Three-dimensional rendering of computer-generated holograms acquired from point-clouds on light field displays

Athanasia Symeonidou\textsuperscript{a,b,*}, David Blinder\textsuperscript{a,b}, Beerend Ceulemans\textsuperscript{a,b}, Adrian Munteanu\textsuperscript{a,b} and Peter Schelkens\textsuperscript{a,b}

\textsuperscript{a}Vrije Universiteit Brussel (VUB), Dept. of Electronics and Informatics (ETRO), Pleinlaan 2, B-1050 Brussels, Belgium; \textsuperscript{b}iMinds, Technologiepark 19, B-9052 Zwijnaarde, Belgium

\textbf{ABSTRACT}

Holograms, either optically acquired or simulated numerically from 3D datasets, such as point clouds, have special rendering requirements for display. Evaluating the quality of hologram generation techniques is not straightforward, since high-quality holographic display technologies are still immature. In this paper we present a framework for three-dimensional rendering of colour computer-generated holograms (CGHs) acquired from point-clouds, on high-end light field displays. This allows for the rendering of holographic content with horizontal parallax and wide viewing angle. We deploy prior work, namely a fast CGH method that inherently handles occlusion problems to acquire high quality colour holograms from point clouds. Our experiments showed that rendering holograms with the proposed framework provides 3D effect with depth disparity and horizontal-only with wide viewing angle. Therefore, it allows for the evaluation of CGH techniques regarding functional properties such as depth cues and efficient occlusion handling.

\textbf{Keywords:} Computer generated holograms, colour hologram, HPO, CGH, point cloud, 3D, autostereoscopic display

\section{1. INTRODUCTION}

Holography is the holy grail of three-dimensional (3D) visualisation, since it has the ability to provide all visual depth cues: binocular disparity, motion parallax, accommodation and convergence, without the need for glasses or inducing visual fatigue effects. Contrary to holographic microscopy, it is not possible for macroscopic scenes to use a Mach-Zehnder interferometric setup for capturing the holographic data. Hence, other imaging modalities need to be deployed to capture the scene content and thereafter these modalities need to be converted to a holographic representation using what are called computer generated holography (CGH) techniques. Input modalities can range from classical 2D camera(s) (arrays), depth sensing cameras, light field cameras to computer graphics\textsuperscript{1} e.g. point clouds.

Unfortunately, though the underlying technology necessary for holographic displays has advanced significantly, still major bottlenecks exist with respect to the required computational power for the CGH techniques and display requirements. Increased display requirements appear because of the need for a sufficient wide viewing angle and a large size viewing window, for which very fine pixel pitch and a large number of pixels are required. The space bandwidth product (SBP) is the metric to evaluate the quality of holographic displays. It is defined as the product of the physical dimension and the corresponding 2D bandwidth of the display, i.e. the spatial frequency bandwidth or $1/p^2$, with $p$ being the pixel pitch. For a constant SBP value, there is a trade-off between the viewing angle and the size of viewing window.

Despite the limitations, many holographic display systems have been proposed so far\textsuperscript{2,3}. Three-dimensional display of holograms is traditionally realised with spatial light modulators (SLMs), even though they generally cannot simultaneously modulate the phase and the amplitude. Multi-SLM designs, in combination with curved surfaces, relieve the high bandwidth requirements per SLM, and therefore, are strong candidates for future holographic video displays\textsuperscript{4}. Additionally, several microdisplay technologies have been developed for use in

\* Further author information and correspondence possible by e-mail to: asymeoni@etro.vub.ac.be

\footnotesize{Applications of Digital Image Processing XXXIX, edited by Andrew G. Tescher, Proc. of SPIE Vol. 9971, 99710S · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2237581}
video projectors, head-mounted displays, or camera viewfinders – among them LCD, liquid crystal on silicon (LCOS), and digital micromirror devices (DMD, DLP) – which have the same number of pixels as a direct-view panel but in a much smaller area and thus can create much greater diffraction angles due to the correspondingly higher maximum spatial frequency\(^5\).

Promising efforts to develop a real-time holographic display include display of piecewise calculated fringe patterns in an acousto-optic modulator (AOM)\(^5,6\), systems exploiting multiple SLMs, FPGA boards and GPUs,\(^7\) combinations of electrically addressed spatial light modulators (EASLMs) – for high frame rate and medium complexity, and optically addressed spatial light modulators (OASLMs) – for high resolution\(^8\), eye tracking technologies\(^9\) and materials such as sensitized photorefractive polymer (PRP) for high rates\(^10\). More recently, in 2016, Yamagutchi et. al proposed a 3D touchable holographic light-field display\(^11\).

However, a dynamic holographic display with practical size, high-resolution, and full-color support is still a technological challenge. Consequently, to validate high-end CGH techniques, one needs to fall back to either printed holograms or to make use of autostereoscopic displays that approximate holographic visualisation. The rendering framework proposed in this work can serve as a tool for this matter.

This paper is structured as follows. In Sec. 2, we briefly explain the holographic setup and the CGH method used for the generation of the holograms, detailing the adaptations required for horizontal parallax only and wide viewing angles. Section 3 discusses the proposed framework for rendering of CGHs on high-end 3D displays, explaining the intermediate rendering steps from the hologram to the three-dimensional display. The results of the rendering of the CGHs on our autostereoscopic light field display are reported in Sec. 4, and comparison to the numerical reconstruction is shown. Finally, we provide summarising conclusions in Sec. 5.

### 2. GENERATION OF HOLOGRAPHIC DATASET FROM POINT CLOUDS

Rendering of holograms on light field displays can be very useful for evaluating and validating CGH methods, especially for high quality holograms. In this section, we describe the holographic setup considered for the generation of the holograms, motivate the chosen parameters and explain the CGH method followed to acquire CGHs with wide field of view (FOV), targeting visualisation of the holograms on a specific autostereoscopic screen.

Since only horizontal parallax is supported by the majority of current light field displays, we decided to consider a horizontal parallax only (HPO) setup\(^12\). Compared to full-parallax holograms, this yields high-resolution on the horizontal axis, while reducing the computational requirements. However, any of the two can be used for the framework described in Sec. 3. HPO CGHs facilitate modulation, scanning and display, while on the other hand, HPO causes constrained viewing zones and astigmatic output due to the diminished spatial resolution in the vertical direction\(^5\).

To generate horizontal parallax only holograms with a wide field of view, sampling with a small pixel pitch is required, according to the grating equation\(^13\) given by:

\[
\sin \theta = \frac{\lambda}{2p}
\]

where \(\theta\) is the maximum angle of diffraction, \(\lambda\) is the wavelength and \(p\) is the pixel pitch. The minimum distance between the object and the hologram plane to comply with the Shannon criterion of the holographic signal, is given by:

\[
z_{\text{min}} = \frac{Np^2}{\lambda}
\]

where \(N\) is the pixel resolution, considering square dimensions of the hologram plane.

To demonstrate the proposed framework we will use an Holografika HoloVizio 722RC\(^14\) light field display, which provides with a viewing angle support of 70°. Therefore, since we aim for \(2\theta = 70^\circ\), we choose a holographic setup with a pixel pitch of 0.55 \(\mu m\) and 23.4 \(\mu m\) for the horizontal and vertical axis, respectively and high resolution equal to 32,768-by-768 pixels, while the wavelength of the reference beam is 640 \(nm\). Applying Eqs. (1) and (2) for these parameters, results in holograms with a FOV (= \(2\theta\)) angle of 71.1° and a minimum
distance of 6.3 mm between the object and hologram plane. For this work several holograms have been generated by applying our previously proposed multiple wavefront recording planes (WRP) method \(^\text{15}\). This technique uses multiple parallel wavefront recording planes (WRPs) and it is based upon an intra-WRP light wave propagation strategy utilising pre-computed propagation kernels stored in look-up tables (LUTs) that provide support for forward and backward light propagation. Additionally, to generate high-quality object reconstructions, we adhere a volume to the points by attributing a Gaussian distribution profile such that the rendered objects depict a smoother, continuous surface. To account for diffuse reflections, the spectral response of the look-up table content is modified with random phase, as described in Ref. \(^\text{16}\), so that light is scattered over a wide angular range and consequently provides with a wide field of view. Inverted Gaussian filters are used in the propagation process to model occlusions by locally blocking light. This method is originally suggested for fast computation of holograms that support full parallax \(^\text{15}\). However, we adapted the algorithm for HPO holograms by computing the contribution of the points to hololines, i.e. 1D holograms, only diffracting along the line, and not to the full hologram plane. The concept of the method is illustrated in Fig. 1.

Furthermore, all the wavefield propagations in the algorithm are applied between parallel planes. Hence, angular spectrum (AS) propagation is an appropriate choice for our algorithm. For a monochromatic source field input \(g(x, y, 0)\) the 2D propagation is given by:

\[
g(x, y, z) = g(x, y, 0) \ast h(x, y, z)
\]

where, \(h(x, y, z)\) is the propagation kernel and is given by:

\[
h(x, y, z) = \exp(\frac{i2\pi r}{r} (\frac{1}{2\pi r} + \frac{1}{i\lambda}))
\]

where, \(r = \sqrt{x^2 + y^2 + z^2}\) and \(\lambda\) is the wavelength.

Based on the convolutional theorem the above equation is equivalent to:

\[
G(u, v; z) = G(u, v; 0)H(u, v; z)
\]

where, \(G(u, v; 0) = \mathcal{F}\{g(x, y, 0)\}\) is the spectrum and \(H(u, v; z) = \mathcal{F}\{h(x, y, z)\} = \exp(i2\pi wz)\) the transfer function. \(\mathcal{F}\) represents the Fourier transform and \(u, v\) and \(w\) are Fourier frequencies in \(x, y,\) and \(z\) directions, respectively \(^\text{17}\), with \(w\) given by:

\[
w = w(u, v) = \begin{cases} (\lambda^{-2} - u^2 - v^2)^{1/2} & u^2 + v^2 \leq \lambda^{-2} \\ 0 & \text{otherwise} \end{cases}
\]

However, the small sampling pitch leads to strong diffusion of the light field; i.e. the light field difuses beyond the borders of the computation window in the output plane. In other words, the SBP of the hologram is not supported by the AS propagation due to the too low bandwidth in the Fourier domain \(^\text{18}\). Moreover, aperiodic functions such as \(g(x, y, z)\) and \(h(x, y, z)\) cause errors at the edges of the computation window. More specifically,

**Figure 1.** Holographic system of the horizontal parallax only CGH method for point clouds with multiple wavefront recording planes
the convolution with the transfer function using the Fast Fourier Transform (FFT) is a circular convolution which only behaves properly for periodic functions. As a result, the bandwidth of the propagation field has to be limited such that the Nyquist sampling bound is respected.

This is achieved by the band-limited angular spectrum method (BL-ASM)\(^{17}\). In this case, in the convolution of Eq. (5) the propagation kernel is given by:

\[
H'(u, v; z) = H(u, v; z) \text{rect}\left(\frac{u}{2u_{\text{limit}}}, \frac{v}{2v_{\text{limit}}}\right)
\]

where, \(2u_{\text{limit}}\) and \(2v_{\text{limit}}\) are the bandwidth that the transfer function must be clipped in. However in practice, the area of the calculation window in the source plane is doubled and the additional sampling points in the source plane are padded as zeros. After the calculation, the output window is cropped to the original window size at the destination plane. BL-ASM is used for all the wave field propagations during the CGH computation, i.e. LUT generation and inter-WRP propagations, as well as during reconstruction.

To acquire colour holograms, the points of the point cloud are attributed a texture consisting of three intensity values for the Red, Green and Blue channels to maintain the colour information of the 3D model. The final hologram – and the WRPs – consist of the three channels all computed for the same wavelength i.e. red, to maintain the wide viewing angle for all channels, but with 3 different intensities per point to each corresponding channel.

3. RENDERING FRAMEWORK

Multiview screens often require to be provided with the reconstruction images for all supported viewing angles, to render the 3D content. As such, to display a hologram on an autostereoscopic display, several pre-processing steps are required. The framework for rendering holograms on autostereoscopic displays, proposed in this paper, is depicted in the block diagram of Fig. 2. It consists of four steps that are applied to the hologram to acquire the set of reconstruction images that correspond to the views from a camera rotating around the scene. The resolution of these images is normally equal to the 2D resolution of the screen.

![Block diagram of the proposed framework for three-dimensional rendering of holograms on light field displays](image)

More specifically, to acquire each view per colour channel, we perform the following pre-processing steps:

1. **View extraction**
   To extract the different views from the hologram, a window with the resolution of the vertical axis of the hologram moves along the horizontal axis to acquire the sub-holograms that simulate a pinhole camera view. The apertures extracted can be chosen densely enough to overlap, since increasing the number of views improves the final rendering. However, the FOV targeted is also crucial for the number of views chosen, since bigger FOVs require more views and increased computational complexity. This step is illustrated in Fig. 3(b).

2. **Suppression of aperture diffraction**
   The extracted aperture from the hologram can produce aperture diffraction during numerical reconstruction, due to the sharp intensity edges of the rectangular aperture, therefore apodization is proposed\(^{19,16}\). This method smoothly brings the aperture edges to zero, as it suppresses side lobes leakage which would otherwise be produced upon propagation. On the other hand, a decrease in resolution may appear due to
the limited signal area. To apply the aperture apodization we use a 1D Hanning window function, which is expressed by:

$$h_n(x) = \cos^2 \left( \frac{\pi x}{2\alpha} \right)$$

where, $\alpha$ is the full width at half maximum (FWHM). An example of this step is depicted in Fig. 3(c).

3. Back propagation

The apodised aperture is zero padded to the size of the hologram, to represent the hologram from that viewing position and it is back propagated with BL-ASM (see Sec. 2) to reconstruct the hologram for the corresponding view. To visualise the reconstructed object from this view, the magnitude i.e. the square root of the intensity, matching the gamma curves for displays, of the complex wavefield computed by the back propagation is extracted and stored as a 2D image.

4. Colour balancing

However, the intensities at the three different colour channels can vary, and extremely high values can still appear due to constructive interference phenomena at some pixels that are inherent to diffraction. Therefore to create a balanced RGB image for the reconstructed view, first percentile clipping is applied, to suppress the high intensity outliers. The maximum intensity $I_{max}$ per colour channel is given by the maximum intensity value after clipping the higher values that belong to the high 0.15 percentile. Subsequently, the intensity range is modified by histogram stretching, based on the following principle:

$$I(x, y) = \frac{I(x, y) - I_{min}}{I_{max} - I_{min}}$$

where, $I_{min}$ and $I_{max}$ are the minimum and maximum value of the intensity. The effect of this step is depicted in Fig. 4.
The proposed framework can be integrated in autostereoscopic displays to support visualisation of holograms. The rendering can be performed in real-time by exploiting GPU parallel computing and raster OpenGL graphics.

4. RESULTS

For the creation of our 3D scenes, we employed 4 different point clouds and four 2D images as backgrounds in our experiments. The scenes used for this work are shown in Fig. 5. The simulations ran in MATLAB code on a computer with a 3.3 GHz Intel Core i7-5820 CPU processor and Windows 8 (x64) as operating system.

![Figure 5. Scenes captured by our CGH method, each consisting of a point cloud and a 2D background (a) Earth - 306,372 points (b) Venus - 267,251 points (c) Dice - 142,903 points and (d) Skater - 84,095 points.](image)

To demonstrate the proposed framework for high-end 3D visualization of holograms on autostereoscopic displays, we made use of an Holografika HoloVizio 722RC light field display, which allows display with a viewing angle support of 70°. The display is an instance of a scalable light field system design based on a specially arranged array of 72 projectors and a screen.

For each hologram, 70 views were extracted to support the 70° angle with an angular resolution of 1° while each view has a 2D resolution of 1280-by-768 pixels. For all the reconstructions of this work the camera is focusing at the front part of the object. Figure 6 shows the numerical reconstruction of the hologram from dataset Dice, generated as described in Sec. 2, from 3 different viewing angles. It is important to notice that the occlusion handling is correct and not depicting artifacts related to self-occlusion, background and inter-object occlusion. Figure 7 depicts pictures taken from the HoloVizio screen at the same angles for the four holograms rendered with the proposed framework. Additionally, a video demonstrating the rendered holograms on the screen from different viewing angles can be viewed at [http://www.erc-interfere.eu/downloads.html#Framework](http://www.erc-interfere.eu/downloads.html#Framework).

The performance of the framework regarding computational requirements is not high since the main component is the back propagation which requires only 1D FFTs, with pre-computed kernel, due to the same distance. Table 1 shows the computational complexity and the computation time of the framework per processing step, thus, the computational complexity of the framework is $O(NM)$.

![Figure 6. Numerical reconstructions from the CGH Dice from different viewing angles (a) -35 degrees (b) 0 degrees and (c) +35 degrees](image)
Figure 7. Rendered CGHs from the 4 tested datasets. The views shown are taken in front of the multiview screen with a photographic camera from 3 different viewpoints. (a) -35 degrees (b) 0 degrees and (c) +35 degrees.

Table 1. Computational complexity of the proposed framework for $V$ views for a hologram with M-by-N resolution

<table>
<thead>
<tr>
<th>Step</th>
<th>Complexity</th>
<th>Computation time per view [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. View extraction</td>
<td>$\mathcal{O}(N^2)$</td>
<td>0.04</td>
</tr>
<tr>
<td>2. Suppression of aperture diffraction</td>
<td>$\mathcal{O}(N^2)$</td>
<td>0.38</td>
</tr>
<tr>
<td>3. Back propagation</td>
<td>$O(M \log_2 2M) + \mathcal{O}(NM)$</td>
<td>16.33</td>
</tr>
<tr>
<td>4. Colour balancing</td>
<td>$\mathcal{O}(NM)$</td>
<td>1.19</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

In this work, we have proposed a three-dimensional rendering framework for colour holograms. The holograms are calculated from point clouds and displayed on an autostereoscopic screen to facilitate the evaluation of CGH methods and the 3D perception of rendered holograms.

In addition, an extension of our previous work on a computer-generated holography technique is presented. This method uses multiple parallel wavefront recording planes and pre-computed look-up tables and includes an occlusion processing technique. The method was adapted for horizontal parallax only holograms to decrease computational needs and to allow for higher resolution by computing one hololine instead of 2D wavefields per point.

The framework proposed includes 4 preprocessing steps: (1) view extraction from the hologram, (2) suppression of the aperture diffraction (3) back propagation of the sub-hologram and (4) colour balancing of the three colour channels. The generated images serve as input for the multiple projectors of the autostereoscopic display and allow for display with 3D effect and wide viewing angle.

We report that high quality visualisation with horizontal parallax only and a FOV of 70° was achieved. It was shown that the technological limitations of current holographic displays can be bypassed by simulating the display of holographic content on light field displays. Validation of our CGH method was achieved, regarding occlusion handling and depth disparity. Additionally, this paper demonstrates a 3D rendering pipeline that deploys point cloud, holographic representations and rendering on light field displays.

ACKNOWLEDGMENTS

We would like to thank Geert Braeckman and Jan Hanca for their assistance with the multiview lightfield display. The models of Earth and Skater are courtesy of Joerg Schmit from GrabCad.com and Miniature 3D from Sketchfab.com, respectively. The research leading to these results has received funding from the European Research Council under the European Unions Seventh Framework Programme (FP7/2007-2013)/ERC Grant Agreement n.617779 (INTERFERE).

REFERENCES