensions and enhancing calculational speed for hologram generation, researchers have proposed a dual-WRP method [19]. In this method, each WRP records partial wavefront information from a segment of the 3D object. To overcome the limitation of conventional WRP methods in handling 3D objects with significant depth variations, researchers proposed the least-square tilted-plane WRP method [20]. This method optimizes the WRP position and tilt angle using the least-squares criterion to minimize computational load. The resulting WRP may be non-parallel to the hologram plane.

To enable the generation and reconstruction of curved holograms, researchers proposed the warped WRP method [21]. This method achieves rapid calculation of 3D objects by recording their light field information onto a curved WRP through non-uniform sampling and quadratic modulation of the sampling interval. To address the issue of color non-uniformity caused by intensity distribution during color reconstruction inherent in traditional WRP methods, researchers developed the depth-related uniform multiplexing WRP method [22]. This method enhances color uniformity by generating depth-related WRPs, thereby accelerating hologram generation using a uniform active area. To reduce the calculation time for the diffraction of 3D objects onto the WRP, researchers introduced the CLUT-based WRP method [23]. Additionally, a WRP-like method for polygon-based holograms was proposed [24]. A WRP is positioned near the object, and the diffracted fields from all polygons are aggregated onto it. This ensures that the fields propagating from the polygonal mesh affect only a small region of the WRP rather than the entire area. The proposed method significantly reduces the practical computational kernel size by utilizing sparse sampling in the frequency domain. Furthermore, researchers have developed the Viewing Area Analysis-based WRP (VAA-WRP) method [25], which substantially improves computational speed by optimizing sub-hologram sizing.

In this paper, an efficient hologram generation method via multi-layer WRPs and optimal segmentation is proposed. By analyzing the effective viewing area and eliminating

redundant calculations, we achieve highly accurate diffraction simulations through a hybrid approach combining the NLUT method and the WRP method. Compared with the traditional method, the proposed method has the following advantages: (1) Traditional methods typically generate the WRP using entire sub-CGHs, which contain significant areas of invalid diffraction data. This inherent inefficiency leads to relatively slow computation speeds. In contrast, the proposed method calculates only the optimized diffraction regions (ODRs) within each sub-CGH. This targeted approach significantly reduces computational complexity and accelerates processing speed. (2) In our latest work [25], points on the 3D object located at different depth planes exhibit varying distances relative to the WRP. Crucially, points farther from the WRP require substantially more computation. The proposed method effectively mitigates this issue by assigning a dedicated WRP to each distinct depth plane of the 3D object. This depth-adaptive strategy significantly improves the overall computational speed for generating the hologram. In summary, the proposed method achieves an 82.4% acceleration in hologram calculation speed compared to the traditional method while maintaining high-quality visual output. This technique demonstrates strong feasibility and broad application potential in holographic displays.

2. Materials and Methods

The process of the proposed method is shown in Figure 1. Firstly, the 3D object is discretized into individual object points, which are then classified into n groups based on depth information. For any given object point group l_i , the position of its corresponding WRP _{i} is calculated independently. Subsequently, based on Fresnel diffraction theory, the sub-hologram of each object point in l_i diffracted onto WRP _{i} is calculated. In the third step, based on viewing area analysis, each sub-hologram is optimally segmented to obtain the ODR on WRP _{i} . These ODRs are then coherently superimposed to generate the complex amplitude distribution on WRP _{i} . Finally, the complex amplitude distribution on the WRP _{i} is propagated via angular spectrum diffraction to the holographic plane. Final CGH reconstruction is achieved by coherently superimposing the complex amplitude distributions of all object point groups on the holographic plane. The CGH is loaded onto SLMs to enable holographic display. By assigning an independent WRP to each object point group and optimizing segmentation calculations, the calculational efficiency of CGH generation is significantly enhanced.

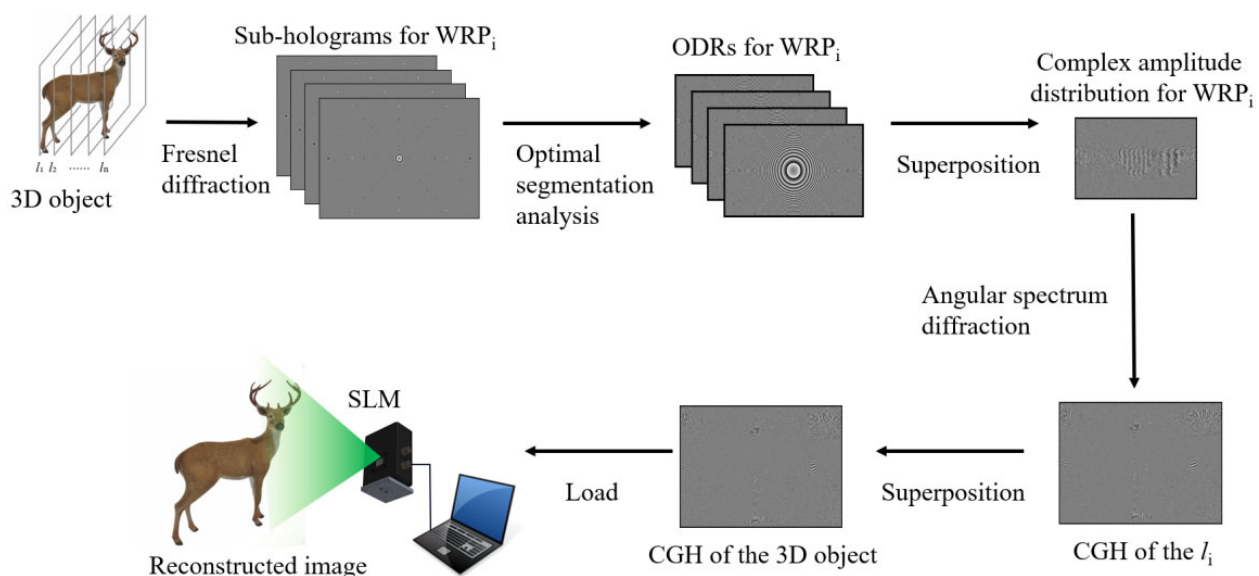


Figure 1. Process of the proposed method.

2.1. Three-Dimensional Object Discretization and Grouping

In the first step, the 3D object is discretized into individual object points, which are then classified into n groups based on depth information. To enhance calculational efficiency, a WRP is introduced between the 3D object and the holographic plane. The complex amplitude distribution of the 3D object on the WRP is first calculated using the point source method, which is then diffracted to the holographic plane to obtain the final CGH. In the traditional WRP method, only a single WRP is used, shown in Figure 2. The holographic plane coincides with the SLM plane. Where q represents the distance from object points to the WRP, and p denotes the distance between the WRP and the holographic plane, and points A and B are on the 3D object. The sub-hologram size for an object point on the WRP is m . The modulation diffraction angle α is constrained by the incident light wavelength λ and the SLM pixel size d , as expressed in Equation (1):

$$\alpha \leq \arcsin\left(\frac{\lambda}{2d}\right), \quad (1)$$

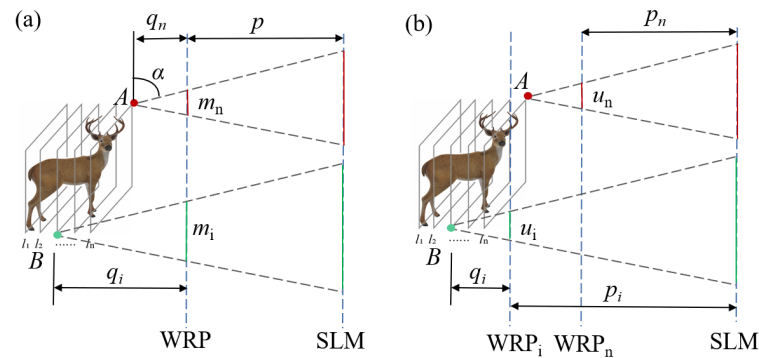


Figure 2. Comparison of WRP assignment strategies. (a) Traditional method; (b) Proposed method.

2.2. Multi-Layer WRP Position Calculation

The holographic reconstruction quality of the WRP method is highly sensitive to the WRP position. However, when only a single WRP is used, the relative position coefficient t ($t_i = q_i / (q_i + p_i)$) differs for object points A and B located on different depth planes. This results in uneven holographic reconstruction quality for object points located at different depths on the 3D object. Additionally, the sub-hologram size m_i for point B on the WRP is significantly larger than the size m_n for point A , negatively impacting hologram calculation speed. To overcome these limitations, we propose a hologram generation method based on multi-layer WRPs, as shown in Figure 2b. Specifically, for any given object point group l_i , the position of its corresponding WRP_i is calculated independently. This ensures that the relative position coefficient remains constant within each object point group. Furthermore, the sub-hologram size for point B on its dedicated WRP is substantially smaller than in the traditional single-WRP method, effectively improving calculational speed.

2.3. Sub-Hologram Calculation and Optimal Segmentation

In the second step, the sub-hologram of each object point is calculated separately according to the Fresnel diffraction theory, which can be expressed as Equation (2):

$$U_i(x, y) = \frac{\exp(jkq_i)}{j\lambda q_i} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} U_0(x_0, y_0) \exp\left\{j\frac{k}{2q_i}[(x - x_0)^2 + (y - y_0)^2]\right\} dx_0 dy_0, \quad (2)$$

where $U_i(x, y)$ represents the complex amplitude distribution of the object point on the WPR_i, λ represents the wavelength, q_i represents the diffraction distance, and $U_0(x_0, y_0)$ represents the complex amplitude distribution of the object point (x_0, y_0) .

In the third step, to achieve efficient hologram generation, each sub-hologram is optimally segmented to identify the ODR through viewing area analysis. The visual field characteristics of the holographic reconstructed light field are presented in Figure 3a. In this optical system, the optical axis coincides with the z-direction, while the 3D object is positioned on the left side of the SLM, and its reconstructed image is located on the right, separated by a reconstruction distance Z_0 . The observer plane is situated at a viewing distance R , with the SLM height denoted as S_0 and the 3D object height as L_0 . Points P and Q represent the upper and lower endpoints of the object point group l_i . For point P , the reconstructed image P' can be observed from any position within the viewing region V_P . Similarly, point Q' can be observed within the region V_Q for point Q . Consequently, the observer can only perceive the entire reconstructed hologram when both P' and Q' are simultaneously visible, which strictly requires that the viewing position lies within the overlapping area of V_P and V_Q (designated as V_U). This region is defined as the effective visual field. The portion of the hologram contributing to the effective visual field is termed the core diffraction region (CDR). Other regions, while consuming substantial computational resources, exert no influence on the effective visual field. Here, CDR refers to the effective diffraction region on the hologram plane for the sub-hologram of each object point. This CDR maintains a spatial mapping relationship with the ODR. The ODR generates the CDR on the hologram plane when propagated through diffraction.

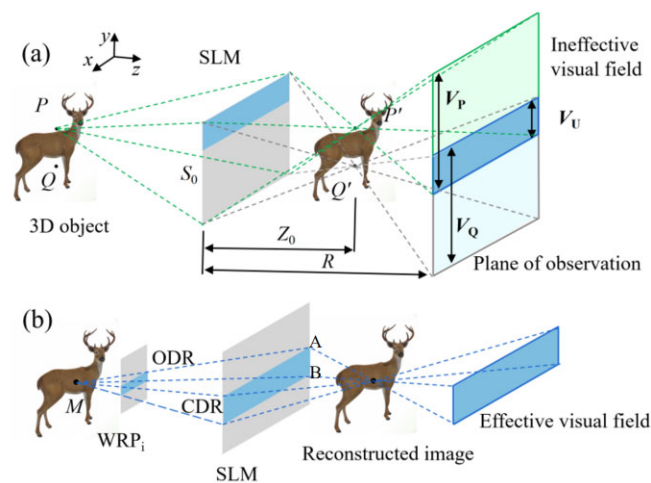


Figure 3. Sub-hologram optimal segmentation. (a) Visual field characteristics of holographic reconstructed light field; (b) accurate sub-hologram diffraction calculation approach.

Point M is an arbitrary point on the 3D object. Its corresponding effective visual field, CDR, and ODR are illustrated in Figure 3b. By analyzing the size and position of the CDR and ODR corresponding to point M , we can determine these parameters for any object point on the 3D object. Taking the y -axis as an example, geometric analysis demonstrates that the two endpoints of the CDR— $A(0, y_1)$ and $B(0, y_2)$ —satisfy the following condition:

$$y_1 = -\frac{S_0}{2} + \frac{R(2y_0 + L_0)}{2(R - Z_0)}, \quad (3)$$

$$y_2 = \frac{S_0}{2} + \frac{R(2y_0 - L_0)}{2(R - Z_0)}, \quad (4)$$

where R is the observation distance, L_0 denotes the size of the reconstructed image along the y -direction, and y_0 represents the vertical distance from the projection point of an arbitrary object point M on the 3D object to the hologram plane. The CDR size L_{CDR} is the distance between $A(0, y_1)$ and $B(0, y_2)$, which can be calculated according to Equations (3) and (4), given by Equation (5):

$$L_{CDR} = y_2 - y_1 = S_0 - \frac{RL_0}{R - Z_0}, \quad (5)$$

If the preset parameters are determined, the CDR size L_{CDR} for any point is a fixed value. That means the same size matrix can be used to segment all the sub-CGHs in hologram generation. Then, the exact position of the CDR in the sub-CGH is given by Equation (6):

$$L_O = y_2 - y_0 = \frac{S_0}{2} + \frac{2Z_0y_0 - RL_0}{2(R - Z_0)}, \quad (6)$$

where L_O is the distance from the top point of CDR to the center point of the original sub-CGH.

Based on the aforementioned analysis, the sub-holograms on the WRP_i can be further optimized through partitioning, yielding the ODR. After obtaining the CDR corresponding to an arbitrary object point on the 3D object, the size of the ODR can be determined based on the geometric relationships illustrated in Figure 2b. Since the modulated diffraction angles of ODR and CDR are identical, the triangles sharing the same vertex with ODR and CDR as their bases are similar. Thus, we derive the following:

$$\frac{L_{ODR}}{L_{CDR}} = \frac{q_i}{q_i + p_i}, \quad (7)$$

The size of the ODR is given by the following:

$$L_{ODR} = \frac{q_i}{q_i + p_i} L_{CDR} = tL_{CDR}, \quad (8)$$

Geometrically, the centroid coordinates of the ODR align perfectly with those of the CDR in the x - y plane. Therefore, determining the spatial position of the CDR is equivalent to defining the spatial position of the ODR. Based on Equations (5)–(8), each object point's corresponding sub-hologram can be optimally segmented to generate its respective ODR. Subsequently, the complex amplitude distribution on the WRP_i can be obtained by superimposing the ODR on the WRP_i plane. By excluding calculations associated with these invalid regions, this segmentation optimization significantly reduces computational overhead, thereby accelerating CGH generation.

2.4. Wavefront Propagation and Hologram Synthesis

Finally, the complex amplitude distribution recorded on the WRP_i is propagated to the holographic plane through angular spectrum diffraction theory:

$$U_i(x, y; z) = \mathcal{F}^{-1} \{ \mathcal{F} [U_{pi}(x_1, y_1; 0)] \cdot H(k_x, k_y; z) \}, \quad (9)$$

where $U_i(x, y; z)$ is the CGH of the object point group l_i on the holographic plane, $U_{pi}(x, y; z)$ is the complex amplitude distribution on the WRP_i , $H(k_x, k_y; z)$ is the spatial frequency transfer function, $\mathcal{F}$ and $\mathcal{F}^{-1}$ are the Fourier transform and inverse Fourier transform, respectively, and k_x and k_y are the spatial frequencies in the x and y directions, respectively. The integration of Fresnel diffraction and angular spectrum diffraction in the WRP method essentially constitutes a transition from a locally approximated physical model to a globally precise propagation model. Under rigorous paraxial conditions, the propagation results of

Fresnel diffraction are mathematically equivalent to a first-order Taylor series approximation of the angular spectrum method. This means that as long as the WRP is positioned within a distance satisfying paraxial conditions, the initial wavefront inherited by the angular spectrum method for propagation remains theoretically accurate, introducing no conflicts between the underlying models. The final CGH of the 3D object can be obtained by superimposing the $U_i(x, y, z)$. Then, the final CGH is loaded on the SLM, and the complete reconstructed image can be obtained when the hologram is illuminated by the reconstructed light.

3. Results

3.1. Calculation of the Hologram

3.1.1. Comparison with State-of-the-Art

To demonstrate the calculational speed advantage of the proposed method, we compare it with mainstream optimization methods such as the NLUT method, CLUT method, and VAA-WRP method, as shown in Table 1. These LUT-based improved methods all involve partial offline computation. The offline computation phase has no impact on hologram generation speed. Therefore, the table only lists the computational complexity and required operations for the online portion. Here, N_x , N_y , and N_z denote the number of object point layers in the x , y , and z directions of the rectangular 3D object. x_1 and y_1 represent the size of the final hologram. x_2 and y_2 represent the size of the computation area after viewing zone optimization. k_i denotes the scaling coefficient of the VAA-WRP method ($k_i < 1$), and t represents the scaling coefficient of the proposed method ($t \leq \min(k_i)$).

Table 1. Complexity, operation, and advantages comparison among the methods.

Method	Complexity of in-Line	Operation of in-Line	Advantages
NLUT method	$N_x N_y N_z x_1 y_1$	$1+, 1 \times$	Reduces offline data storage volume.
CLUT method	$N_x x_1 + N_y y_1$	$2\exp, 2\sqrt{\cdot}, 8 \times, 2+$	Reduces complexity of in-line.
VAA-WRP method	$N_z \sum_{i=1}^{N_x} N_x N_y x_2 y_2 k_i^2$	$1+, 1 \times$	The introduction of WRPs proportionally reduces hologram computation time.
Proposed method	$N_x N_y N_z x_2 y_2 t^2$	$1+, 1 \times$	Introducing multi-layer WRPs combined with viewing area analysis further enhances hologram computation speed.

The NLUT method effectively reduces the calculation time of LUT methods but does not improve hologram generation speed. The CLUT method accelerates hologram generation through approximate computation but introduces modulation errors in the x and y directions. The VAA-WRP method proportionally reduces hologram computation time through the introduction of WRPs. The proposed method further enhances hologram computation speed by introducing multi-layer WRPs combined with viewing area analysis.

3.1.2. Quantitative Comparison of Calculation Speed

To ensure comparability of computation speeds between the proposed and traditional methods, all hologram calculations were performed on a computer with the following uniform configuration: AMD Ryzen 7 5800X 8-Core Processor @ 3.80 GHz, 16.0 GB RAM, running MATLAB R2017b. A calculational efficiency comparison is conducted between the proposed method and the NLUT method, as shown in Figure 4. To ensure an unbiased evaluation of calculational performance, the test object is intentionally standardized as a randomly generated grayscale pattern with uniform noise distribution, thereby eliminating content-dependent variables. The 3D object is divided into two layers with depths of 10 cm and 15 cm, respectively, with a viewing distance of 40 cm and a relative position coefficient $t = 0.4$. When the number of object points is 1×10^4 , 5×10^4 , 10×10^4 , and 15×10^4 respectively, the calculation times for the NLUT method and the proposed method are

4.95 s/17.60 s, 32.03 s/78.12 s, 112.50 s/212.10 s, and 205.48 s/375.98 s. The calculational efficiencies show improvements of 255.6%, 143.9%, 88.5%, and 83.0%, respectively. Regression modeling further projects an 82.4% acceleration rate under equivalent calculational load conditions.

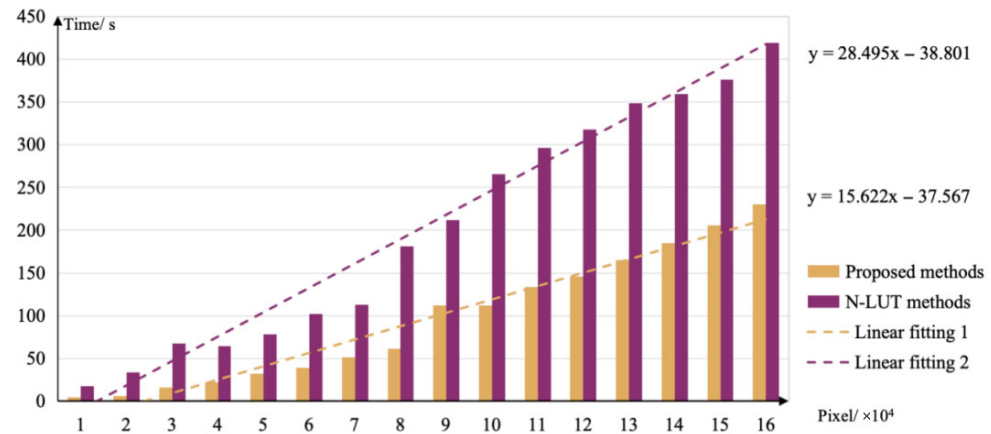


Figure 4. Calculation speed comparison between the proposed method and NLUT method.

Additionally, this study compares the acceleration performance of the proposed method with the VAA-WRP method, WRP method, and NLUT method. A 3D object comprising four distinct patterns at 1100×896 resolution serves as the test image. The calculational efficiencies for hologram generation under single-layer, two-layer, and four-layer configurations are benchmarked in Table 2. In the single-layer case, all patterns maintain a uniform depth of 10 cm. The two-layer configuration features depths of 10 cm and 15 cm, while the four-layer arrangement utilizes depths of 10 cm, 15 cm, 20 cm, and 25 cm. Compared to the VAA-WRP, WRP, and NLUT baseline methods, the proposed method demonstrates significant improvements in computational efficiency across one-layer, two-layer, and four-layer implementations. Specifically, it achieves efficiency gains of 7.4%, 24.8%, and 84.1% over VAA-WRP; 38.9%, 75.5%, and 145.8% over WRP; and 90.1%, 159.5%, and 281.3% over NLUT, respectively. These results establish that the computational acceleration advantage intensifies progressively with increasing depth-layer complexity.

Table 2. Calculation time of the proposed method and the VAA-WRP method.

Method Time Layer	1	2	4
Proposed method	1322.85 s	982.02 s	643.33 s
VAA-WRP method	1420.20 s	1225.61 s	1184.12 s
WRP method	1836.80 s	1723.59 s	1581.06 s
NLUT method	2514.11 s	2548.30 s	2453.28 s

3.1.3. Sensitivity of the Simulation Parameters

To provide a more intuitive analysis of the sensitivity of the proposed method to simulation parameters, the following simulations are conducted. First, the variation in computational cost is simulated as the number of object points increases, while keeping all other conditions constant, as shown in Figure 5a. The 3D object comprises four layers located at depths of 10 cm, 15 cm, 20 cm, and 25 cm, respectively. Each layer has a resolution of $N_x \times N_y$ (where $N_x = 2N_y$). The relative position coefficient t was 0.4, and the observation distance R was 40 cm. The SLM has a resolution of 1920×1080 pixels with a pixel pitch of

6.4 μm . The results show that the computational cost of generating the hologram increases with the number of pixels and eventually approaches 5×10^{10} .

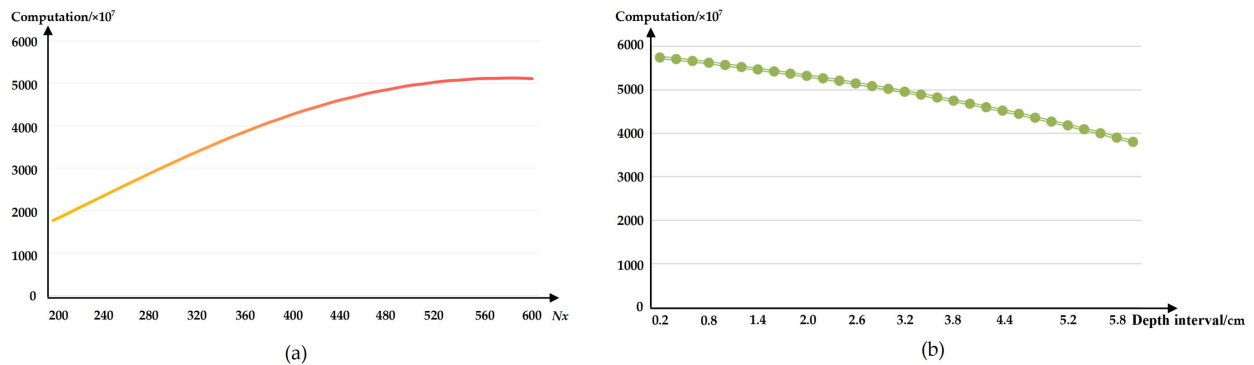


Figure 5. Sensitivity of the simulation parameters. (a) The amount of computation changes as N_x changes; (b) the amount of computation changes as the depth interval changes.

Then, the variation in computational cost is simulated as the depth interval increases, while keeping all other conditions constant, as shown in Figure 5b. Each 3D object layer has a resolution of 400×200 pixels. The computational cost is observed to decrease approximately linearly with increasing depth interval. This validates the advantage of the proposed multi-layer WRPs method. This occurs because, in conventional methods, points farther from the WRP require substantially more computation. The proposed method effectively mitigates this issue by assigning a dedicated WRP to each distinct depth plane of the 3D object.

3.2. Simulations and Experiments

To validate the performance of the proposed method, a holographic display system is constructed, as shown in Figure 6. The system comprises a laser, a beam expander, a beam splitter, an SLM, three lenses, and a filter. The SLM has a resolution of 1920×1080 and a pixel pitch of 6.4 μm . The SLM model is FSLM-2K55-P, a reflective phase-only LCoS device. Its modulation type is phase-only, with a refresh rate of 60 Hz, an operating spectrum of 420–650 nm, and a phase modulation depth of $2\pi@532$ nm. All the lenses have a focal length of 30 cm, and the filter is positioned at the back focal plane of lens 2. The detailed experimental procedures are as follows: the laser, beam expander, and lens 1 generate the collimated plane waves. This collimated plane wave passes through a beam splitter and is incident upon the working area of the LCoS. Simultaneously, the final CGH loaded onto the LCoS is illuminated by these collimated plane waves. The holographic diffraction field modulated by the LCoS passes through a $4f$ optical filtering system (consisting of lens 2, lens 3, and the filter) to reconstruct the holographic image at the observation plane. Within this system, lens 2 performs a spatial Fourier transform on the holographic diffraction field, producing its corresponding spatial frequency spectrum at its rear focal plane. The filter, positioned at the rear focal plane of lens 2, is a bandpass filter that filters out the zero-order light and other stray light, allowing only the target light field to pass. The front focal plane of lens 3 coincides with the rear focal plane of lens 2. Lens 3 then performs an inverse spatial Fourier transform on the filtered target light field, thereby reconstructing the holographic image in space.

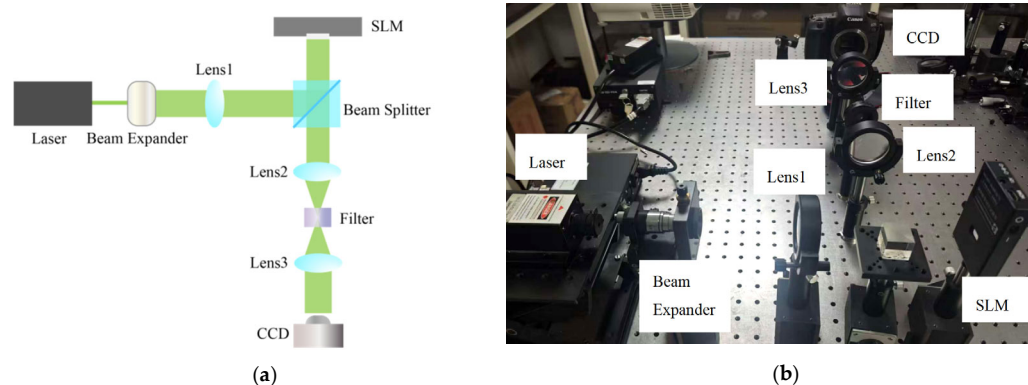


Figure 6. The imaging system used for the optical experiments. (a) The schematic diagram; (b) The actual experimental setup.

To verify that the proposed method can retain the texture and detail information of the input scene, a numerical simulation is conducted, as shown in Figure 7. Figure 7a displays the test image employed in Table 2, undergoing simulated reconstruction at four discrete depths with a reconstruction wavelength of 532 nm. The holographic reconstructed images at depths of 10 cm, 15 cm, 20 cm, and 25 cm appear in Figure 7b–e, respectively. Regions enclosed by red rectangles indicate focal images corresponding to each depth. These focal images achieve PSNR values of 19.506 dB, 19.084 dB, 19.623 dB, and 20.630 dB. Moreover, these focal images achieve SSIM values of 0.7105, 0.7088, 0.7060, and 0.7873. Furthermore, to validate the color reconstruction capability of the proposed method, a 2D ‘strawberry’ image with 990×660 resolution serves as a validation case. The original image and reconstructed results are presented in Figure 7f,g, respectively. In the experimental setup, the recording distance is set to 23 cm, with illumination wavelengths of 671 nm, 532 nm, and 473 nm used during holographic display. The reconstructed image achieved a PSNR of 26.404 dB and an SSIM of 0.8791, demonstrating the method’s effectiveness in high-fidelity scene representation.

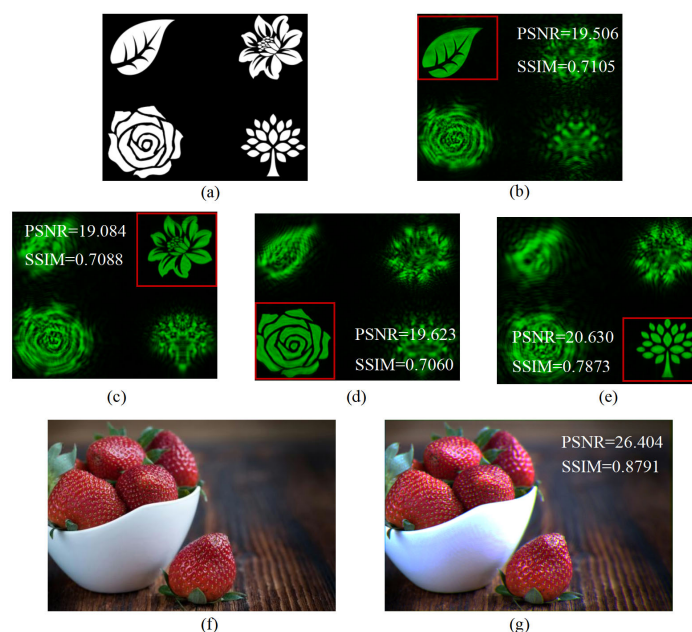


Figure 7. Simulation results of the proposed method. (a) The test 3D image; (b) reconstruction at 10 cm depth; (c) reconstruction at 15 cm depth; (d) reconstruction at 20 cm depth; (e) reconstruction at 25 cm depth; (f) original color image ‘strawberry’; (g) simulation result of the ‘strawberry’.

Experimental results are conducted to validate the proposed method, and the holographic reconstruction results are shown in Figure 8. The 3D object utilized in experiments appears in Figure 7a, with experimental parameters fully consistent with those of the simulation study. The holographic reconstructed images at depths of 10 cm, 15 cm, 20 cm, and 25 cm appear in Figure 8a–d, respectively. Regions enclosed by red rectangles indicate focal images corresponding to each depth. These focal images achieve PSNR values of 16.000 dB, 15.429 dB, 14.847 dB, and 16.820 dB. And, these focal images achieve SSIM values of 0.7188, 0.6896, 0.6890, and 0.6001. As depicted in Figure 8a–d, the 3D reconstruction results of the proposed method at different depths are presented. Both simulation and experimental results demonstrate the effectiveness of the proposed method.

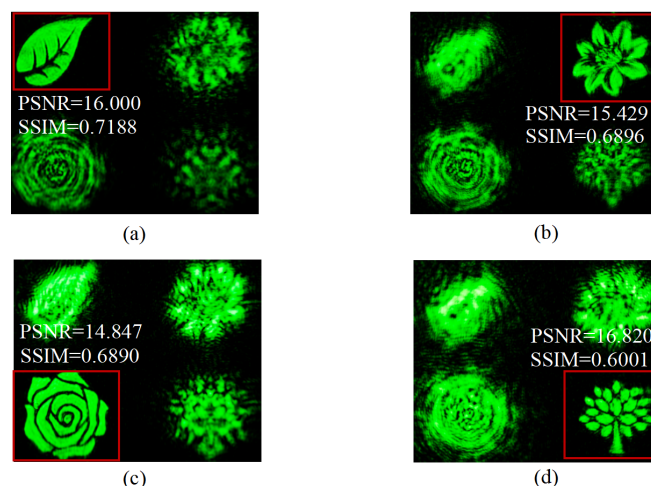


Figure 8. Experimental results of 3D holographic reconstruction of the proposed method. (a) Reconstruction at 10 cm depth; (b) Reconstruction at 15 cm depth; (c) Reconstruction at 20 cm depth; (d) Reconstruction at 25 cm depth.

4. Conclusions

In this paper, an efficient hologram generation method via multi-layer WRPs and optimal segmentation is proposed. The sub-CGH corresponding to each object point in the recorded object is computationally optimized and divided into two distinct parts. Only the ODRs are pre-saved and subsequently used for holographic calculation. Furthermore, the allocation of dedicated WRPs to individual object groups achieves additional compression of the ODR for associated object points, thereby enhancing the reconstruction quality of continuous-depth objects. Experimental results demonstrate a significant improvement in CGH calculation speed compared to traditional methods.

Author Contributions: Y.L. conceived the project and proposed the idea of the manuscript; H.X. proposed the idea of the manuscript, conducted experiments; Z.G. wrote the program, calibrated the experiment results; J.D. checked the literature, translated the article; D.W. provided important guidance for the article. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Abbreviations

The following abbreviations are used in this manuscript:

WRP	Wavefront Recording Plane
ODR	Optimal Diffraction Region
CGH	Computer-Generated Hologram
LUT	Look-Up Table
NLUT	Novel Look-Up Table
VAA-WRP	Viewing Area Analysis-based WRP
SLM	Spatial Light Modulator
CDR	Core Diffraction Region

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