A New Approach for Speckle Reduction in Holographic 3D printer

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Abstract. A Holographic 3D printer produces a high quality 3D image reproduced by a full-color, full-parallax holographic stereogram with high-density light-ray recording. But speckle-pattern noise localized behind the reconstructed image is causing a loss of the display quality. This noise is originated from the speckle generated by a diffuser for equalizing the intensity distribution of the object light on the recording medium. We analyze some conventional ways for speckle reduction using a band-limited diffuser, and it is found that these ways cannot reduce the noise sufficiently. Then we propose two methods, one introduces a moving diffuser and the other introduces multiple exposures and a digital diffuser called as 4L-PRPS.

1. Introduction

A holographic 3D printer produces a holographic stereogram (HS) using the 3D data of a subject from a computer and outputs a hardcopy like a conventional image printer [1-3]. The image obtained by this system has full-color, full-parallax and high-density light-ray information.

In this system, by use of the optical system shown in figure 1, an array of small elementary reflection-type holograms is recorded in a thick recording material. The recording medium is translated horizontally and vertically after each exposure so that the whole surface of the hologram is exposed by an array of small elementary holograms. An aperture is placed to avoid leaking object light to the next elementary hologram. The image displayed on a spatial light modulator (SLM), in this case a liquid-crystal display (LCD) panel, is a geometrical projection of the 3D object calculated by a computer-graphic technique. In the reconstruction stage, since each elementary hologram is a volume reflection grating, full-parallax 3D image can be displayed even under ordinary white light illumination.

Since recording medium is placed on the Fourier plane, the intensity variation on the hologram plane depends on the spatial frequency component of the image displayed on the SLM. This image usually has a small high-frequency component. The phase distribution is almost dependent on the amplitude pattern since the phase is also modulated along with the amplitude by the LCD panel. Therefore the low-frequency component is dominant even in the phase pattern, and the object beam has a large intensity variation on the hologram plane and strong DC peak. As a result, two problems occur, (1) the recording of a hologram with high efficiency is difficult because dynamic range of recording medium is limited, and (2) reconstructed image gets dark because the elementary hologram...
has low aperture ratio.

To solve these problems, a lot of ways have been proposed. To smooth the Fourier spectrum distribution, one may simply move the recording medium slightly away from the focal plane so that the average intensity become almost uniform by defocus [4]. Then, however, the problem of low aperture ratio remains.

Another method is to use a phase modulation. Using a typical diffuser to equalize the Fourier spectrum within the aperture courses a loss of the object light and the speckle noise that appear behind the reconstructed image. Therefore various phase masks called band-limited diffuser were proposed [5-14]. However, these methods with single exposure cannot reduce the speckle noise sufficiently. This is described in the next section.

In this paper, we propose two new approaches to solve the problems described above. The first is "Moving diffuser method". This method was tried in the HS with horizontal parallax only (HPO) [20], but details of experimental result have not been reported. We first tried this method to Holographic 3D printer that generates full-parallax HS. In the result, we found through experiments that this method can reduce the speckle-pattern noise localized behind the reconstructed image, while alternative high-frequency noise appeared on the hologram plane. This is described in section 3.1.

To solve the problem of first method, we propose the second one "Multiple exposures method". In this approach, by introducing a multiple exposures and one of digital-diffusers, effective speckle reduction is possible. This will be described in section 3.2.

2. Conventional methods

2.1. Using typical diffuser

If HS is recorded with a typical diffuser, a speckle pattern affects LCD image and is recorded in the elementary hologram. When using the static diffuser, since a same speckle pattern is recorded in all elementary holograms, this pattern becomes localized at infinity of the reconstructed image. An average size of the speckle spot depends on the aperture size, and the smaller the aperture size is made for high-density recording, this pattern becomes more apparent because speckle size becomes large.

Also high spatial coherence of an illuminated light reduces the blur of both the reconstructed image and the speckle-pattern noise. This is critical problem for high quality HS recording.

2.2. Limitation of band-limited diffusers

Band-limited diffusers optimized to Fourier transform holograms has been analyzed for holographic data storage applications and also have been applied to HS recording [15-17]. However, the problem of this method has not been described in detail. In this paper, we describe the characteristics of one of the band-limited diffusers called digital diffuser, which is designed by digital process that is for example pseudorandom phase sequences (PRPS) [11] or iterative Fourier transform (IFTA) [14]. We
evaluate smoothness inside the aperture on Fourier plane and a speckle contrast [22] on LCD plane by a numerical simulation. The smoothness and the speckle contrast are written as:

\[ \text{Smoothness} = \frac{\langle I_F \rangle}{I_{F_{\text{max}}}} \quad \text{Speckle Contrast} = \frac{\sigma_{\text{LCD}}}{\langle I_{\text{LCD}} \rangle} \]

Where \( I_F \) is the intensity of Fourier plane, \( I_{\text{LCD}} \) is the intensity of LCD plane and \( \sigma_{\text{LCD}} \) is the standard deviation of \( I_{\text{LCD}} \). The results of 50 times iterations in IFTA are shown in figure 2 with the case of 6L-CPRPS [11], which is one of the PRPS. The result shows that there is a trade-off between the smoothness and the speckle contrast. We can understand that this is a limitation of single exposure with digital diffuser.

![Figure 2](image1.png)

**Figure 2.** Speckle contrast vs. smoothness of digital diffusers designed by IFTA and 6L-PRPS in numerical simulations. One of the intensity distributions of (a)(c) LCD plane and (b)(d) Fourier plane.

3. New Approach for speckle reduction

3.1. Approach 1. Moving diffuser

Moving the diffuser after each exposure, different speckle patterns are recorded in each elementary hologram. These patterns are superposed at observer’s retina in reconstructed step, and then the speckle contrast at infinity seems to be reduced. We evaluate this effect quantitatively through experiments. Figure 3 shows the reconstructed images, and Figure 4 shows the relation between speckle contrast at infinity and the number of phase pattern M, which corresponds to the number of illuminated positions on the diffuser.

If the moving distance is greater than the average size of the speckle on LCD plane, uncorrelated speckle patterns are superposed in observer’s retina since HS is reconstructed with incoherent light. Therefore the speckle contrast at infinity reduces in proportion to \( 1/\sqrt{M} \) theoretically. The number of rays toward the same direction entering the observer’s pupil determines limitation of speckle reduction by this approach. When the diameter of the pupil is 3.5mm and the pitch of elementary hologram is 0.2mm, about 250 rays superposed on the retina, so that the speckle contrast reduces in proportion to \( 1/\sqrt{250} \approx 0.063 \).

On the other hand, it was found that high-frequency noise appeared on the surface of the reconstructed HS. This noise is shown in (c) of figure 3. Also the relation between the number of phase pattern M and the energy of this noise are shown in figure 5. When recording by a static diffuser, a very low frequency noise appears at the HS surface, and this noise does not bother the reconstructed image while the infinity noise is more noticeable. When using moving diffuser, since each elementary
hologram reconstructs speckle pattern that is different from each other, observer perceives various brightness at the elementary holograms when he or she focuses on the HS surface. This noise is perceived when the value $M$ become large to some extent, and the maximum value of the frequency depends on the pitch of elementary hologram. In addition, when the point of view moves, the high frequency noise is perceived as a flicker. This is the problem of moving diffuser.

3.2. Approach 2. Multiple exposures with 4L-PRPS

3.2.1 Principle. "Moving diffuser method" is effective to reduce the speckle-pattern noise behind the reconstructed image, but has the problem of the high frequency noise at the HS surface. We propose a new method to solve this problem. In photo-polymers for holographic data storage applications, multiple exposures are employed. Therefore, we consider applying the multiple exposures to reduce
the speckle noise in HS. For example, an elementary hologram is recorded by multiple exposures to several times (M times) while the diffuser is shifted after each exposure. Then, if each speckle pattern recorded in the single elementary hologram is uncorrelated, the speckle noise reconstructed from the single elementary hologram reduces in proportion to $1/\sqrt{M}$, so that speckle noise on retina also reduced, and then high frequency noise at the HS surface does not appear in case of the multiple exposures using same sets of positions on the diffuser. In this way, the speckle noise behind the reconstructed image can be reduced without increasing high-frequency noise on the hologram plane.

However, the number of multiple exposures cannot be increase so much because it takes a large recording time to shift the diffuser and the diffraction efficiency is affected by multiple exposures. Therefore the factor of $1/\sqrt{M}$ is inefficient. If it is possible that each speckle pattern recorded by multiple exposures have a negative correlation, we can reduce the speckle contrast effectively smaller than $1/\sqrt{M}$ [19].

According to this concept, we propose a new method. Let us consider the phase modulation applied to the digital diffuser designed by 4Level-PRPS (4L-PRPS). It has the random phase sequences in which the phase step at each boundary is either $+\pi/2$ or $-\pi/2$. When the size of the elementary hologram is $2\lambda f/p$, where $\lambda$ is the wavelength, $f$ is the focal length of Fourier lens and $p$ is the pitch of the phase cell in digital diffuser, the reconstructed image recorded by 4L-PRPS becomes dot-like pattern. Exposing an elementary hologram four times with shifting the diffuser half-length of the phase cell pitch, dot-like pattern reconstructed from the elementary hologram is superposed on observer's retina. Then, since dot-like pattern and the shifted pattern have negative correlation, the speckle contrast is effectively reduced as shown in figure 7.
3.2.2 Numerical simulations. We show the effect of proposed method by numerical simulation. Recording of one elementary hologram is divided into four exposures with shifting the digital diffuser after each exposure. Shifting directions are vertical, horizontal and both of them, and the each shift amount is half-length of the phase cell pitch. The result is shown in figure 8. Both the smoothness on the Fourier plane and the speckle contrast of reconstructed image in proposed method show good results beyond the trade-off line of single exposure with optimized digital diffuser. The speckle contrast is reduced almost 0.1 even as $1/\sqrt{4} \approx 0.5$ in case of $M=4$, avoiding the high frequency noise at the HS surface. This means that it is effective approximately five times compared to the approach with a typical moving diffuser and multiple exposures.

4. Discussions
In the second proposed method, there are some issues for the optical implementation. The digital diffuser, that is a diffractive optical element (DOE), is implemented by an optical element such as fabricated glass or a phase only SLM. If the former case, it is necessary to move the DOE mechanically. Then, it requires longer moving time and introduces vibration to the recording system. When producing the full-color HS, three DOE and complicated optical system are also needed. In contrast, the latter case, there are not problems described above. But, in case of the phase only SLM such as PAL-SLM [23], a blur of phase modulation is concerned.

The evaluations of human speckle perception are studied for laser projection systems [24]. In future, considering a human perception is also necessary for the speckle noise evaluations of a holographic display in addition to the speckle contrast.

5. Conclusions
We propose two methods for the speckle reduction in holographic 3D printer, which produces full-color full-parallax HS with high-density light ray information. Conventional methods have the limits of speckle reduction such as trade-off between smoothness of Fourier plane and the speckle contrast of reconstructed ray distributions. Then, we evaluated "Moving diffuser method" and found that this method is effective to reduce the speckle-pattern noise behind the reconstructed image, but the problem of the high frequency noise at the HS surface appears. "Multiple exposures method" is also proposed to solve this problem. This approach is shown to be effective by numerical simulation. We will show the experimental result and high quality HS in future works.
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