Method of Speckle Noise Suppression for Holographic Zoom Display Based on Layered-Pixel-Scanning Algorithm

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ABSTRACT In this paper, a method of speckle noise suppression for holographic zoom display based on layered-pixel-scanning (LPS) algorithm is proposed. Different from the traditional algorithm, the proposed method suppresses the speckle noise based on a new algorithm design and light source optimization. The LPS algorithm is designed to calculate the phase-only hologram of the 3D object. By extracting the initial complex hologram of the 3D object and scanning the hologram by pixel, the errors of the complex amplitude can be reduced as much as possible. Then a hologram subsampling method based on the LPS algorithm generated is proposed, so the scaling of the reproduced image can be achieved easily. At the same time, the pattern with different random phase is generated and loaded on the spatial light modulator so that the reconstructed light can be optimized. When the optimized light irradiates on the phase hologram of the object, the reconstructed image with suppressed speckle noise can be displayed. The experimental results show that the proposed method has an excellent reproduction effect. Moreover, the feasibility and unique advantages of the proposed method in the holographic augmented-reality display, zoom display and multi-plane display have been proved. We believe that this method can promote the application of the holographic display.

INDEX TERMS Display, holographic display, zoom display.

I. INTRODUCTION

Holographic display technology can completely record and reconstruct the wavefront information of 3D objects [1]–[3], then richer information can be presented. Therefore, the holographic display can provide important auxiliary role for medical treatment, industry, entertainment and other fields [4], [5]. However, in the holographic display, each point on the hologram contains all the information of the object. Due to the huge amount calculation for the 3D object, the calculation speed of the hologram is difficult to meet the requirements of the real-time display [6]–[10]. In addition, speckle noise exists in the reconstructed image, which seriously degrades the quality of the reconstructed image [11], [12].

Due to the coherence of the laser, each reconstructed point can form an Airy disk during the holographic reconstruction, and the coherent superposition between these Airy disks will cause the speckle noise [13], [14]. Besides, most existing spatial light modulators (SLMs) are of pure phase type, while the spatial distribution of the 3D object is a complex amplitude function [15]–[18]. In the optical reconstruction, the complex amplitude function needs to be converted into the phase value. So, the error occurs when the phase-only hologram is used for reconstruction, and this error will be reflected by the speckle noise in the reconstructed image. In order to suppress the speckle noise in the holographic display, many optimization algorithms have been proposed, such as the time average method [19], [20], down-sampling method [21], [22], complex amplitude modulation method [23], [24], pixel separation method [25], error diffusion method [26], [27] and the numerical Multi-Look method [28], [29].
The pixel separation method reduces the overlap between the Airy disks by increasing the distance between the adjacent pixels. The time average method requires the calculation of multiple holograms, and the noise can be homogenized by superimposing multiple reproduced images. However, the loading of multiple holograms has a high requirement on the refresh rate of the SLM. In addition to the SLM and lens, the optical system used in the complex amplitude modulation method also needs additional filter system and other components. So, the systems are often complex and difficult to operate. Some researchers also optimize the light source to improve the quality of the image. By using several light sources with slightly different central frequencies [30], or using the light source with a wide spectral bandwidth instead of the traditional laser [31], the speckle noise in the reproduced image can be suppressed to a certain extent. Moreover, adding some additional optical elements can also reduce the coherence of the light source, such as the optical fibers, fast-scanning micromirrors, movable diffusers, gradient-structured prisms, variable mirrors, and rotatable diffraction optical elements [32]–[40]. However, these methods may increase the cost and complexity of the system.

In this paper, a method of speckle noise suppression in holographic display based on the layered-pixel-scanning (LPS) algorithm is proposed. The LPS algorithm is designed to calculate the phase-only hologram of the 3D object. The 3D object is divided into many layers, and the initial complex hologram of the 3D object is extracted by calculating the hologram of each layer. Then the superposition complex hologram is scanned according to the pixel sequence so as to suppress the error as much as possible. The final phase hologram is generated by extracting the phase information of the optimized complex amplitude. The generated phase hologram is subsampled so that the scaling of the reproduced image can be achieved. At the same time, the pattern with different random phase is generated and loaded on the SLM, so the coherence light can be optimized. When the optimized light irradiates the phase hologram of the object, the reconstructed image with suppressed speckle noise can be displayed. Compared with the traditional method, the proposed method has the following advantages: 1) It considers both hologram algorithm generation and light source optimization, which is more comprehensive than the other methods that only optimize the algorithm or light source. The comparative experiments show that the quality of the reconstructed images is much higher than that of the other methods. 2) The LPS algorithm is designed, which has high reproduced quality and fast calculation speed simultaneously. When the sampling size of the hologram changes, the reproduced image can also be scaled easily. This feature can be used in the holographic zoom display or color display in the future. 3) The proposed method is simple and easy to operate without complicated optical system. At the end of this paper, the effects of the proposed method used in the holographic augmented reality (AR) display, video display and multi-plane display are verified.

**FIGURE 1. Flowchart of the proposed method.**

**II. PRINCIPLE OF THE METHOD**

**A. PROCESS OF THE PROPOSED METHOD**

The flowchart of the proposed method is shown in Fig. 1. For a 3D object, the information of the 3D object is extracted firstly. The 3D object is regarded as many 2D layers with different depths. By calculating the complex hologram of each layer, the complex amplitude information of the object in different layers can be extracted. Secondly, the complex amplitude information of the holograms for different layers is superimposed together to produce the initial complex hologram of the object. By scanning the complex hologram based on the pixel sequence, the complex amplitude information of the hologram for 3D object can be optimized and the phase-only hologram can be generated. By subsampling the phase-only hologram, the holographic zoom function can be realized. Thirdly, the pattern with different random phase is generated and loaded on the SLM. So, the reconstructed light can be optimized. When the optimized light irradiates the phase hologram of the object, the reconstructed image with suppressed speckle noise can be seen on the receiving screen.

**B. LPS ALGORITHM**

In the proposed method, the LPS algorithm is used for generating the phase hologram. As shown in Fig. 2, the 3D object is divided into \( L \) layers with different depth. \( L_i \) represents the \( i \)th layer, \( i = 1, 2, 3 \ldots L \). The diffraction distribution of the object is calculated based on the angular propagation theory. When the propagation distance \( z = 0 \), the complex amplitude distribution of the plane wave is \( A(f_x, f_y; 0) \). Then the angular spectrum distribution \( A(f_x, f_y; z) \) at the distance of \( z \) can be expressed as follows [41]:

\[
A(f_x, f_y; z) = A(f_x, f_y; 0) \exp(2i\pi z \sqrt{\frac{1}{\lambda^2} - f_x^2 - f_y^2}).
\]  

(1)

where \( (f_x, f_y) \) is the propagation direction of the plane wave, \( \lambda \) is the wavelength. The complex amplitude distribution is
calculated as follows:

\[ U(x, y, z) = \int \int A(f_x, f_y; 0) \exp(2\pi z \frac{1}{\lambda^2} - f_x^2 - f_y^2) \times \exp(2\pi i (f_x x + f_y y) df_x df_y). \]  

(2)

For the 3D object, the amplitude information of each layer can be obtained from the rendered image, and the uniform phase information is added to each layer. The complex amplitude of each layer can be calculated based on the angular spectrum propagation theory, which can be expressed as follows:

\[ H_l = F^{-1} \{ H(f_x, f_y) \cdot F(L_l) \}, \]

where \( H_l \) is the complex amplitude of the \( l \)th layer, \( H(f_x, f_y) \) is the angular spectrum propagation function, \( F \) is the Fourier transform and \( F^{-1} \) is the inverse Fourier transform.

By calculating the distribution information of each layer, the complex amplitude information of the holograms for the \( L \) layers can be generated. The initial complex hologram of the object can be obtained by superimposing the complex holograms of all sublayers. Then the initial complex hologram of the object is scanned in pixels from the first pixel. For each pixel \((i, j)\) on the hologram, the initial complex amplitude is:

\[ h(i, j) = A(i, j) \exp[i\phi(i, j)], \]

where \( A(i, j) \) is the amplitude and \( \phi \) is the phase value. The amplitude value is discarded, and the phase term is taken to obtain the pure phase value.

\[ p(i, j) = \exp[i\phi(i, j)], \]

where \( p(i, j) \) is the pure phase value. The error between the pure phase value and the original complex amplitude value is expressed by \( e(i, j) \). Besides, this error is diffused into other pixels which have not been scanned. The optimized complex amplitude can be updated as follows:

\[ e(i, j) = A(i, j) \exp[i\phi(i, j)] - \exp[i\phi(i, j)]. \]

\[ h'(i + 1, j - 1) = h(i + 1, j - 1) + a \cdot e(i, j), \]

where \( h \) is the original complex amplitude, \( h' \) is the updated complex amplitude, \( a \) is the error scan coefficient. The error \( e(i, j) \) is spread to the adjacent pixels \( h(i, j + 1), h(i + 1, j - 1), h(i + 1, j), h(i + 1, j + 1) \) in the ratio of 7: 3: 5: 1. The sum of the error scan coefficients is set to be 1. In this way, the complex amplitude values of the unscanned pixels can be optimized.

After all the pixels have been scanned, the optimized complex amplitude distribution of the hologram for the object can be generated.

By scanning the initial complex hologram of the object in the above way, the optimized complex amplitude information of the hologram for 3D object can be obtained. Finally, the phase information is extracted to generate the phase-only hologram.

In order to realize the zoom function, the phase-only hologram is subsampled, as shown in Fig. 3. We take one-dimensional form as an example to describe the zoom principle in the diffraction process. The generated phase-only hologram is represented as \( h(u) \), and the reconstructed image \( f(x) \) can be calculated based on Fresnel diffraction:

\[ f(x) = \int h(u) \exp[i\pi u^2 \frac{2}{\lambda d} + i\pi x^2 \frac{2}{\lambda d} - i2\pi u x \frac{2}{\lambda d}] du, \]

where \( d \) is the diffraction distance. Assume that the current hologram has a sampling rate \( \Delta u \), when the sampling rate is changed to \( \Delta u_1 = a\Delta u \), it can be considered that the size of the hologram becomes \( a \) times of the original size. So, the coordinates of the new hologram are also changed to \( u_1 = au \). Then the reconstructed image can be expressed as follows:

\[ f(x) = \int h(u_1) \exp[i\pi u_1^2 \frac{2}{\lambda d_1} + i\pi x^2 \frac{2}{\lambda d_1} - i2\pi u_1 x_1 \frac{2}{\lambda d_1}] du, \]

where \( d_1 = a^2d \), \( x_1 = a^2x \). It can be seen that when the sampling rate of the hologram becomes \( a \) times of the original hologram, the new hologram will reconstruct the image at a new distance \( d_1 \), and the reconstructed image size is \( a^2 \) times of the original reconstructed image. In this way, the size of the reconstructed image can be changed according to subsampling the phase-only hologram.
C. SPECKLE NOISE SUPPRESSION METHOD
The proposed method suppresses the speckle noise according to the hologram algorithm and light source optimization simultaneously. The phase information of the reconstructed plane is very important for the quality of the reconstructed image. The interference superposition between the Airy disks on the reconstructed plane cannot be eliminated completely. When the phase difference between the adjacent pixels increases, their Airy disks will have a larger intensity after the interference superposition. Therefore, the phase unevenness between the pixels will result in the final image intensity showing obvious light and dark differences [12], that is, the speckle noise. When there is almost no phase difference between the pixels, the intensities of the Airy disks will not change much after the interference superposition and the speckle will be suppressed. In the proposed method, the LPS algorithm is used to calculate the phase information of the 3D object. The algorithm not only optimizes the amplitude information of the reconstructed light field, but also controls the phase information greatly. So, the phase distribution becomes uniform and smooth and the reconstructed image can be displayed with less speckle noise.

![FIGURE 4. Principle of the speckle noise suppression.](image)

The light source used in the holographic display system is usually highly coherent. Then the optical components used in the optical experiment (such as filters, solid lenses and SLM) will have the influence on the reconstructed light. So, the speckle noise is introduced, which also results in the difference between the actual optical experiment and the computer simulation. In order to reduce the coherence of the laser, the pattern with different random phase is generated. When the laser is modulated by the random phase, the reference light has a random phase factor and its coherence is decreased. As the random phase changes, the random phase distribution of the laser changes accordingly. According to the refresh rate of the SLM, different random phase holograms are generated, as shown in Fig. 4. After the modulation of the random phase, the laser will have different random phase distributions at different moments. So, the coherence of the reconstructed light can be reduced. The laser with reduced coherence is used as the reconstructed light to irradiate the phase hologram of the 3D object, and the reconstructed image can be displayed. Different random phase patterns are loaded on the SLM sequentially. Since the frame rate of the random phase pattern is times that of the object hologram, the hologram can produce sub-images with different speckle noise. The switching time of the random phase patterns needs to meet the human visual persistence time. Through time multiplexing, the sub-images form a final reconstructed image. We record the speckle noise contrast of the final image and the sub-image as and respectively. According to the statistics rule of speckle noise, the contrast satisfies the following equation:

\[ C = \frac{C_0}{\sqrt{T}}. \]  

So, when the optimized light source irradiates the phase hologram of the 3D object, the reconstructed image with suppressed speckle noise can be displayed on the receiving screen.

III. SIMULATION, EXPERIMENTS AND RESULTS
In order to verify the feasibility of the proposed method, the simulation and optical experiments are performed. The wavelength of the light source used in the experiment is 532 nm. The resolution and pixel pitch of the SLM are × 1080 and 6.4 μm, respectively. The frame rate of the SLM is 60 Hz and it can provide a phase modulation range of [0, 2π] at the wavelength of 532nm. The SLM is manufactured by Xi’an CAS Microstar Optoelectronic Technology Co., Ltd. and its model is FSLM-2K55-P. The pixel pitch of the object and the resolution of the hologram are set to be 6.4 μm and × 1080, respectively. The diffraction distance of the object is set to be 500 mm.

A. SIMULATION EXPERIMENT
To verify the feasibility of the LPS algorithm, three different objects are used for the simulation experiment. The resolutions of the recorded object ‘mango’, ‘bear’, and ‘letter’ are × 534, × 598, and × 737, respectively. When the recorded object is a 2D object, the number of layers is 1. When the recorded object is a 3D object, the number of layers is larger than 1. Take the ‘mango’ as an example, we extract the amplitude information from the rendered image and the uniform phase information is added. The initial complex amplitude of the hologram can be calculated accordingly. Then the hologram is scanned by pixel and the optimized complex amplitude information can be obtained. The phase hologram of the ‘mango’ is finally generated according to the optimized complex amplitude information. When the phase hologram is used for reconstruction, speckle noise can be suppressed obviously. Fig. 5 is the reconstructed images by using the LPS algorithm when the sampling rate is 6.4 μm.

From Fig. 5 we can see that the reconstructed image with good quality can be displayed. The signal to noise ratio (SNR) values of ‘mango’, ‘bear’, ‘letter’ by using the proposed method are 11.0127, 18.7998 and 11.613 respectively.
Then the part information of the object is extracted for magnification observation, as shown in the red boxes of Fig. 5. Since the LPS algorithm can scan each pixel and control the error to the minimum, the phase difference between the adjacent pixels is relatively small. The result shows clearly that the intensity of the object in the red box is evenly distributed. At the same time, other algorithms are used for the comparative experiments. When the traditional angular spectral method and Gerchberg-Saxton (GS) algorithm are used to generate the phase holograms of the objects, the results are shown in Figs. 6 and 7, respectively. The SNR values of ‘mango’, ‘bear’, ‘letter’ by using the traditional angular spectral method are 1.1179, 2.4997 and 2.063 respectively. The SNR values of ‘mango’, ‘bear’, ‘letter’ by using the GS algorithm are 5.3205, 5.9203, 6.7432, respectively. The iteration number of the GS algorithm is set to be 20 for comparison. Though the angular spectral method and GS algorithm can optimize the phase information as well as the amplitude information of the object, there are significant differences in the optimization of the phase information compared with the LPS algorithm. Since the phase in the angular spectral method and GS algorithm is random, the phase distributions of the reconstructed light fields are uncontrolled and random. In the red boxes of Figs. 6 and 7, the speckle noise in the reproduced images can be clearly seen, and the intensities of the objects are not uniform. This noise will directly affect the effect of the reconstructed image.

The comparison between the complex amplitude hologram and the proposed phase hologram is shown in Fig. 8. Fig. 8(a) is the complex amplitude hologram of ‘mango’ by using the traditional angular spectrum method, and Fig. 8(b) is the phase hologram by using the proposed algorithm. The results show that the phase distribution by using the proposed algorithm is very uniform.

When the sampling rate of the phase hologram changes, the size of the reconstructed image changes accordingly. In the initial state, the sampling rate of the hologram $\Delta u$ is equal to the pixel pitch of the SLM. When the sampling rate of the hologram becomes $0.7\Delta u$, $0.8\Delta u$, $1.1\Delta u$ and $1.3\Delta u$, the result of the reproduced image is shown in Figs. 9(a)-(d). From the results we can see that by using the subsampling method, the holographic zoom function can be realized easily.

On the other hand, we verify the feasibility of the random phase pattern to optimize the reconstructed light source by using VirtualLab software. In the experiment, 10 random phase patterns are generated and loaded on the SLM to modulate the light. The random phase range is $0-2\pi$. The resolution and the pixel size of the random phase pattern are
1920 × 1080 and 6.4 µm, respectively. When the parallel laser illuminates the random phase, it is modulated and the coherence is decreased. We observed the mass of the spot at a diffraction distance of 500 mm, the result is shown in Fig. 10. When no random phase is used to optimize the light, a large number of interference fringes exist in the diffraction light, resulting in the speckle noise. When 1 random phase pattern is used, the speckle noise is well suppressed although the brightness decreases. When 10 random phase patterns are used, the diffraction light is almost uniform and speckle noise cannot be seen. In this way, the light source is greatly optimized.

### TABLE 1. Parameters of the experiment.

| Object            | ‘Letter’ | ‘Reader’ | ‘Runner’ |
|-------------------|----------|----------|----------|
| Resolution of the hologram | 1920×1080 | 1920×1080 | 1920×1080 |
| Resolution of the object | 900×737   | 960×786  | 880×746  |
| Pixel pitch of the hologram | 6.4µm     | 6.4µm    | 6.4µm    |
| Pixel pitch of the object | 6.4µm    | 6.4µm    | 6.4µm    |
| Wavelength       | 532.0nm  | 532.0nm  | 532.0nm  |
| Diffraction distance | 500mm    | 500mm    | 500mm    |

In order to verify the feasibility of the proposed method, an optical system is built, as shown in Fig. 11. The system consists of a laser, an aperture, a solid lens, a beam splitter (BS), two SLMs, a filter and a receiving screen. The laser, aperture and the solid lens are used to generate the collimated light. The filter is used to eliminate the undesirable light. In order to reduce the coherence of the laser, three different random phase patterns are generated and loaded on SLM1 in turns. SLM2 is loaded with the hologram of the recorded object. When light passes through SLM1, the laser will have different random phase distributions. The parallel light irradiates the random phase patterns vertically, and then irradiates the phase hologram of the object. The angle between the reconstructed light and SLM2 is less than 5°. After the modulation of SLM2, the reconstructed image with suppressed speckle noise can be displayed on the receiving screen. The parameters of the experiment are shown in Table 1. Fig. 12 shows the results of the reconstructed image of the 2D object. When part information of the object is extracted for magnification observation, we can see clearly that the proposed method can suppress the speckle noise effectively.

In order to verify the effect of light source optimization, a comparative experiment is carried out. When no phase is loaded on SLM1, the reproduced image is shown in Fig. 13(a). When the random phase patterns are loaded on SLM1, the reproduced image is shown in Fig. 13(b). The speckle noise of Fig. 13(b) is less than that of the Fig. 13(a). So, the result of using the optimized light source is better than that of using the ordinary light source.
In addition, 3D objects ‘cube’ and ‘cone’ are also used in experiments. The ‘cube’ and the ‘cone’ have different depths. We divide the 3D object in two layers and use LPS algorithm to generate the phase hologram. At the same time, the traditional layer-based method is used for comparison [42]. When the optimized light source is used to illuminate the hologram of the object, the experimental results are shown in Fig. 14. Figs. 14(a), (b), (c) and (d) give the results when the ‘cone’ is focused by using the proposed method, when the ‘cube’ is focused by using the proposed method, when the ‘cone’ is focused by using the traditional layer-based method and when the ‘cube’ is focused by using the traditional layer-based method, respectively. The speckle contrast in Figs. 14(a)-14(d) is 0.0354, 0.0333, 0.0589, and 0.0682, respectively. The intensity of the reconstructed image is shown in Fig. 15. As can be seen from Fig. 15, there are a lot of speckle noise in the reconstructed image by using the traditional method, while the information of the object can be well reproduced in the proposed method and the speckle noise is well suppressed.

By changing the sampling size of the hologram, the size of the reconstructed image can also be changed to achieve the zoom function. In traditional Fresnel diffraction, when the sampling size of the hologram changes, the quality of the reconstructed image will be seriously affected. In the proposed method, speckle noise in the reconstructed image is suppressed by the pixel scanning, so the quality of the reconstructed image can be guaranteed during the zoom process. Fig. 16 is the results when the sampling size of the reconstructed image changes.

**IV. APPLICATIONS**

**A. AR DISPLAY**

Due to the high imaging quality of the reconstructed image by using the proposed method, it can also be used in the AR display. The experiments are also performed to verify the feasibility. We add a BS prism at the end of the reproduction light path. When the reconstructed image passes through the BS, it can be reflected. Besides, a ‘panda’ and a ‘small tree’ are placed at different distances in the transmission direction of the BS. The 3D object is used for reconstruction, and a CCD is used to capture the reconstructed image. As shown in Fig. 17, the ‘cone’ and the ‘cube’ are with different depths. The ‘cone’ and the ‘tree leaves’ have the same depth, while the ‘cube’ and the ‘panda’ have the same depth. When the ‘cone’ is focused, the leaves on the small tree can be seen clearly. While when the ‘cube’ is focused, the ‘panda’ can be seen clearly. Besides, a rotating ‘cup’ is used as an example to record the effect of the video display. We move the ‘small tree’ away. When the ‘cup’ is rotated, we can clearly see the rotating ‘cup’ and the real ‘panda’ through the BS at the same time. The results are shown in Fig. 18, where the different moments are displayed when the ‘cup’ is rotated. The dynamic video of the AR display is included in Visualization 1.
By using the proposed method, the 3D AR display with good quality can be achieved. As the holographic 3D display can completely reconstruct the wavefront information of the hologram for the 3D objects, it has unique advantages compared with the other AR display technologies. In the experiment, the AR display effect of the 3D object can be clearly seen. Since the speckle noise is suppressed greatly, the quality of the reconstructed image can satisfy the viewing requirement. We believe that the proposed method can promote the application of the holographic AR display greatly.

B. MULTI-PLANE DISPLAY

The proposed method is also expected to be applied to the multi-plane display. According to Eq. (9) we know that when the sampling rate of the hologram becomes a times of the original hologram, the new hologram will reconstruct the image at a new distance \( d_1 \), and the reconstructed image size is \( a^2 \) times of the original reconstructed image. In other words, by adjusting the sampling rate of the hologram, the hologram can be moved in the depth direction. The simulation results are shown in Fig. 19. Fig. 19(a) is the reconstructed image when the sampling rate of the hologram is \( \Delta u \), and Fig. 19(b) is the reconstructed image when the sampling rate of the hologram is \( 0.9 \Delta u \). In this way, objects with different depths can be reconstructed easily. Due to the change of sampling rate, the size of the reconstructed image will change at the same time. In the multi-plane display, we can compensate the original image with equal proportion, and then the reconstructed image can be displayed with the same size in different planes. When the sampling rate of the hologram is \( 0.9 \Delta u \), the reconstructed image after compensating the original object is shown in Fig. 19(c). In this way, holographic multi-plane display without distortion can be realized.

Besides, the calculation time of the proposed method is calculated. The processor model used is Intel (R) Core (IM) i7-8750H CPU @2.2 GHz and the memory is 8G. A ‘train’ is used for calculation. The resolution of the object point is \( 100 \times 57 \). The resolution of the hologram is set to be \( 1024 \times 1024 \) and the 3D object is divided into two layers for calculation. The calculation time of the proposed method is 4.183 s. When the resolution of the object point is \( 500 \times 283 \), the calculation time is 4.260 s. Then the novel-look-up-table (NLUT) algorithm is also used to for comparison [43]. When the resolution of the object point is \( 100 \times 57 \) and \( 500 \times 283 \), the processing time by using the NLUT algorithm is 23.292 s and 164.401 s respectively. So, compared with the NLUT algorithm, the calculation speed of the proposed method is greatly increased.

During the calculation of the 3D object, the holograms is generated by the layered process. When the number of the layers increases, the quality of the reconstructed image can be further improved, but the calculation speed will be decreased accordingly. Through calculation, we find that for the object with the resolution of \( 800 \times 450 \) (the hologram resolution is set to \( 1024 \times 1024 \)), the processing time is 7.542 s when the number of the layers is 20. While when the number of the layers is 40 and 60, the processing time is 12.249 s and 16.614 s, respectively. However, the current speed is not enough for high speed dynamic holographic displays. In the future, we will continue to improve the calculation speed of the proposed method by using the algorithm and hardware accelerations, hoping that the holographic technology can be applied as soon as possible.

Compared with the traditional methods, the proposed method has the following differences and advantages:

1) The traditional error diffusion methods are often used to realize the reconstruction of digital holography or projection. The initial complex amplitude is calculated according to the traditional Fresnel diffraction, and the hologram of the 2D object is generated by calculating each object point. These methods reproduce 2D images, not holographic 3D display, while the proposed method focuses on the computer-generated holographic 3D images based on the SLM. At present, the holographic 3D display has not been applied due to the 3D reconstruction quality. The key innovation of the proposed method is the design of the LPS algorithm and the light source optimization, which is more comprehensive than those that only optimize the algorithm or light source. The proposed method can greatly improve the reconstruction quality of the holographic 3D display and make the holography well used in AR display, video display and
multi-plane display. Currently the holographic 3D display is difficult to achieve such good reconstruction quality and be used in these applications.

2) Besides, in the proposed method, the LPS algorithm is designed to calculate the phase only hologram of the 3D object. The LPS algorithm used to calculate the hologram of the 3D object is based on the angular spectrum propagation and layered processing. The amplitude information of each layer is obtained from the rendered image, and the uniform phase information is added to each layer. By calculating the hologram of each layer, the complex hologram of the object in different layers is extracted. Then the holograms of the different layers are superimposed together to produce the initial complex hologram of the object. The generation process of the initial complex hologram of the object is different from the traditional methods.

3) Moreover, the subsampling method is proposed based on the LPS algorithm, so the scaling of the reproduced image can be achieved. However, in the traditional methods, when the sampling size of the hologram changes, the quality of the reconstructed image will be seriously affected. In the proposed method, speckle noise in the reconstructed image is suppressed by using the pixel scanning, so the quality of the reconstructed image can be guaranteed during the zoom process. In this way, holographic zoom display can be achieved easily. By using the proposed method, holographic multi-plane display without distortion can be realized. We believe that the proposed method can promote the application of the holographic display.

V. CONCLUSIONS
In this paper, a holographic display method for speckle noise suppression based on LPS algorithm is proposed. By calculating the initial complex amplitude of the 3D object and scanning the pixels of the hologram, the error of the complex amplitude can be optimized as much as possible. At the same time, the pattern with different random phase is generated and loaded on the SLM, so the reconstructed light can be optimized. Based on the new algorithm design and light source optimization, the proposed method can suppress the speckle noise effectively. Experimental results verify the feasibility of the proposed method. Besides, the feasibility and unique advantages of the proposed method in the holographic AR display, video display and multi-plane display have been proved.

REFERENCES
[1] R. Hirayama, D. M. Plascencia, N. Masada, and S. Subramanian, “A volumetric display for visual, tactile and audio presentation using acoustic trapping,” Nature, vol. 575, no. 7782, pp. 320–323, Nov. 2019.
[2] J. Park, K. Lee, and Y. Park, “Ultrathin wide-angle large-area digital 3D holographic display using a non-periodic photon sieve,” Nature Commun., vol. 10, no. 1, p. 1304, Dec. 2019.
[3] X. Li, L. Chen, Y. Li, X. Zhang, M. Pu, Z. Zhao, X. Ma, Y. Wang, M. Hong, and X. Luo, “Multicolor 3D meta-holography by broadband plasmonic modulation,” Sci. Adv., vol. 2, no. 11, Nov. 2016, Art. no. e1601102.
[4] K. Wakanami, P.-Y. Hsieh, R. Oi, T. Senoh, H. Sasaki, Y. Ichihashi, M. Okui, Y.-P. Huang, and K. Yamamoto, “Projection-type see-through holographic three-dimensional display,” Nature Commun., vol. 7, no. 1, p. 12954, Dec. 2016.
[5] S. Tay, P.-A. Blanche, R. Voorakaranam, A. V. Tunç, W. Lin, S. Rotkutanda, T. Gu, D. Flores, P. Wang, G. Li, P. S. Hilaire, J. Thomas, R. A. Norwood, M. Yamamoto, and N. Peyghambarian, “An updatable holographic three-dimensional display,” Nature, vol. 451, pp. 694–698, Feb. 2008.
[6] D. Wang, C. Liu, C. Shen, Y. Xing, and Q.-H. Wang, “Holographic capture and projection system of real object based on tunable zoom lens,” PhotonX, vol. 1, no. 1, p. 6, Dec. 2020.
[7] T. Sugie, T. Akamatsu, T. Nishitsuji, R. Hirayama, N. Masada, H. Nakayama, Y. Ichihashi, A. Shiraki, M. Oikawa, N. Takada, Y. Endo, T. Kakue, T. Shimobaba, and T. Ito, “High-performance parallel computing for next-generation holographic imaging,” Nature Electron., vol. 1, no. 7, pp. 254–259, Apr. 2018.
[8] T. Nishitsuji, T. Shimobaba, T. Kakue, and T. Ito, “Review of fast calculation techniques for computer-generated holograms with the point-light-source-based model,” IEEE Trans. Ind. Informat., vol. 13, no. 5, pp. 2447–2454, Oct. 2017.
[9] T. Shimobaba, T. Kakue, and T. Ito, “Review of fast algorithms and hardware implementations on computer holography,” IEEE Trans. Ind. Informat., vol. 12, no. 4, pp. 1611–1622, Aug. 2016.
[10] P. Tsang, W.-K. Cheung, T.-C. Poon, and C. Zhou, “Holographic video at 40 frames per second for 4-million object points,” Opt. Express, vol. 19, no. 16, pp. 15205–15211, 2011.
[11] V. Bianco, P. Memmolo, M. Leo, S. Montresor, C. Distante, M. Paturzo, P. Picart, B. Javidi, and P. Ferraro, “Strategies for reducing speckle noise in digital holography,” Light., Sci. Appl., vol. 7, no. 1, Dec. 2018, Art. no. 48.
[12] Q. Cheng, J. Xia, L. Yang, W. Lei, Z. Yang, and J. Chen, “Speckle-suppressed phase-only holographic three-dimensional display based on double-constraint Gerchberg–Saxton algorithm,” Appl. Opt., vol. 54, no. 23, pp. 6994–7001, 2015.
[13] Y. Qi, C. Chang, and J. Xia, “Speckless holographic display by complex modulation based on double-phase method,” Opt. Express, vol. 24, no. 26, pp. 30368–30378, 2016.
[14] D. Wang, N.-N. Li, C. Liu, and Q. H. Wang, “Holographic display method to suppress speckle noise based on effective utilization of two spatial light modulators,” Opt. Express, vol. 27, no. 8, pp. 11617–11625, 2019.
[15] J. R. Moore, N. Collings, W. A. Crossland, A. B. Davey, M. Evans, A. M. Jezierska, M. Komarcevic, R. J. Parker, T. D. Wilkinson, and H. Xu, “The silicon backplane design for an LCOS polarization-insensitive phase hologram SLM,” IEEE Photon. Technol. Lett., vol. 20, no. 1, pp. 60–62, Jan. 1, 2008.
[16] A. Jesacher, S. Bernet, and M. Ritsch-Marte, “Colour hologram projection with an SLM by exploiting its full phase modulation range,” Opt. Express, vol. 22, no. 17, pp. 20530–20541, 2014.
[17] T. Kozacki and M. Chilipala, “Color holographic display with white light LED source and single phase only SLM,” Opt. Express, vol. 24, no. 3, pp. 1849–1859, 2019.
[18] J. Cho, S. Kim, S. Park, B. Lee, and H. Kim, “DC-free on-axis holographic display using a phase-only spatial light modulator,” Opt. Lett., vol. 43, no. 14, pp. 3397–3400, 2018.
[19] H. Ma, J. Liu, M. Yang, X. Li, G. Xue, and Y. Wang, “Influence of limited random-phase of objects on the image quality of 3D holographic display,” Opt. Commun., vol. 385, pp. 153–159, Feb. 2017.
[20] Y. Takaki and M. Yokouchi, “Speckle-free and grayscale hologram reconstruction using time-multiplexing technique,” Opt. Express, vol. 19, no. 8, pp. 7567–7579, 2011.
[21] P. W. M. Tsang, Y. T. Chow, and T. C. Poon, “Generation of phase-only Fresnel hologram based on downsampling,” Opt. Express, vol. 22, no. 21, pp. 25208–25214, 2014.
[22] P. W. M. Tsang, T.-C. Poon, and A. S. M. Jiao, “Embedding intensity image in grid-cross down-sampling (GCD) binary holograms based on block truncation coding,” Opt. Commun., vol. 304, pp. 62–70, Sep. 2013.
[23] X. Li, J. Liu, T. Zhao, and Y. Wang, “Color dynamic holographic display with wide viewing angle by improved complex amplitude modulation,” Opt. Express, vol. 26, no. 3, pp. 2349–2358, 2018.
[24] G.-Y. Lee, G. Yoon, S.-Y. Lee, H. Yoon, J. Cho, K. Lee, H. Kim, J. Rho, and B. Lee, “Complete amplitude and phase control of light using broadband holographic metasurfaces,” Nanoscale, vol. 10, no. 9, pp. 4237–4245, 2018.
[25] M. Makowski, “Minimized speckle noise in lens-less holographic projection by pixel separation,” Opt. Express, vol. 21, no. 24, pp. 29205–29216, 2013.
[26] P. W. M. Tsang and T.-C. Poon, “Novel method for converting digital Fresnel hologram to phase-only hologram based on bidirectional error diffusion,” Opt. Express, vol. 21, no. 20, pp. 25680–25686, 2013.
[27] P. W. M. Tsang, A. S. M. Jiao, and T.-C. Poon, “Fast conversion of digital Fresnel hologram to phase-only hologram based on localized error diffusion and redistribution,” Opt. Express, vol. 22, no. 5, pp. 5060–5066, 2014.

[28] S. Montrésor, P. Memmolo, V. Bianco, P. Ferraro, and P. Picart, “Comparative study of multi-look processing for phase map de-noising in digital fresnel holographic interferometry,” J. Opt. Soc. Amer. A, Opt. Image Sci., vol. 36, no. 2, pp. A59–A66, Feb. 2019.

[29] P. Memmolo, V. Bianco, M. Paturzo, B. Javidi, P. A. Netti, and P. Ferraro, “Encoding multiple holograms for speckle-noise reduction in optical display,” Opt. Express, vol. 22, no. 21, pp. 25768–25775, 2014.

[30] Y. Zhang, H. Dong, R. Wang, J. Duan, A. Shi, Q. Fang, and Y. Liu, “Demonstration of a home projector based on RGB semiconductor lasers,” Appl. Opt., vol. 51, no. 16, pp. 3584–3589, 2012.

[31] N. E. Yu, J. W. Choi, H. Kang, D.-K. Fu, J.-W. Liou, A. H. Kung, H. J. Choi, B. J. Kim, M. Cha, and L.-H. Peng, “Speckle noise reduction on a laser projection display via a broadband green light source,” Opt. Express, vol. 22, no. 3, pp. 3547–3556, 2014.

[32] J. A. Gilber, T. D. Duderar, and A. J. Boehnlein, “Ultra low frequency holographic interferometry using fiber optics,” Opt. Lasers Eng., vol. 5, no. 1, pp. 29–40, Jan. 1984.

[33] V. Yurlov, A. Lapchuk, S. Yun, J. Song, and H. Yang, “Speckle suppression in scanning laser display,” Appl. Opt., vol. 47, no. 2, pp. 179–187, 2008.

[34] B. Redding, M. A. Choma, and H. Cao, “Speckle-free laser imaging using random laser illumination,” Nature Photon., vol. 6, no. 6, pp. 355–359, Jun. 2012.

[35] T. Wang, W. Shen, S. Wu, P. Zhou, J. He, and H. Yu, “The implementation of laser speckle reduction based on MEMS two-dimensional scanning mirror,” Proc. SPIE, vol. 10022, Oct. 2016, Art. no. 100222U.

[36] J.-W. Pan and C.-H. Shih, “Speckle reduction and maintaining contrast in a LASER pico-projector using a vibrating symmetric diffuser,” Opt. Express, vol. 22, no. 6, pp. 6464–6477, 2014.

[37] P.-H. Yao, C.-H. Chen, and C.-H. Chen, “Low speckle laser illuminated projection system with a vibrating diffractive beam shaper,” Opt. Express, vol. 20, no. 15, pp. 16552–16566, 2012.

[38] D. Lee, C. Jang, K. Bang, S. Moon, G. Li, and B. Lee, “Speckle reduction for holographic display using optical path difference and random phase generator,” IEEE Trans. Ind. Informat., vol. 15, no. 11, pp. 6170–6178, Nov. 2019.

[39] Y. Kuratomi, K. Sekiya, H. Satoh, T. Tomiyama, T. Kawakami, B. Katagiri, Y. Suzuki, and T. Uchida, “Speckle reduction mechanism in laser rear projection displays using a small moving diffuser,” J. Opt. Soc. Amer. A, Opt. Image Sci., vol. 27, no. 8, pp. 1812–1817, 2010.

[40] D. S. Mehta, D. N. Naik, R. K. Singh, and M. Takeda, “Laser speckle reduction by multimode optical fiber bundle with combined temporal, spatial, and angular diversity,” Appl. Opt., vol. 51, no. 12, pp. 1894–1904, 2012.

[41] T. Shimobaba, K. Matsushima, T. Kakue, N. Masuda, and T. Ito, “Scaled angular spectrum method,” Opt. Lett., vol. 37, no. 19, pp. 4128–4130, 2012.

[42] Y. Zhao, L. Cao, H. Zhang, D. Kong, and G. Jin, “Accurate calculation of computer-generated holograms using angular-spectrum layer-oriented method,” Opt. Express, vol. 23, no. 20, pp. 25440–25449, 2015.

[43] S.-C. Kim and E.-S. Kim, “Effective generation of digital holograms of three-dimensional objects using a novel look-up table method,” Appl. Opt., vol. 47, no. 19, pp. D55–D62, Jul. 2008.

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