Deep Learning-Based Self-Interference Incoherent Digital Holography Encoding for Optical Reconstruction

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Abstract

We propose a self-interference incoherent holography encoding method for enhancing the optical reconstruction performance using deep learning. Self-interference incoherent digital holography records complex holograms under incoherent illumination conditions. However, conventional optical reconstruction of self-interference incoherent digital holography is conducted by phase-only modulation or amplitude-only modulation. Considering non-linear representation ability of deep neural networks, we utilize the multi-layer perceptron as a non-linear phase mapping function. We design the optimization pipeline to find the phase encoding for phase-only holographic displays and, an optical demonstration of the proposed phase encoding method is presented.

Author Keywords

Digital holography; Hologram encoding; Deep learning-based holography; Incoherent holography

1. Introduction

Holography records and reproduces both the phase and amplitude of light based on the wave nature of light, and has been studied as the ultimate form of three-dimensional (3D) display. Modern holographic displays primarily utilize liquid crystal-based spatial light modulators (SLMs), which achieve wide viewing angles through pixel pitches approximately ten times smaller than conventional display devices. However, due to these small pixel pitches, methods to increase the space-bandwidth product of holograms are essential for implementing large-screen holographic displays. Various solutions have been proposed, including multiple SLMs [1], eye-tracking with viewing windows [2], and beam diffractors [3].

While computer-generated holography (CGH) has been proposed with the objective of solving the diffraction equations and enhancing image quality by using various 3D data. Recently, with the advent of deep learning, numerous techniques have been proposed for the acquisition of high-quality holograms with a moderate computational time. However, the acquisition and generation of holograms for real-world scene conditions necessitates a more intricate process. The initial step is to obtain 3D data. This can be achieved through the utilization of slice-based hologram generation based on depth maps or multiview-based holograms based on multiple cameras [4]. However, these methods necessitate sophisticated sensor fusion or may exhibit a number of disadvantages when synthesized into a hologram. For instance, the generation of holograms based on depth maps gives rise to the same issues as those encountered in other conventional 3D displays, such as the challenge of accurately reproducing natural occlusion. Furthermore, the amount of computation required increases in proportion to the depth range or the number of objects.

In order to address these issues, our proposed method is to physically acquire the interference pattern. A number of techniques have been investigated to acquire holograms based on holographic microscopy. However, the interferometer highly depends on the coherence of light, is susceptible to external disturbances, and possesses a substantial external structure, which constrains their potential for integration with a conventional camera. Incoherent digital holography represents a potential solution to these limitations, as it enables the construction of an interferometer that generates holograms based on an incoherent light source. There are numerous methodologies for incoherent holography; however, this study focuses on self-interference incoherent digital holography (SIDH), which involves splitting the light incident on the interferometer into two branches and modulating them differently to obtain the interference pattern through mutual interference. Although this method can be implemented using a variety of polarization-based optical devices, the optical device utilized in this study is a geometric phase (GP) lens, which employs SIDH with a polarization-selective lens [5].

In this work, we bridge SIDH-based hologram acquisition with practical holographic display implementation. We propose a novel deep learning-based hologram encoding technique that enhances the quality of reconstructed holograms by optimizing the phase-only modulation through a multi-layer perceptron (MLP) model. The proposed method is validated through optical reconstruction experiments comparing different MLP configurations.

2. Proposed method

GP-SIDH exploits the phase shift of the half-wave plate that occurs with the separation of the wavefront in the GP lens [5]. This enables the acquisition of complex holograms via the four-step phase-shift method, which exploits the relative phase difference depending on the incident polarization angle. The complex hologram acquired with parallel phase shift method using the intensity after the rotation of polarizer can be derived as:

$$\psi_H = I_{135^\circ} - I_{45^\circ} - i(I_{90^\circ} - I_{0^\circ}). \tag{1}$$

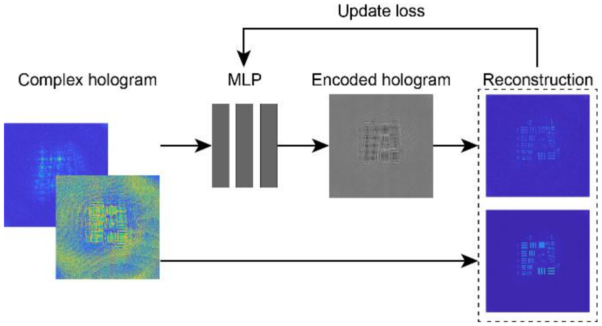

Figure 1. Optimization pipeline of proposed deep learning-based SIDH encoding.

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Figure 1 illustrates the proposed deep learning-based hologram encoding technique. Each hologram serves as the input for the MLP. MLP is a fully connected network in which the input from the previous layer affects every part of the next layer. The non-linear activation functions between each layer can help solve the implicit neural representation tasks including representing the higher-order derivatives and differential equation solvers [6]. We use this nonlinear transformation of the MLP as a phase extraction step, whereby the phase constraints that allow for the most holographic reconstruction to be represented lossless are identified. The objective function of optimization technique based on this can be expressed as follows:

$$\mathcal{L} = \left|\left|F_{ASM}(\psi_H; z_r) - F_{ASM}\left(exp\left(i \cdot F_{MLP}(\psi_H)\right);\ z_r\right)\right|\right| \tag{2}$$

where $F_{\mathrm{ASM}}(\cdot)$ is angular spectrum free space propagation function to propagation distance z_r, and $F_{\mathrm{MLP}}(\cdot)$ is MLP function to extract the phase-only hologram. MLPs are composed of three or more hidden layers, and activation functions such as leaky-ReLU are employed. Moreover, hyperbolic tangent function is employed as the activation of the final layer, reflecting the attributes of the phase hologram, which spans from $-\pi$ to π. Moreover, the characteristics of the hologram are contingent upon the amplitude distribution of the hologram input. To ensure accurate representation, a positional encoding technique is employed to compensate for the hologram's constituent parts by reflecting their respective positions. The process of positional encoding involves taking the input to the model, normalizing a term for the position of each pixel in the hologram, and combining it with the original complex hologram to encode the hologram. This is one of the deep learning methodologies employed for modeling physical causation, which can then be applied to processes such as super-resolution or interpolation of holographic data.

3. Experimental results

To validate the proposed hologram encoding technique, a phase modulation-based holographic display system is employed for verifying the optical reconstruction. We implement GP-SIDH with a customized GP lens with a focal length of approximately 250 mm. The image sensor is a polarized image sensor from LUCID Vision Labs, and the final resolution of the hologram acquired by the parallel phase shift method is 1024×1024. To construct the phase-only holographic display, we use liquid crystal-based micro-display with Pluto from Holoeye Inc. at a resolution of 1920×1080.

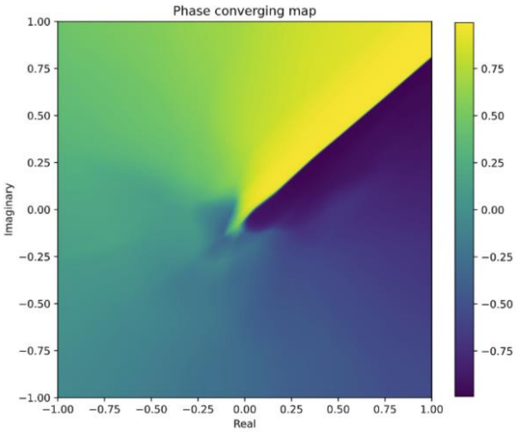

Figure 2. MLP output results with arbitrary complex number input.

Figure 2 shows the phase encoding outputs that are generated when an arbitrary complex value is provided without positional encoding. The x-axis and y-axis represent the real and imaginary components of the complex values, respectively, ranging from -1.0 to 1.0. The color map indicates the phase convergence characteristics. A notable feature is observed near the origin (0,0), where there is a distinct transition in the convergence pattern, characterized by a sharp boundary. This discontinuity indicates a phase constraint found by the representation feature of MLP.

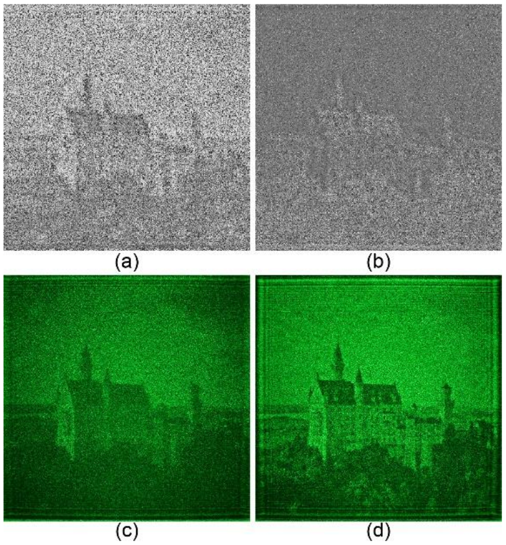

Figure 3. CGH-based hologram compensation result. (a) Input phase hologram, (b) output phase hologram, (c) optical reconstruction of input hologram, (d) optical reconstruction of output hologram.

Figure 3 shows the input phase hologram and the optical reconstruction result based on CGH. Before applying MLP on SIDH, we employed CGH on MLP which is calculated by angular spectrum method. CGH was calculated by a single propagation with randomly initialized phase to 100 mm distance. Compared with optical reconstruction results according to proposed method in Fig. 3(c) and 3(d), optical reconstruction results clearly show image quality enhancement with noise suppression and edge preservation.

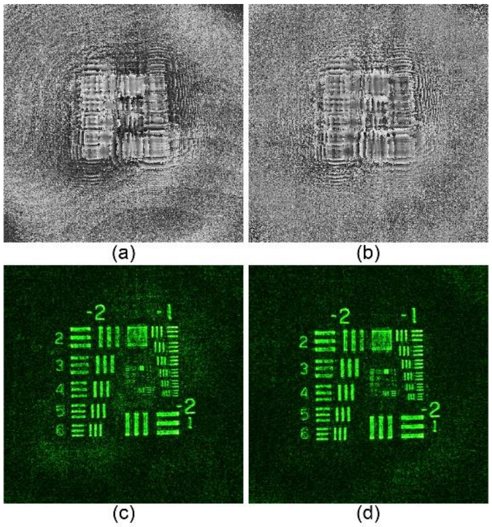

Figure 4. Phase part of input and output hologram and optical reconstructions. (a) Input phase hologram, (b) output phase hologram, (c) optical reconstruction of input hologram, (d) optical reconstruction of output hologram.

Figure 4 shows the comparison between phase hologram and optical reconstruction for the USAF resolution target-based hologram. In the case of the acquired hologram, a wavefront compensation algorithm is applied to average the hologram by extracting the biased wavefront over the real and imaginary parts in order to compensate for various errors introduced by the customized GP lens [7]. Consequently, a kind of contour-like noise is introduced in the phase plane, which can be observed in the optical reconstruction as a slight contour in the center. In contrast, the holograms generated by the model exhibit a reduction in contouring and an enhancement in the central bias signal of the hologram in the optical reconstruction.

4. Conclusion

In this work, we propose an MLP-based holographic encoding technique for complex holograms acquired by SIDH to achieve optical reconstruction quality optimized for phase-only holographic displays. We demonstrate that the proposed MLP network reduces the noise inherent in the holograms and improves the quality of optical reconstruction. We aim to further improve the performance of optical reconstruction by constructing simulations similar to actual optical reconstruction scenarios in which the free space propagation kernel contains physically generated noise.

Acknowledgements

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