Lensless zoomable holographic projection using scaled Fresnel diffraction

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Abstract: Projectors require a zoom function. This function is generally realized using a zoom lens module composed of many lenses and mechanical parts; however, using a zoom lens module increases the system size and cost, and requires manual operation of the module. Holographic projection is an attractive technique because it inherently requires no lenses, reconstructs images with high contrast and reconstructs color images with one spatial light modulator. In this paper, we demonstrate a lensless zoomable holographic projection. Without using a zoom lens module, this holographic projection realizes the zoom function using a numerical method, called scaled Fresnel diffraction which can calculate diffraction at different sampling rates on a projected image and hologram.

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References and links
1. Introduction

Laser displays, which use spatial light modulators (SLMs) and lasers, are attractive because they offer high-contrast and wide color gamut images, and low power consumption. Laser displays are used for very large screens with over 2,000 inches or micro- and pico-projectors [1, 2].

One type of laser display is a holographic projection [3, 4]. In holographic projection, we first calculate a hologram from the image we want to project, and we next reconstruct the projected image from the hologram. The optical system becomes very simple with one lens or lensless setup. It is an attractive technique because it offers not only the above properties of laser displays but also aberration-free, color reconstruction with only one SLM, and an optical system size that is reducible. Therefore, holographic projection is especially suitable for micro- and pico-projectors. However, there are some problems, for example, speckle noise, the long time needed for calculating holograms, and zooming a projected image.

Projectors require a zoom function. It is generally realized using a zoom lens module composed of many lenses and mechanical parts; however, using the module increases the system size and cost, and requires manual operation of the module. A zoomable holographic projection system using a liquid crystal (LC) lens was demonstrated instead of using a zoom lens [5, 6]. As the LCD lens can display Fresnel lens pattern, the magnification of the projected image can be electrically controlled by the focal length of the Fresnel lens pattern. However, this method requires the additional device of the LC lens.

Holographic projection inherently requires no lenses. Using this property, it is easy to numerically realize a zoomable holographic projection by an image magnified by image interpolation techniques. However, the calculations are time consuming and require huge memory to generate a hologram for the magnification. We have already proposed a method to improve this problem by using different sampling pitches on a projected image and hologram, and verified the effectiveness of this method by numerical simulation [7–9]. We used Shifted-Fresnel diffraction [10], which is a scaled diffraction calculation that calculates diffraction at different sampling rates on a projected image and hologram. Although this zoomable projection with the Shifted-Fresnel diffraction could magnify the projected image only by adjusting the sampling pitch on the projected image, an aliasing noise will occur in the projected image due to the property of the Shifted-Fresnel diffraction.

In this paper, we demonstrate a lensless zoomable holographic projection using “aliasing-reduced scaled and shifted Fresnel diffraction” (ARSS-Fresnel diffraction) [11] instead of Shifted-Fresnel diffraction. ARSS-Fresnel diffraction is a scaled Fresnel diffraction calculation. In addition, we verify the effectiveness in numerical and actual experiments.

Projected images of holographic projections are prone to large speckle noise. To improve this, many methods have been proposed [12–16]. We used a speckle reduction method [15] with ARSS-Fresnel diffraction. In Section 2, we explain a lensless zoomable holographic projection
with ARSS-Fresnel diffraction. In Section 3, we present the results. Section 4 concludes this work.

2. Lensless zoomable holographic projection

Figure 1 shows the optical system of our lensless zoomable holographic projection. As can be seen, the optical setup is very simple, that is, it consists of a laser with optical fiber (the wavelength is 671 nm), SLM (Holoeye Pluto, a phase-only liquid crystal on silicon with 1,920 × 1,080 pixels with a pixel pitch of 8 µm) and a non-polarizing beam splitter cube. We placed the output of the fiber and a projection screen at 50 mm and z from the SLM. The output of the fiber can be regarded as a point light source because the diameter is 1 µm. We observe zoomable projected images on the projection screen by displaying holograms calculated by ARSS-Fresnel diffraction and speckle reduction method. The direct light from the output of the fiber is overlapped on the projected image; however, the direct light diffuses over the projection screen.

![Fig. 1. Optical setup for our lensless zoomable holographic projection.](image)

2.1. ARSS-Fresnel diffraction

We briefly describe ARSS-Fresnel diffraction derived from Fresnel diffraction. Normal Fresnel diffraction cannot calculate diffraction with different sampling pitches on source and destination planes, while ARSS-Fresnel diffraction can calculate such diffraction. One-dimensional Fresnel diffraction is expressed by,

\[ u_2(x_2) = \frac{\exp(ikz)}{i\lambda z} \int u_1(x_1) \exp\left(\frac{ip}{\lambda z} (x_2 - x_1)^2\right) dx_1, \quad (1) \]

where \( k \) is the wave number, \( \lambda \) is the wavelength of light, \( u_1(x_1) \) is the source plane (an image that we want to project), \( u_2(x_2) \) is the destination plane (a hologram), and \( z \) is the propagation distance between the source and destination planes.

For the scale and shift operations, we used \((x_2 - sx_1 + o)^2\) instead of \((x_2 - x_1)^2\) in Eq.(1) where \( s \) is the scaling parameter and \( o \) is offset from the origin. The scaling parameter is defined as the ratio of \( \Delta_1/\Delta_2 \) where \( \Delta_1 \) and \( \Delta_2 \) are the sampling pitches on the projected image and hologram. Substituting the relation \((x_2 - sx_1 + o)^2 = s(x_2 - x_1)^2 + (s^2 - s)x_1^2 + (1 - s)x_2^2 + 2ox_2 - 2sox_1 + o^2\) to Eq.(1), we can obtain ARSS-Fresnel diffraction:

\[ u_2(x_2) = C_z \mathcal{F}^{-1} \left[ \mathcal{F} \left[ u_1(x_1) \exp(i\phi_h) \right] \mathcal{F} \left[ \exp(i\phi_h) \text{Rect} \left( \frac{x_h}{2x_{\text{max}}} \right) \right] \right], \quad (2) \]
where $\text{Rect}(\cdot)$ is the rectangular function that reduces aliasing noise, $x_h$ is a variable for the generation of $\exp(i\phi_h)$, $x_{\text{max}}$ is the aliasing-free area and $\exp(i\phi_h)$ and $C_z$ are defined by $\exp(i\phi_h) = \exp(i\pi((s^2 - s)x_1^2 - 2sx_1)/\lambda z)$, $\exp(i\phi_h) = \exp(i\pi x_h^2/\lambda z)$ and $C_z = \exp(i\phi_h)/(i\lambda z) = \exp(ikz + i\pi((1 - s)x_1^2 + 2ax_2 + a^2)/\lambda z))$. It is a straightforward way of extending to two-dimensional ARSS-Fresnel diffraction because Fresnel diffraction allows separation of variables. See [11] for details.

2.2. Hologram generation with speckle reduction

Although we can calculate a zoomable hologram using ARSS-Fresnel diffraction, the hologram will occur speckle noise. In order to reduce the speckle noise, we used the speckle reduction method used by Makowski, which is referred to as the “multiple random phase method” [15], with ARSS-Fresnel diffraction.

In Fig. 2(a), we used the Gerchberg-Saxton (GS) algorithm for optimizing holograms. We start the iteration by multiplying an initial random phase with an original image. After calculating the diffractions from the original image with the random phase by scaled diffraction with different sampling pitches on the original image and hologram, we extract only the phase components (“Phase constraint” in Fig. 2(a)). We used Shifted-Fresnel diffraction and ARSS-Fresnel diffraction as the scaled diffractions. A comparison of the projected images when using these diffractions is shown in Section 3.

The phase hologram is reconstructed by inverse scaled diffraction with different sampling pitches. We replace the amplitude of the reconstructed result with those of the original image (“Amplitude constraint” in Fig. 2(a)). We can optimize a hologram step by step to repeat the aforementioned iteration. We multiply the final result after the iteration with a phase of a converging lens with a focal length of 50 mm due to canceling the spherical wave of the fiber in Fig. 1. In this paper, we used five iterations because it reached the ceiling in an early iteration.

We used the multiple random phase method in order to further suppress the speckle noise. As shown in Fig. 2(b), this method uses $N$ different initial random phase distributions and calculates $N$ holograms by GS algorithm. “Hologram 1” and “Hologram N” in Fig. 2(b) mean the generated holograms with GS algorithm and initial random phase 1 and N, respectively. We can observe speckle-reduced projected images because speckle noise suppression is realized by alternately displaying the $N$ holograms at high speed. In this experiment, we used different initial random phase distributions of $N = 20$. 

Fig. 2. Optimizing holograms. (a) Gerchberg-Saxton (GS) algorithm with scaled diffraction calculation (b) multiple random phase method.

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3. Results

Figure 3 shows a numerical reconstruction of projected images calculated by GS algorithm alone and multiple random phase method. Figures 3 (a) and (b) were calculated by GS algorithm alone with five and 100 iterations, respectively. Comparing these figures, the image quality is similar. The projected image has speckle noise. In contrast, Fig. 3 (c) was calculated by the multiple random phase method with five iterations and \( N = 20 \). The projected image had reduced speckle noise, compared with those shown in Figs. 3 (a) and (b).

![Fig. 3. Numerical reconstruction of projected images calculated by GS algorithm alone and multiple random phase method. (a) GS algorithm with five iterations. (b) GS algorithm with 100 iterations (c) multiple random phase method with five iterations and \( N = 20 \).](image)

Figure 4 shows a numerical reconstruction of projected images calculated by two scaled diffraction calculations: Shifted-Fresnel diffraction and ARSS-Fresnel diffraction. The values at the upper left of the images mean the sampling pitch on the projected image. We used a distance of \( z = 200 \text{ mm} \), a sampling pitch on the hologram of \( 8 \mu \text{m} \) and a wavelength of 671 nm as the calculation conditions. In addition, the holograms were optimized by the multiple random phase method with five iterations and \( N = 20 \). The upper images are the projected image calculated by Shifted-Fresnel diffraction, when changing the sampling pitch of the projected image from 10\( \mu \text{m} \) to 14\( \mu \text{m} \). In the sampling pitch of the projected image of over 12\( \mu \text{m} \), an aliasing noise is incurred in the projected images. The bottom images are the projected image calculated by ARSS-Fresnel diffraction. In the projected images, the aliasing noise is incurred. Moreover, the light is not wasted on the aliasing artifacts, which allows a brighter reconstruction of the main central image.

![Fig. 4. Numerical reconstruction of projected images calculated by two scaled diffraction calculations: Shifted-Fresnel diffraction and ARSS-Fresnel diffraction.](image)

Figure 5 shows optical reconstruction of projected images calculated by the multiple random phase method and ARSS-Fresnel diffraction. The images were captured directly on the CMOS
matrix of the Canon EOS 5D mk2 digital camera. We used Fig. 1 as the optical system and \( z = 450 \) mm. We can observe zoomable projected images only by changing the sampling pitch on the projected image. When the sampling pitch of the projected image is 18\( \mu \)m, the image size is approximately 37mm \( \times \) 37mm. Note that the pixel number of the projected image is 2,048 \( \times \) 2,048. When using a large sampling pitch on the projected image, the brightness of the projected image is darker because the light power is spread on a large area. We used our computational wave optics library, CWO++ [17], in the calculation above. The calculation time of GS algorithm with the five iteration is about 1.5 seconds using GPU version of CWO++ library. The calculation time involves the processing times of ARSS-Fresnel diffraction, the generation of initial random phase.

![Fig. 5. Optical reconstruction of projected images calculated by the multiple random phase method and ARSS-Fresnel diffraction (Media 1).](image)

4. Conclusion

We demonstrated a lensless zoomable holographic projection. Using a scaled diffraction calculation, ARSS-Fresnel diffraction, this holographic projection was realized only by changing the sampling rate on the projected image. We compared the image quality of projected images calculated by Shifted-Fresnel diffraction and ARSS-Fresnel diffraction. In addition, we reduced the speckle noise in the projected image by the multiple random phase method. As our next work, we plan to develop a color version of this projection system. The some noise in Fig. 5 will be improved by using the latest speckle reduction method [16] proposed by M. Makowski.

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