Improving Defocus Blur in Holographic Displays

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Abstract

In this paper we present a novel multiplane computer generated hologram calculation approach that enables artifact free and realistic-looking defocus blur for optical reconstructions in a holographic display. We introduce a new targeting method and a loss function that evaluates the focused and defocused parts of the reconstructed images. We demonstrate that our method is applicable to various standard hologram generation routines such for both iterative and non-iterative CGH calculation methods. We also demonstrate our new gradient descent-based optimization with double phase constraint combined with our targeting scheme and loss function provides the best image quality. We validate our findings for both the numerical reconstructions and optical captures that are acquired from our holographic display prototype.

Author Keywords

holographic displays; computer-generated holography; multiplane image reconstruction; edge fringes; defocus blur.

1. Introduction

A holographic display (1) aims to produce genuine 3D light fields using the optical phenomena of diffraction and interference with coherent light (2). Spatial Light Modulator is a programmable device that can modulate the incoming beam to represent the desired diffraction and interference patterns.

On the other hand, computer generated holography (CGH) is a set of techniques to compute a hologram that generates the desired light distribution over a target surface when displayed on a spatial light modulator (SLM) (1). Hologram calculation with CGH is known to be computationally expensive due to complexity of physical simulation models used in CGH (3). The recent advancements in deep learning spark the development of new algorithms that promise hologram generation at interactive rates (4) in the future. In these recent works, machine learning techniques and accelerated computing capabilities that are adapted to hologram calculation increased the image quality of CGHs tremendously.

However, there are still limitations to achieve lifelike visuals with CGH, specifically in the defocused parts of a scene. Both in the literature and industry CGH based displays are often considered as the ultimate display technology as they claim to offer near-correct optical focus cues (5). As typical CGH displays are relies on coherent light sources, it makes defocused parts of a scene look unrealistic to a human observer. Born and Wolf (6) explains this phenomenon as the edge fringe issue in 3D holography. This issue is demonstrated in Figure 1. Therefore, even with all the promise of near accurate depth cues of holographic displays, the defocused parts of the optical reconstruction that can be achieved in these displays does not look natural to the human observer due to the different transfer characteristics of the coherent and incoherent light.

Our work addresses the difference between coherent and incoherent blur in multiplane CGH. We propose an improved targeting scheme and a new loss function that accounts for these differences. Our method helps to create incoherent defocus blur in CGH when reconstructing multiplanar images with coherent light Our contributions are:

- ***Loss function and targeting scheme.*** We introduce both a new targeting scheme and a loss function that evaluates focused and defocused parts of target images in multiplane CGH.
- ***Multiplane hologram optimization pipeline.*** We demonstrate that our proposed loss function and targeting scheme are compatible with various optimization methods. We establish a hologram generation pipeline that combines double phase constraints with SGD optimizations.
- ***Holographic display prototype.*** We build a proof-of-concept holographic display prototype using multiwavelength light source, a phase-only SLM and off the shelf optical parts.

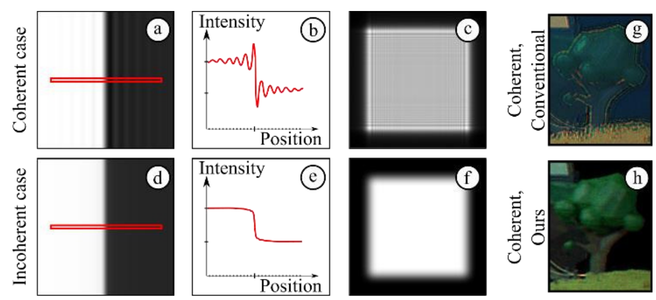

Figure 1. Characteristics of defocus blur whit coherent and incoherent illumination. The fringe artefacts are typical in 3D holograms at the defocused parts when using coherent illumination (a, b), whereas incoherent illumination (d, e) case shows smoother response. Coherent (c) and incoherent (f) illumination often differ in defocus blur visually. (g) Real captures of a conventional coherent hologram with fringes, and (h) our hologram without fringes.

2. Targeting Scheme and Loss Function

Targeting Scheme. In literature, a typical multiplane CGH reconstruction, given 3D scenes are represented with target amplitude and depth images. The commonly used method, a naïve approach (7), discretizes these target and depths images by quantizing amplitude images with respect to depth images. These quantized layer targets represent the optical reconstruction that is desired for each focus plane, and they are composed of cropped parts of a target amplitude image from each pixel depth level. Each layer target at each focus plane is represented as a sparse image filled with black pixels surrounding in-focus pixels. This would cause optimizer for CGH would force the image reconstruction solution to provide black pixels at places where defocus blur of other objects should appear. This method typically causes to noisy reconstructions in defocus parts. This issue for multiplane CGH reconstruction should be governed during the the problem

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formulation. Therefore, we propose a new targeting method for creating layer targets for multiplane CGH computation. We argue that this proposed method can improve multiplane image reconstructions in CGH while providing better defocus blur.

Inspired by the Depth-of-Field (DoF) rendering (8) in computer graphics we introduce a new targeting scheme that can account for the defocused part of the target images at each plane in depth. Firstly, we quantize the given target images with respect to their depth map and desired quantization level. We quantize the images between 1 to 16 consecutive planes. Our choice in the number of planes emerges from an earlier analysis from Aksit et al. (9). Our quantized depth images help us identify regions from target images P_{target_k} as in-focus regions, P_{focus_k} and out of focus, P_{out_k} at each depth level, k. We convolve regions of $Poutk$ with a Gaussian kernel to approximate the defocus in incoherent case, $P_{defocus_k}$. Our Gaussian kernel's size is in inversely proportional to the distance to the focus plane. We weighted sum them leading to the final target form,

$$P_k = w_2(w_0 P_{defocus_k} + w_1 P_{focus_k}),$$

where P_k is the target image at k^{th} plane, and w_0, w_1, w_2 represents weights. These weights control the brightness levels of sharp parts, blurry parts and overall image.

Loss function. When calculating multiplane images in CGH computation, optimization-based methods require a loss function that can evaluate the image quality of the reconstructed images. The most common metric that is used for hologram calculation is measuring L_2 distance between each element of layer targets. With our proposed targeting scheme, we argue that a multiplane image reconstruction problem requires a more complex metric. We believe that that different parts of the image will come into focus at each depth level while the remaining parts must contain defocus blur. Therefore, we suggest that out of focus parts of the reconstructed images should also be considered when optimizing holograms. With this idea in our mind, we propose a new loss function that is formed as a weighted sum of two different loss functions,

$$L_m = m_0 L_2(P_k, I_k) + m_1 L_2(M_k P_k, M_k I_k),$$

where m_0, m_1 represents weights, I_k represents a reconstructed image at a k^{th} plane, and M_k represents a mask for the sharp parts in a k^{th} plane. In our experiments we have tested various values of m_0 and m_1 in a brute-force manner. In our observations, choosing $m_0 = 1.0, m_1 = 2.1$ leads to the best results.

3. Optimizing Multiplane Holograms

Now that we have our targeting scheme and loss function, the next step in our pipeline is calculating the phase hologram to represent the given scenes in accordance with our method. In our holographic display, 3D images are reconstructed near to the SLM region. Therefore, the desired light model should account for the propagation distances from 0 mm to few millimeters. A typical hologram encoding method for this region is double phase (DP) method (10). However direct representation of complex field as phase only representation does not entirely solve all our issues related to image quality and improved defocus blur. Another method that we have tested to optimize the holograms at some far distance and directly shift that phase with DP method. Therefore, we asked ourselves whether it is possible to optimize a phase hologram at SLM plane which requires 0 mm propagation distance. Given that the propagation distances are small, the common light transport models cannot produce meaningful results at these distances. In our experiments, we find out that if we divide the light transport model in to two parts, first propagate to valid distance (e.g., $r = 30\ cm$) for light propagation models and propagate it back to the near SLM planes (e.g., r = -30 cm), we were able to reconstruct meaningful images. We formulated our forward model as

$$u(x,y) = (O_h(x,y,) * h_r(x,y)) * h_{-r}(x,y),$$

where h_r and h_{-r} represent light transport and u represents the reconstructed image. Our choice for light transport model is band-limited angular spectrum (11). For our implementation we relied on the differentiable form of it that is available in our scientific computing library for optics, computer graphics and visual perception (12). For optimizing holograms, we used this forward model in SGD based optimization with phase update that is constrained with DP method.

4. Holographic Display Prototype

Our holographic display prototype begins with a multiwavelength laser source LASOS MCS4, that combines three distinct laser light sources that peak at 473 nm, 515 nm, and 639 nm. We use the Thorlabs SM1D12 pinhole aperture to restrict the divergent beams leaving our fiber. Light beams arrive at our phase-only SLM, Holoeye Pluto-VIS. A 4f imaging system comprised of two 50 mm focal length achromatic doublet lenses, Thorlabs AC254-050-A, and a pinhole aperture, Thorlabs SM1D12, for removing unmodulated light. We use a Point Grey GS3-U3-23S6M-C USB 3.0 image sensor mounted on an X-stage (Thorlabs PT1/M travel range: 0-25 mm, precision: 0.01 mm) to take pictures of the reconstructed images. The design layout and capture of our holographic display prototype is demonstrated in Figure 2 with annotations.

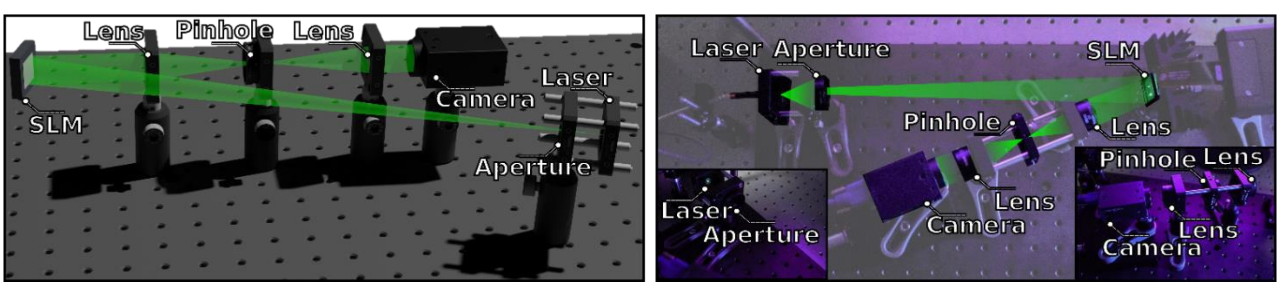

Figure 2. Holographic display prototype. (Left) A 3D layout of our holographic display design for the optical and optomechanical components. (Right) A capture of our prototype with annotations of primary components. The path of the light is indicated with a green beam.)

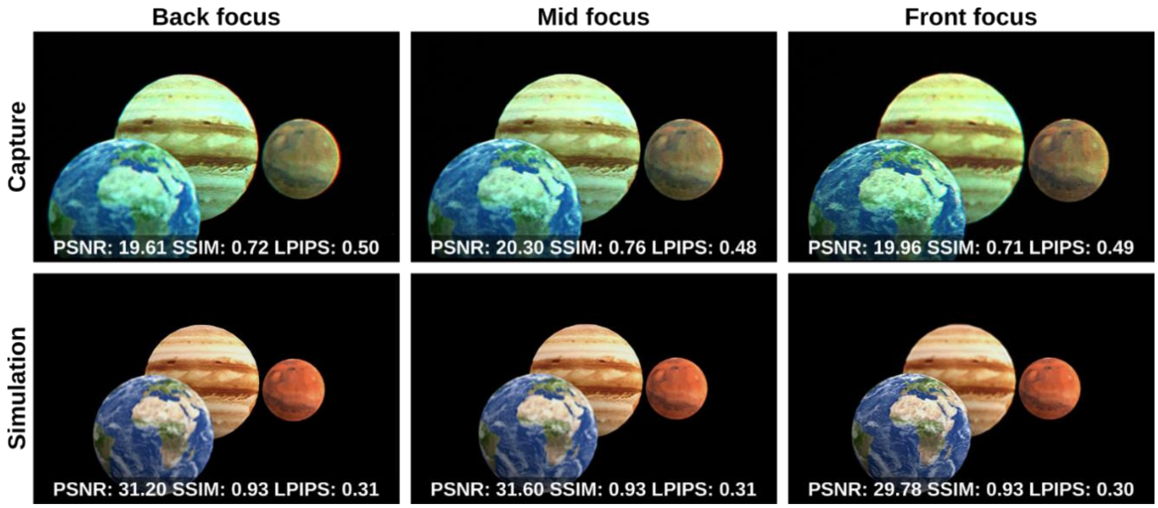

Figure 3. Experimental captures and simulation results of our method. There are six target image planes in depth with 1 mm separation between each depth plane (-2.5 mm and +2.5 mm with respect to an SLM).

5. Evaluation

We provide both optical and simulated results for our method is provided as in Figure 3. The traditional image quality metrics for both our experimental and simulated results are presented. We believe our experimental results match with our simulated results. All experimental results we present are captured with 20 ms exposure time using our holographic display.

Our method is compatible with various multiple quantization levels in depth and the proposed multiplane CGH generation pipeline can generate multiplane reconstructions with any desired depth number. It also offers customizability for the blur size, rendering scenes.

6. Conclusion

In this work, we explore using CGH to represent 3D scenes as multiplane images without the coherence artifacts such fringes or unrealistic defocus blur. Our method enables us to generate holograms that can simultaneously reconstruct images at different depths.

7. Codebase

The code base of our work is available at our repository (12).

8. Acknowledgements

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