Phase-only encoding of wide-angle 3D computer generated hologram

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Abstract—Wide-angle capability is essential for holographic near-eye displays. Most of these employ phase-only spatial light modulators, so CGH must be encoded as phase-only holograms (PoHs). Thus, this paper investigates three known encoding methods: double phase hologram (DPH), direct phase only hologram (D-PoH), and complex amplitude modulation (CAM). To determine the most optimal phased-encoding method, we evaluate them by field of view, image quality, and diffraction efficiency. It was found that CAM gives very low brightness and quality; thus, improvement of the CAM is proposed. Also, we conclude that D-PoH is the optimal method for the wide-angle case.

Holographic displays are considered one of the most suitable technologies for the human visual system, particularly in the context of holographic near-eye display (HNED) systems. Like other 3D display techniques, they can deliver high-quality images across a wide field of view (FoV). However, unlike other methods, holographic displays reproduce 3D images with correct focus cues. This advantage is reflected in the diffraction imaging principle when reproducing objects. HNEDs are devices that project 3D images directly to the observer's eyes. Human eyes are very challenging; they require projections in a wide field of view (FoV), encompassing central (60°) and peripheral (120°) vision [1]. Thus, HNEDs must generate a wide-angle image that meets human eyes' expectations. In holographic displays, images are mainly created digitally using CGH algorithms that represent 3D objects using phase and amplitude signals. Such CGHs can be reconstructed on a holographic display by modulating the encoded 3D image using spatial light modulators (SLMs).

Most holographic displays employ phase-only SLMs because of their high diffraction efficiency and high-quality imaging. Therefore, the CGH must be encoded as a phase-only hologram (PoH). The simplest approach is to take the phase of the complex CGH H, which can be described as $exp(iARG(H))$, where $ARG(Z)$ is the argument of Z. This approach is referred to as direct PoH (D-PoH). More advanced techniques are applying cyclic diffraction computations [2–4]. A popular solution is to use iterative algorithms such as the Gerchberg-Saxton (GS) algorithm [2], which produces high-quality images with low noise, but at the cost of long computations. The error diffusion algorithms achieve a low noise level and relatively high computational speed; however, these algorithms are limited by image sharpness [3]. The most advanced and promising PoH CGH algorithms are based on learning architectures [4]; these solutions can be fast and generate high-quality, noise-free reconstructions. However, the solutions based on cyclic diffraction calculations cannot be used in wide-angle displays because they require fast diffraction calculations that are not available.

The computational problem can be alleviated by using single-step methods such as double phase hologram (DPH) [5,6] and the complex amplitude modulation (CAM) [7]. In the DHP, the two complementary phase wave fields are calculated and superposed into a 2×2 or 4×4 chessboard pattern to obtain PoH. CAM algorithm employs phase coding as the cosine function, where the proper image information is contained in the +1-diffraction order. DPH and CAM holograms require a spatial filter at the Fourier plane of a 4f setup. For a wide-angle display, FoV is proportional to the bandwidth of the reconstructed CGH. Thus, a smaller filter means a smaller FoV.

This paper investigates known methods for PoH encoding of wide-angle CGH of 3D objects: D-PoH, DPH, and CAM. Three parameters are analyzed: FoV size, image quality, and diffraction efficiency, to find the optimal phased-encoding solution for wide-angles. We show that, for the wide-angle case, DPH provides the highest diffraction efficiency, but with the smallest FoV. In contrast, direct CAM gives very low brightness and quality; thus, an improvement is proposed called BE-CAM. This modification allows for a trade-off between these two metrics. With BE-CAM, achieving the highest image quality at the expense of diffraction efficiency is possible. In contrast, at the current state of the art, considering image size, image quality, and diffraction efficiency, reconstruction from the D-PoH CGH is the optimal encoding method for hologram generation at a wide angle.

FoV is an important device parameter as it defines the maximum image size. Typically, the FoV of an HNED device, which is illustrated in Fig. 1, is limited by the hologram's pixel spacing Δ at the eyebox. For the plane reference wave system, the FoV is given as:

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$$FoV = 2sin^{-1}\left(\frac{\lambda}{2\Delta}\right), \quad (1)$$

where λ is a wavelength used. Thus, for wide-angle systems, small pixel is required. However, such FoV is only achievable if the SLM can modulate the phase and amplitude, while the SLMs only allow phase modulation. Hence, CAM methods encode the amplitude-phase hologram with a phase hologram. There are two known solutions DPH and CAM. Both require a 4F system and a filter in the Fourier plane. Using a filter reduces the bandwidth of the hologram at the eyebox. In the DPH, the filter decreases the bandwidth by a factor of four in both directions [6], which reduces the FoV by two or four. CAM allows the use of a larger filter. This filter reduces the bandwidth in one direction by two; in the other, the filter passes the full bandwidth. Consequently, the FoV decreases by two in one direction only.

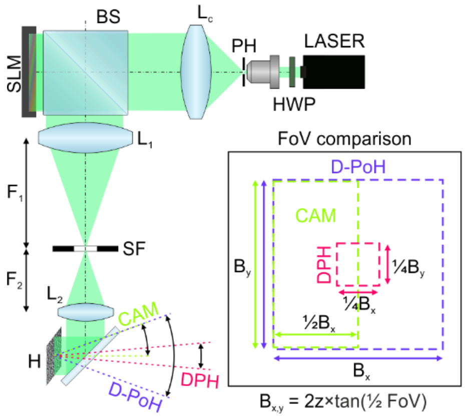

Fig. 1. HNED diagram: SLM pixel 3.45 µm, F_1 = 200 mm, F_2 = 21 mm.

For the display system presented in Fig. 1, the CGH was generated using the Frequency Domain Method [8] and reconstructed with [9]. The HNED has parameters: λ = 520 nm, F_1 = 200 mm, F_2 = 21 mm, pixel size Δ = 0.393 µm and resolution 4160 × 2464, FoV = 83°. CGH was generated for the 3D model of a 74-gun Bellona-class third-rate ship of the line of the Royal Navy. The 3D object was resized to fit the FoV. The objects have dimensions: 1.26 m (height) × 1.58 m (width) × 0.58 m (depth) and 10 million points, respectively. The object is about z = 0.75 m from the observer.

Figure 2 compares D-PoH, CAM, and DPH for FoV evaluation. As mentioned, CAM and DPH reduce the bandwidth of the hologram. Figure 2(a) shows that D-PoH enables full-field imaging, providing a significant advantage over CAM (Fig. 2(b)) and DPH (Fig. 2(c) and (d)). CAM reduces the image size to half for the *x*-direction, while DPH reduces it to half or quarters for *x* and *y*.

Besides the FoV, image quality and brightness are equally important display parameters. To quantify brightness, we use the diffraction efficiency:

$$\eta = \sum_{i=1}^{n} a_m^2(x_i, y_i) \Big/ \sum_{i=1}^{n} a_p^2(x_i, y_i), \quad (2)$$

where $a_m(x, y)$ and $a_p(x, y)$ are respectively the amplitudes of reconstructions using evaluated method and D-PoH. Therefore D-PoH is a reference method, thus η = 1. The PSNR and SSIM were selected to assess the image quality, which were determined for the image shown in Fig. 2 and the area of the dashed rectangle. The PSNR and SSIM were calculated using Matlab. For simulation of the experimental SLM, all simulations are performed for phase quantization with 8-bit depth of phase levels. Both metrics require a reference image without noise. For this purpose, an amplitude-phase hologram was used.

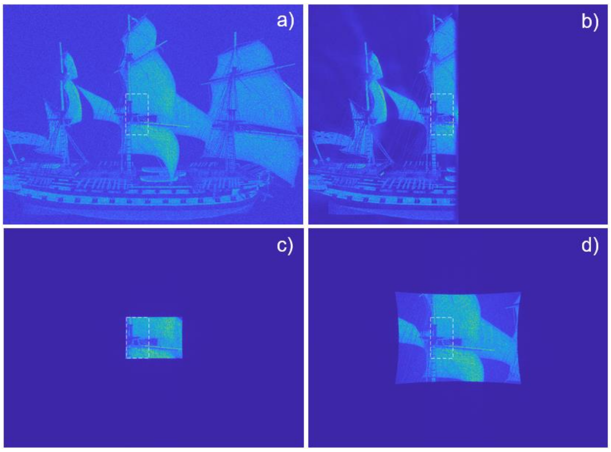

Fig. 2. FoV evaluation for different methods: D-PoH (a), CAM (b), DPH with 4×4 chessboard pattern (c), DPH with 2×2 chessboard pattern (d). Highlighted areas show zoomed fragments of the ship (Fig. 5).

PSNR and SSIM as a function of diffraction efficiency are shown in Fig. 3. For DPH, there are two points, one with higher diffraction efficiency and SSIM and PSNR. This point corresponds to the small FoV case shown in Fig. 2(c). For this case, the SSIM and PSNR are slightly larger, e.g., the PSNR increases by 0.4 dB. However, the image is much brighter, i.e., by a factor of 0.8. Considering the result for the D-PoH method, it can be seen that the quality (PSNR = 26.28; SSIM = 0.86) is comparable to the DPH method, and the image brightness is not much lower compared to DPH with a larger FoV (Fig. 2d).

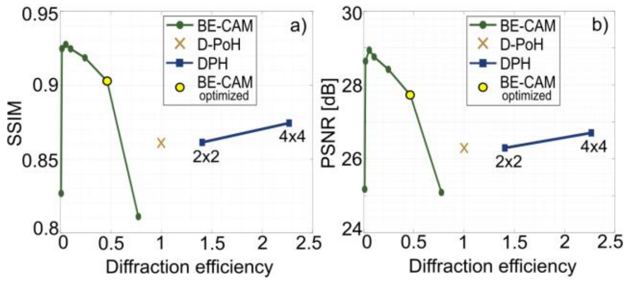

Fig. 3. SSIM (a) and PSNR (b) as a function of diffraction efficiency.

Direct use of CAM leads to results with very low diffraction efficiency η = 0.009 and poor quality (PSNR = 25.18; SSIM = 0.83). This is due to the very narrow dynamic range of CGH obtained via CAM. CGH is encoded using only three phase levels out of 256 available, as shown in the histogram in Fig. 4(a). Therefore, a modification called BE-CAM (Brightness Enhanced CAM) is proposed, which broadens the histogram to increase the number of phase levels of the encoded hologram and, as a result, to improve the information distribution. Figure 4(a) shows a histogram obtained by CAM, while Figure 4(b) shows an expanded histogram of BE-CAM. BE-CAM is essential because the experimental reconstruction with CAM was not visible without it. The graph in Fig. 3 was obtained when the histogram was gradually expanded. The initial expansion of the histogram led to a fast increase in quality. Once the maximum was reached, further expansion improved performance but resulted in a noticeable drop in quality. As shown in Fig. 3, this final point marks the diffraction efficiency limit. Due to the relatively low quality for this case, an optimum with slightly lower diffraction efficiency but still high quality (PSNR = 27.73; SSIM = 0.9) was chosen. Figure 4 compares the initial histogram obtained for CAM and the optimized BE-CAM. Note that in the maximum SSIM case, BE-CAM is optimized for the highest image quality.

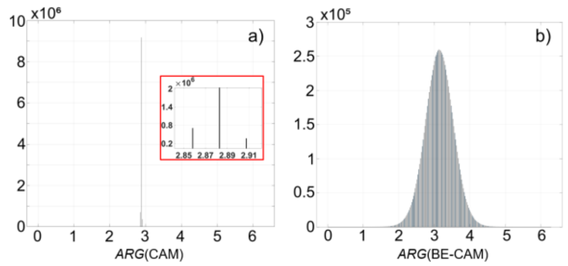

Fig. 4. Direct CAM (a) and optimized BE-CAM (b) histograms. The histogram has 256 bins, which is the number of phase levels of SLM.

Figure 5 visually compares the results obtained with the coding methods investigated. Figure 5(a) shows the reconstruction using the complex amplitude signal used in this article as a reference noise-free image. Images 5(b) and 5(c) correspond to the DPH. The former offers higher diffraction efficiency (η = 2.27) and quality but small FoV, while the latter has increased FoV but reduced brightness (η = 1.41), PSNR, and SSIM.

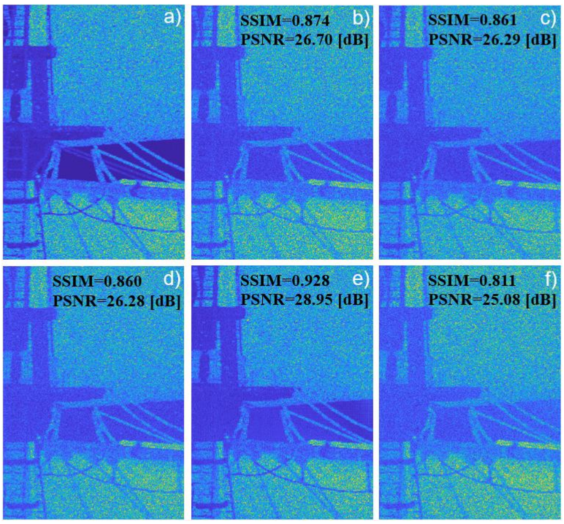

Fig. 5. Quality comparison for different methods: amplitude-phase hologram (a), DPH with 4x4 (b) and 2x2 (c) chessboard, D-PoH (d), Higher quality BE-CAM (e), Higher diffraction efficiency BE-CAM (f).

The D-PoH (Fig. 5(d)) provides quality comparable to DPH and lower diffraction efficiency (η = 1), but it has full FoV. The BE-CAM method (Fig. 5(e)(f)) offers a choice between higher quality and lower brightness or lower quality and higher brightness. Its FoV is larger than that of DPH's, although it is half the FoV of the D-PoH.

The PoH encoding methods were tested experimentally using an HNED configuration built with the same parameters (see Fig. 1). Figure 6 shows the reconstructions of the generated CGHs, encoded using D-PoH, CAM, and DPH. Previously, two cases were considered in the DPH method, as they did not differ excessively in quality, it was decided to reconstruct the case with the larger FoV. Analyzing the results, the differences in FoV, discussed in the numerical section, are also clearly visible here. The bottom row of Fig. 6 shows enlarged sections of the vessel for visual quality assessment. It can be seen that BE-CAM provides the highest quality, while D-PoH and DPH provide slightly lower comparable quality.

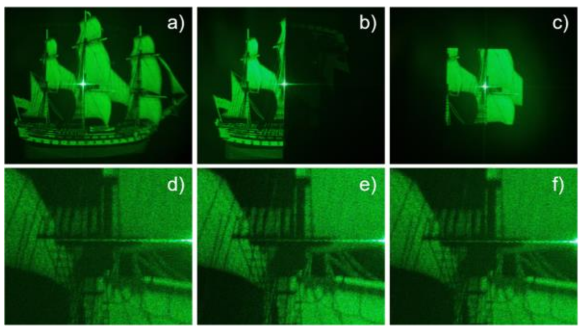

Fig. 6. Experimental CGH reconstruction: D-PoH (a), BE-CAM (b), DPH with 2x2 chessboard (c). Images (d-f) show zoomed-in fragments.

In conclusion, this paper presents and compares PoH encoding methods for wide-angle CGH of 3D objects, evaluated in terms of FoV, image quality, and diffraction efficiency. Numerical and experimental results show that the DPH offers the highest diffraction efficiency but suffers from the smallest FoV. In contrast, the BE-CAM method provides the highest image quality, but at the cost of significantly reduced diffraction efficiency. Considering all three key parameters, the D-PoH method is the most balanced and optimal solution for wide-angle cases.

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