Animated Computer-Generated Cylindrical Hologram
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ABSTRACT
Since a general flat hologram has a limited viewable area, we usually cannot see the other side of a reconstructed object. Therefore, we proposed the computer-generated cylindrical hologram as 360 deg viewable display. In this paper, we realize the more entertainment-type computer-generated cylindrical hologram. Since the previous holograms can be displayed is only dead object and it is not attractive for entertainment. Therefore, we have investigated an animated computer-generated cylindrical hologram by changing object data according to the viewpoint. Then, we print these fringes with our prototype fringe printer. As a result, we obtain a good reconstructed image from a computer-generated cylindrical hologram.

INTRODUCTION
Holograms have all three-dimensional information such as the binocular parallax, the convergence, the accommodation, and so on. Therefore, an image of a hologram provides the natural spatial effect. However, since a general flat hologram has a limited viewable area, we usually cannot see the other side of the recorded object. A cylindrical hologram\(^1\) can solve this problem.

An image of a cylindrical hologram can be seen from all sides. For optical cylindrical holograms, there are two methods to accomplish this: the multiplex hologram\(^3\) and the laser reconstruction 360 deg hologram\(^1\). The multiplex hologram is known as a holographic stereogram, and this hologram can be reconstructed with a white light. Since a multiplex hologram consists of many two-dimensional images, the reconstructed image from this hologram is not truly three dimensional. In contrast, our previous research\(^3\) is a computer-generated hologram version of laser type cylindrical hologram, and this hologram is based on the Fresnel hologram. Therefore, the reconstructed image has the true three-dimensional effect. By using this method, we have obtained good crisp reconstructed image which can be seen from all sides. However, the displayed image was only dead object and it is not attractive for entertainment. Therefore, we have investigated an animated computer-generated cylindrical (ACGCH) hologram by changing object data according to the viewpoint. To print the fringe pattern, we have used the fringe printer\(^4\). As a result, we obtain a good reconstructed image which shows the animation in horizontal direction from the computer-generated cylindrical hologram (CGCH).

CYLINDRICAL HOLOGRAM

Optical Cylindrical Hologram
The cylindrical hologram was proposed by Jeong\(^1\). This hologram can be seen from all sides. Since the optical system is simple, making the cylindrical hologram is easy. Figure 1 shows the optical setup for recording the optical cylindrical hologram. A film is set in the cylindrical shape, and an object is placed at the center of the film. To record the hologram, an expanded laser beam illuminates the object and the film. For the reconstruction, the same laser beam is used to illuminate the hologram. Since the shape of the hologram is a cylinder, the reconstructed image has a 360 deg viewable area.

Computer-Generated Cylindrical Hologram
When we make the cylindrical hologram using an optical system, we usually illuminate the object from the top as shown Fig. 1. Therefore, if the upper part of the object is larger than the lower part, the lower part is not illuminated and we cannot record this part. We can solve this problem by using an additional illumination source placed at the bottom. However, the optical system becomes complicated. Moreover,
if the object has a lot of asperity, it is difficult to illuminate the whole object. Therefore, we need to consider the proper shape of the object. On the other hand, since the CGCH uses the propagation of an object beam calculated by a computer, we can use variously shaped objects. The calculation method of the CGCH follows the calculation method of the Fresnel hologram.

**Calculation Method for a Cylindrical Hologram**

Since the shape of the hologram is a cylinder, we employ the cylindrical coordinate system. In the following discussion, we assume that the \(i\)-th object point is located at \((r_i, \theta_i, z_i)\). The intensity pattern of the light \(I\) on the hologram point \((r, \theta, z)\) is determined by

\[
I(\theta,z) = \sum_{i=1}^{N} \frac{a_i}{d_i} \cos[kd_i + \varphi_R(\theta,z) + \phi_i],
\]

where \(N\) is the number of object points, \(a_i\) is the real-valued amplitude of the \(i\)-th point, \(d_i\) is the distance from a point on the hologram plane to the \(i\)-th point of the object, \(\varphi_R\) is the phase of reference beam and \(\phi_i\) is the relative phase of the \(i\)-th point. The wavenumber is defined as \(k = \frac{2\pi}{\lambda}\), where \(\lambda\) is the freespace wavelength of the light.

Since the Eq. (1) includes cosine function and square-root operation, it takes much time to calculate the fringe pattern of the Fresnel hologram with a personal computer. To realize the proper hidden surface removal, the fringe pattern is divided into the small segments whose numbers are \(k_x\) as shown in Fig. 2. Therefore, by using look-up table for CGCH, we can decrease the calculation time.

**OBJECT DATA CALCULATION**

In our previous work, to realize the 360 deg viewable hologram, we have made and used the several object data to display the proper reconstructed image. These reconstructed images are only dead objects and it is not attractive for entertainment. Therefore, by changing the object data, we display the 3D animation.

Figure 3 shows the process of taking perspective images. For the CGCH, we need several object data for each viewpoint, to make occlusion correct. Taken image and the depth information are combined to get the object data. Therefore, in this paper, we change the object for each viewpoint. To use this method, we can calculate the fringe pattern of ACGCH without changing of the fringe equation.

**RESULT**

**Calculation Parameter of ACGCH**

Table 1 shows the parameters of the CGCH made in this research. We use our fringe printer to record the fringe pattern of the ACGCH. The maximum diffraction angle of the hologram depends on the pixel pitch of the fringe printer. The spatial resolution of the fringe printer is constant and we cannot change this parameter. The required pixel pitch of the
Table 2. Parameter of Fringe Printer

<table>
<thead>
<tr>
<th></th>
<th>Moving area [mm$^2$]</th>
<th>Focal length (L3) [mm]</th>
<th>Focal length (L4) [mm]</th>
<th>Demagnification rate</th>
<th>Wavelength (laser) [nm]</th>
<th>Resolution [pixels]</th>
<th>Pitch [μm]</th>
<th>Gray-scale level [bit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fringe Printer</td>
<td>200 x 200</td>
<td>150</td>
<td>12.5</td>
<td>1/12</td>
<td>540</td>
<td>1,400 x 1,050</td>
<td>10.4</td>
<td>8</td>
</tr>
<tr>
<td>LCoS</td>
<td></td>
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Fig. 4 Schematic of the fringe printer system

Fig. 5 Perspective images of the object data from several viewpoints

Fig. 6 Reconstructed images from different viewpoints
hologram is determined by

\[2d(\sin \theta_{out} - \sin \theta_{ill}) = \lambda, \quad (2)\]

where \(d\) is the pixel pitch of the fringe, \(\lambda\) is the wavelength of the laser, \(\theta_{out}\) is the output angle from the hologram and \(\theta_{ill}\) is the incident angle to the hologram.

**Fringe Printer**

For printing the CGCH, we use a fringe printer that consists of a laser, an x-y stage, and liquid crystal on silicon (LCoS) as a spatial light modulator as shown in Fig. 4. A fractional part of the entire holographic fringe is displayed on the LCoS, and the demagnified image of it is recorded on a holographic plate. Then the plate is translated by the x-y stage to write the next part of the fringe. Table 2 shows the fringe printer’s parameter.

**Reconstructed Image**

Figure 5 shows the perspective images of the object from several viewpoints. The average number of the object points is approximately 15,000. As a recording material for the fringe printer, we used VRP-M manufactured by SLAVICH. Since the maximum moving distance of our printer is 200 mm x 200 mm, we recorded the hologram in four parts. It took 15 h to record the whole hologram. The total calculation time is approximately 260 h with one PC (CPU : Intel Core2Duo E6600 2.40GHz). However, in this research, we used several PCs for parallel computation. Therefore, it took approximately 45 h in total calculation time.

Figure 6 shows the reconstructed images of the ACGCH from different viewpoints in horizontal direction. The reconstructed images are crisp and exhibit good contrast. Comparisons with Fig. 5 show that the reconstructed images are almost same as the perspective images. Therefore, this hologram shows that the reconstructed image changed in the horizontal direction.

**CONCLUSION**

In this research, we have realized an ACGCH that is viewable in 360 deg and displays the changing object. The reconstructed images show good contrast. Since average of approximately 15,000 object points are used for this research, we have proved the ability to reconstruct a complex and transmutative object.

However, since this reconstructed image is only a single color, we are trying to make a full-color ACGCH. Since the whole calculation time is 45 h, even if several PCs are used, we are also trying to further reduce the calculation time.

**REFERENCE**