Speckle noise reduction for computer generated holograms of objects with diffuse surfaces

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ABSTRACT

Digital holography is mainly used today for metrology and microscopic imaging and is emerging as an important potential technology for future holographic television. To generate the holographic content, computer-generated holography (CGH) techniques convert geometric descriptions of a 3D scene content. To model different surface types, an accurate model of light propagation has to be considered, including for example, specular and diffuse reflection. In previous work, we proposed a fast CGH method for point cloud data using multiple wavefront recording planes, look-up tables (LUTs) and occlusion processing. This work extends our method to account for diffuse reflections, enabling rendering of deep 3D scenes in high resolution with wide viewing angle support. This is achieved by modifying the spectral response of the light propagation kernels contained by the look-up tables. However, holograms encoding diffuse reflective surfaces depict significant amounts of speckle noise, a problem inherent to holography. Hence, techniques to improve the reduce speckle noise are evaluated in this paper. Moreover, we propose as well a technique to suppress the aperture diffraction during numerical, view-dependent rendering by apodizing the hologram. Results are compared visually and in terms of their respective computational efficiency. The experiments show that by modelling diffuse reflection in the LUTs, a more realistic yet computationally efficient framework for generating high-resolution CGH is achieved.

Keywords: Computer generated holograms, CGH, holography, speckle, diffuse reflection, speckle noise reduction, look-up table

1. INTRODUCTION

Holography is a technique to record and reconstruct the complex-valued wave field of light (both amplitude and phase) by means of diffraction and interference phenomena, thereby enabling high resolution 3D visualisation. The physical process of light propagation can be modelled and simulated on a computer, facilitating the generation of computer generated holograms (CGHs). CGHs have the advantage that they eliminate the need for a physical holographic recording set-up; therefore, they are not subject to noise or optical aberrations during the recording phase, and moreover they allow the representation of synthetic objects. Holograms can be calculated from various input modalities such as multi-camera setups, light field cameras, point clouds and mesh models. The latter two can be generated from regular input images or video, LiDAR scanners or via computer graphics. In this paper, we will focus on point cloud data.

A high-end CGH system should account for all surface properties of the scene’s objects, ideally accounting for the complete bidirectional reflectance distribution function (BRDF) of the surface, including – for example – colour-dependent light distributions. However, in this paper we limit the calculation to monochromatic holograms of diffuse objects. In a classical Mach-Zender capturing set-up, diffuse holograms are typically acquired either by diffuse illumination – i.e. the object beam passes through a diffuser – or by recording the wave field of objects with diffuse surfaces. Diffuse materials have typically rough surfaces (e.g. cloth, sand, etc.) and they scatter light over a wide angular range. Hence, the use of diffuse illumination in optical holography is analogous to introducing uniformly distributed random phase in digital holography. Specular surfaces (e.g. glossy surfaces, mirrors, glass)
are very reflective, and tend to reflect the light with a narrow angular distribution. An inherent property of holography is speckle noise, especially for small apertures. Speckle noise is an interference phenomenon that appears when the holographic signal that is composed of multiple additive complex components with independent amplitude and phase, is reconstructed using a coherent light source [1]. The contrast of the speckle pattern depends on the coherence properties of the incident light. As we reduce the spatial or temporal light coherence, i.e. increasing the diffusive properties of the light source, the contrast of the speckle pattern will decrease.

Several speckle noise reduction techniques have been proposed for digital holography. Most of these techniques aim to decrease the temporal or spatial coherence of the reconstructed hologram. The temporal coherence can be reduced using wavelength-multiplexing and time-multiplexing of several reconstructed images [2–3], or iterative methods using phase retrieval algorithms based on the iterative Fresnel ping-pong two-plane algorithm [4] or the Gerchberg-Saxton algorithm [5]. Other approaches include digital processing by subsampling and median filtering [6] and 3D Gaussian filtering [7]. Lately, point-based techniques using ray-sampling plane [8] and angular diversity [9] were proposed, while random-phase free methods are also investigated [10], where the object light is multiplied with the virtual convergence light. Speckle noise suppression has also been attempted in the context of compressive holography based on the assumption that the incoherent scattering density of a diffuse object is sparse in some basis [11].

In our prior work [12], a fast CGH method handling occlusion processing has been proposed for point cloud data. The method uses pre-computed look-up tables and multiple parallel wavefront recording planes (WRPs). This paper extends the method to account for diffuse reflections by modifying the spectral response of the look-up table content. Moreover, various speckle noise reduction techniques are integrated in the forward propagation model and a comparative, experimental evaluation is provided.

This paper is structured as follows. In Sec. 2, we briefly explain the CGH method used and detail the adaptations required to support diffuse reflection. Subsequently, in Sec. 3 details on the holographic setup and datasets used in this paper. Section 4 discusses the examined speckle noise reduction techniques and reports the results of our experiments. The methodology and results of the suppression of aperture diffraction by apodization of the hologram are reported in Sec. 5. Finally, we provide summarising conclusions.

2. CGH METHOD WITH MULTIPLE LOOK-UP TABLES

Computer generated holograms can be generated by many methods and from various sources. In this paper we utilise a fast CGH method proposed in our prior work, which is based on the wavefront recording plane method [13]. The concept of the method is illustrated in Fig. 1 and we refer to Ref. 12 for more details.

This method calculates the local hologram based on the points within a fixed sized neighbourhood of a WRP, i.e. \( \pm \frac{1}{2} \) the distance between two successive WRPs. 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. Inverted Gaussian filters are used in the propagation process to model occlusions by locally blocking light. 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. The planar Gaussian distribution in a particular depth plane is given by the formula:

\[
g(x, y) = \exp \left( -\frac{x^2 + y^2}{2\sigma^2} \right)
\]

where, \( \sigma^2 \) is the variance of the distribution (\( \sigma \) is the standard deviation). By changing the value of \( \sigma \), the smoothness of the surface patch can be tuned. For \( \sigma \to 0 \), we approximate a Dirac delta function, which corresponds to dimensionless points. To calculate the inter-WRP light propagation, pre-computed propagation kernels – stored as well in LUTs – are deployed.

The intra-WRP and inter-WRP light propagations are calculated using the angular spectrum method (ASM) [14], which is a convolution-based diffraction method defined by:

\[
u_2(x_2, y_2) = \mathcal{F}^{-1} \left[ \mathcal{F}[u_1(x_1, y_1)] \cdot \exp \left( -2\pi iz\sqrt{1/\lambda^2 - \omega_x^2 - \omega_y^2} \right) \right]
\]

(2)
where $\mathcal{F}$ and $\mathcal{F}^{-1}$ are the Fourier and inverse Fourier operators, $u_1(x_1, y_1)$ and $u_2(x_2, y_2)$ are the source and destination planes with their corresponding coordinates $x_1, y_1$ and $x_2, y_2$ respectively, $z$ is the distance between them and $\omega_x, \omega_y$ are the spatial frequencies of $x_1, y_1$ in the Fourier domain. This propagation method provides the advantage of maintaining the sampling rate on both planes and being suitable for small distance propagation, contrary to other methods such as discrete Fresnel transforms [15]. This gives the advantage of reusing LUTs for all WRPs.

To simulate a surface with a diffuse reflection, the Gaussian profile of the points (1) will be modulated by a random phase factor $\exp(ip(x, y))$, where $p(x, y)$ represents the uniform random phase distribution between 0 and $2\pi$. This results in a near-uniform spectral response, i.e. light is reflected in a diffuse or wide angle manner. Hence, the calculated propagation kernels in the LUT for each (quantized) depth are modulated with this random phase pattern:

$$g(x, y) = \exp\left( -\frac{x^2 + y^2}{2\sigma^2} + ip(x, y) \right)$$

(3)

Nonetheless, using pre-calculated intra-WRP and inter-WRP LUT can give rise to artifacts as the same (randomized) pattern will be reutilized for all points across the WRP, creating spurious frequencies which will degrade the visual quality. Measures to counteract this drawback will be investigated in Sec. 4.1.

3. GENERATION OF HOLOGRAPHIC TEST DATA

To generate full parallax holograms with a wide field of view, high resolution holograms with a small pixel pitch are required, according to the grating equation given by [16]:

$$\sin \theta = \frac{\lambda}{2p}$$

(4)

where $\theta$ is the maximum angle of diffraction, $\lambda$ is the wavelength and $p$ is the sampling pitch. The minimum distance between object and 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.

The CGH resolution for all our experiments is 8,192-by-8,192 pixels, the pixel pitch is 1 \( \mu \text{m} \) and the wavelength of the reference beam is 633 nm. Applying Eqs. (4) and (5) for these parameters, results in holograms with a FOV angle of 36.9\(^\circ\) and a minimum distance of 12.9 mm between the object and hologram plane.

We employed 6 different point clouds in our experiments (see Table 1). Figure 2 shows the numerical reconstructions from all the datasets. The CGHs were generated by using 64 LUTs and the images show the right view of the reconstructed objects. The simulations ran in MATLAB code on a computer with a 2.10 GHz Intel Core i7-4600U CPU processor and Windows 8.1 (x64) as operating system.

Table 1. Dataset parameters and simulation results for all experiments

<table>
<thead>
<tr>
<th>Point model</th>
<th>Number of points</th>
<th>Computation time [s]</th>
<th>Number of WRPs</th>
<th>Occlusion mask size (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat(^{17})</td>
<td>27,894</td>
<td>54</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>Earth</td>
<td>50,393</td>
<td>270</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Venus(^{18})</td>
<td>80,589</td>
<td>205</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Chess pieces</td>
<td>185,188</td>
<td>527</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>Perforated Ball</td>
<td>218,640</td>
<td>54</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Dragon(^{19})</td>
<td>3,609,455</td>
<td>1,058</td>
<td>30</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 2. Numerical reconstruction results of the right view of holograms generated from (a) Perforated ball, (b) Dragon, (c) Venus, (d) Cat, (e) Chess pieces and (f) Earth, with focus at the front part of the objects, showing occlusion effect and full parallax with an aperture of 2,048 pixels. Video 1 http://dx.doi.org/doi.number.goes.here
Figure 3. Numerical reconstruction results when viewing from (a) left, (b) right, (c) top and (d) bottom, with focus at the objects at the back, demonstrating the occlusion effect and full parallax with an aperture of 2,048 pixels.

The full parallax properties of the CGHs and correct handling of occlusions can be demonstrated by reconstructing the holograms from different viewing angles. In Fig. 3 this is illustrated for the 3D scene “Chess pieces” by selecting sub-holograms with a window aperture of 2,048-by-2,048 pixels from the hologram plane. The front objects (3 pawns) are positioned at a distance of 14 mm from the hologram plane, while the back objects (horse, king, queen, bishop) are positioned at 16 mm from the hologram plane. The depth of each chess piece is 1 mm. Additionally, we have also illustrated the parallax by depicting several numerical reconstructions at different viewing angles of the hologram generated from the dataset “Earth” (Video 1 in Fig. 2).

In the following sections, we will propose techniques to further improve the quality of the holograms by examining speckle reduction techniques, both during the CGH generation and later on as a post-processing step. Secondly, we address the suppression of aperture diffraction during numerical reconstruction by apodizing the hologram.

4. SPECKLE NOISE REDUCTION TECHNIQUES

4.1 Different number of random LUTs

In the ideal case of generating CGH with an exhaustive ray-tracing approach, each model point has a random phase and an individual propagation contribution to the hologram. In the CGH method described above, reuse of the same propagation kernels from the LUTs can cause constructive and destructive interference phenomena at the hologram plane, resulting in speckle noise artifacts. To demonstrate the effect on the quality of the reconstructed image, we experimented with the number of LUTs deployed. If the number of LUTs is too low, the repeating patterns will introduce spurious frequency content in the hologram.
For this experiment, we generated several holograms with the exact same settings, but used 1, 2, 4, 8, 16, 32, 64, 128 or 256 LUTs. Each LUT was calculated by modulating the Gaussian profile with a random phase factor (see Eq. 3), and then propagated it to the depth levels of the WRP, forward and backward with angular spectrum propagation. Figure 4 shows a zoomed view of the numerical reconstruction of the top sub-holograms of 4 holograms generated using 1 and 64 LUTs, respectively. The focus depth is at the level of the chess pieces in the back. The reconstructed images have a resolution of 2,600 by 1,300 pixels. The region of interest (ROI) indicated by the red square demonstrates the more detailed reconstruction acquired by using more LUTs. We report a small improvement of the reconstructed images with increasing number of LUTs without an extra computational burden, since the computation of the LUTs is done prior to the main CGH generation. The advantage of this method is that the speckle noise reduction is inherent to the CGH generation. On the other hand, the improvement is not sufficient to compensate for the increase of the memory requirements related to the storage of the extra LUTs.

### 4.2 Time-multiplexing of multiple holograms

Another approach to improve the reconstruction and to eliminate coherence artifacts, proposed in [3], is simulating the time-multiplexing of holograms. We simulate the capturing of multiple holograms by calculating the same CGH several times (using random phase modulation). For the reconstruction, multiple reconstructed images from all CGHs are superposed by averaging their intensities.

While, in the context of digital holography capturing up to 100 holograms is proposed, we generated 10 CGHs, and additive reconstructions of 1 up to 10 holograms were tested, to validate the rendering improvement. Taking into consideration the computational burden for the generation of holograms, which in this case is 54 seconds per hologram, the number of holograms superposed has to be fairly small, although the image quality improves with increasing number of holograms. In general, the computation time is \( \alpha N + \beta N \), where \( \alpha \) is the time required for one hologram, \( \beta \) is the time required for a reconstruction and \( N \) is the number of holograms. The second row of Fig. 5 shows the reconstruction of 10 holograms. The reconstruction depths are 14.7 mm and 19.2 mm from the hologram plane, corresponding to the head and the tail of the cat, respectively.

### 4.3 Superposition of reconstruction of multiple wavelength holograms

Following the previous approach, one can suppose that for more incoherence, capturing holograms with different wavelengths and reconstructing them with their corresponding reference light beam, could have the same effect as the method described above. In [20], a method to reduce speckle by superposition of the reconstructed images of holograms recorded at multiple wavelengths was proposed.

To validate this method, we simulated 5 sets of holograms from the same scene, each set consisting of 3 holograms captured with different wavelengths and then we superposed their reconstructions per set. The wavelengths in each set were in a small range of 1-20 nm while one set consisted of the wavelengths of red, green
and blue light. In [20], compensation of the pixel values for the varying wavelength was necessary such that the resolution of the reconstructed image remained independent from the wavelength. Our method exploits angular spectrum propagation, which maintains pixel pitch independently from the chosen wavelength. Therefore, no pixel compensation is required.

The best results were obtained by superposition of the reconstructed holograms rendered with the following wavelengths $\lambda$: 633, 532 and 460 nm. The reconstructed image is shown in the third row of Fig. 5. The computation efficiency of this method is $3(\alpha+\beta)$. Additionally, the results suggest that with multiple wavelength holograms, not only a colour hologram can be acquired by generating the three colour channels, but also speckle noise reduction is achieved by averaging the reconstructions at the same time. However, the superiority of this wavelength set was expected, since the blue wavelength is twice as short as red light, therefore about 4 times as much bandwidth of the object is being captured compared to the red hologram.

Figure 5. Comparative image of reconstructions of the left (1st and 3rd columns) and right sub-holograms (2nd and 4th columns) with focus at the depth of the head and the tail of the cat demonstrating the results from the speckle noise reduction techniques investigated. Images (a)-(d) show the full object, while the rest show only the area in focus zoomed. The images are numerical reconstructions of: (e)-(h) time-multiplexing of 10 same holograms using 64 LUTs, (i)-(l) superposition of 3 reconstructions from 3 holograms with red, green and blue wavelengths using 8 LUTs), and (m)-(p) 1 hologram reconstructed with incoherent light using 1 LUT.
4.4 Reconstruction with incoherent light

A simpler and computationally more efficient approach – applied also in digital holography – is to use only one CGH and to eliminate the coherence artifacts by simulating reconstruction with partially coherent light. For this experiment, we reconstructed the same hologram with 3 wavelengths. 5 sets of 3 wavelengths were tested deviating 0.1-5.0 nm from the wavelength of the reference beam.

The best results were acquired by averaging the 3 reconstructed images of the hologram with the following wavelengths: 633, 632.9 and 633.1 nm. The reconstructed image is shown in the last row of Fig. 5. This method has the advantage of using only one hologram, thus creating less computational burden than the previous methods – i.e $\alpha + 3\beta$, but it suppresses less the speckle noise and gives the worst visual results compared to the two methods above.

5. SUPPRESSING APERTURE DIFFRACTION BY APODIZATION OF THE HOLOGRAM

To reduce the aperture diffraction during numerical reconstruction, it is proposed [21-22] to apodize the hologram aperture. This method is applied to smoothly bring a sampled signal down to zero at the edges of the sampled region. This suppresses side lobes leakage which would otherwise be produced upon propagation, at expense of a decrease in resolution.

In this work, for aperture apodization we use a 2D Hanning window function, which is expressed by:

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

where, $\alpha$ is the full width at half maximum (FWHM). Hence, to visualise the different views on a 3D display, an aperture (sub-hologram) has to be extracted from the hologram, and to avoid sharp intensity edges, the aperture is apodized by a Hanning window function. Then, this apodized hologram is back propagated to reconstruct the image from the corresponding view.

Figure 6 shows the results of the numerically reconstructed holograms from apodized apertures. Comparative reconstructions of the right sub-hologram with focus at the depth of the head of the cat (first row) and with focus at the tail of the cat (second row) are shown. The results demonstrate the improvement of the quality of the reconstructed images when deploying apodized apertures.

6. CONCLUSIONS

In this work, we present a CGH method which uses multiple parallel wavefront recording planes and pre-computed look-up tables and includes an occlusion processing technique for generating holograms from objects with diffuse surfaces. It is an extension of our previous work, adapted to account for diffuse reflection by modifying the spectral response of the look-up table propagation kernels. High quality reconstructions with full parallax and a FOV of 36.9° were acquired and techniques to suppress the speckle noise and further improve the reconstructions were investigated.

It was shown that with multiple LUTs a better approximation of diffusiveness is acquired by adding a random phase factor to the Gaussian LUT entries and maximising incoherence during the CGH generation. Moreover, a comparative investigation of speckle noise reduction techniques for computer generated holography has been reported addressing both visual quality and computational efficiency. Time-multiplexing of multiple holograms delivered the best reconstruction quality, but is computationally the most demanding. Superposition of reconstructions of multiple wavelength holograms gives satisfactory visual improvement with a lower computational cost, and shows promising properties for colour CGH. Reconstruction with incoherent light is very practical and efficient for computations, but showed the worst performance in terms of visual quality.

Finally, suppressing the aperture diffraction by apodization of the hologram with a Hanning window showed an improvement of the quality of the reconstructed images when applied to a CGH. Significant improvement of the visual quality was achieved when combined with one of the methods proposed above, especially time-multiplexing.
Figure 6. Comparative image of reconstructions of the right sub-hologram with focus at the depth of the head of the cat (first row) and with focus at the tail of the cat (second row) using speckle noise reduction techniques and suppression of aperture diffraction. The images are numerical reconstructions of: (a) and (f) a CGH by 64 LUTs, (b) and (g) a CGH by 1 LUT, (c),(h) a CGH by 1 LUT with suppression of aperture diffraction, (d) and (i) 10 same CGHs with superposition, (e) and (j) 10 same CGHs with superposition and suppression of aperture diffraction.

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