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Practical Self-Supervised Denoising for Incoherent Digital Holography Without Ground Truth Data

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Abstract: We propose a practical self-supervised framework for denoising raw incoherent digital holograms. By suppressing sensor noise before bias and conjugate noise elimination, we prevent fourfold amplification without ground truth or paired training data.

1. Introduction

Incoherent Digital Holography (IDH) enables hologram acquisition under natural light or LED illumination without coherent sources like lasers. Self-interference Incoherent Digital Holography (SIDH), particularly noteworthy for capturing interference patterns under short coherence lengths, has seen significant developments including Michelson interferometer-based setups, Fresnel Incoherent Correlation Holography (FINCH) [1, 2], and recent compact systems utilizing Geometric Phase (GP) lenses [3, 4].

However, SIDH faces a critical noise amplification problem. Due to its physical principle of intensity summation, where individual point source intensities accumulate, SIDH produces exceptionally high bias levels compared to meaningful diffraction signals. During the phase-shifting process required to extract complex holograms, this leads to severe noise amplification. Specifically, in an SIDH system where the n-th phase-shifted interferogram is $I_n = |u_1 e^{j\delta_n} + u_2 e^{-j\delta_n}|^2 + \Lambda_n$ with independent sensor noise Λ_n (zero mean, variance σ^2), applying 4-step phase-shifting with $\delta_n = n \times \pi/4$ extracts the complex hologram as $H = (I_0 - I_2) + j(I_1 - I_3)$. The resulting noise power becomes $P_N = E[|(\Lambda_0 - \Lambda_2) + j(\Lambda_3 - \Lambda_1)|^2] = 4\sigma^2$, proving fourfold amplification. In SIDH environments where signal amplitude $u_1 u_2^*$ is extremely small relative to the bias component $(|u_1|^2 + |u_2|^2)$, this amplified noise drastically reduces SNR and severely degrades reconstructed image quality through noise floor $|N|^2$ and signal-dependent fluctuations.

Deep learning-based denoising networks using supervised learning have been proposed to address this noise problem [5]. However, obtaining clean ground truth holograms for training is extremely challenging or impossible in practical SIDH applications, as it requires noise-free imaging under identical optical conditions. This motivates the development of self-supervised denoising methods. In this study, we propose a framework applying the Neighbor2Neighbor (N2N) algorithm at the raw sensor data level before complex hologram synthesis [6], enabling effective noise suppression without requiring ground truth data while maintaining competitive performance with supervised approaches.

The proposed method decomposes the [H, W] raw data acquired via a color polarization image sensor and GP lens into polarization and RGGB Bayered color channels, converting it into a multi-channel tensor of shape $[1, 16, H/4, W/4]$ for network input. The N2N technique leverages the high correlation between adjacent pixels within the input tensor and learns statistical consistency between pairs of sub-tensors generated through random sub-sampling. This allows the network to effectively isolate and remove random noise components without requiring ground truth (GT) data, making it highly suitable for practical optical environments where GT is difficult to obtain.

2. Experimental Results

To validate the proposed framework, training was conducted using synthetic raw data with applied Poisson noise in a simulated SIDH system. A total of 800 images were split into training and validation datasets at an 8:2 ratio, with two random patches extracted per image from the training set to construct the dataset. Training was performed for 400 epochs with a batch size of 4. As a control, conventional supervised training on noisy-clean pairs (N2C) was also conducted in parallel as a baseline. Measurements of PSNR and SSIM were performed on the reconstructed images.

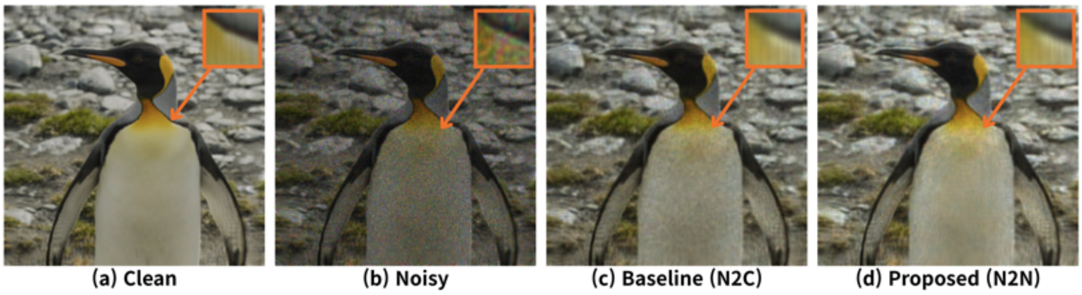

Fig. 1. Reconstruction results from simulated SIDH test sample. Orange box shows the zoomed-in region indicated with the arrow.

For a total of 100 test data, N2C achieved 29.64 ± 2.10 dB while N2N achieved 29.49 ± 2.02 dB in averaged PSNR, demonstrating that the proposed self-supervised approach achieves near-baseline quality without requiring any ground truth data. Given that GT acquisition is impractical or impossible in real SIDH systems, this trade-off strongly favors the N2N framework for practical deployment. Figure 2 shows the results for sample data. All images were converted to holograms and then reconstructed. Figure 2(c) shows the result with N2C, and Fig. 2(d) shows the result with the proposed N2N framework. Experimental results demonstrated that the UNet-based denoising network effectively reduced raw data noise without GT, and the reconstructed image from complex holograms exhibited a significantly lower noise floor compared to conventional methods. During the digital refocusing process via numerical propagation, fine diffraction signals of the object were preserved while background noise was suppressed, leading to a substantial improvement in reconstructed image quality.

3. Conclusion

In conclusion, this study validates that applying N2N at the raw data level effectively resolves the chronic noise amplification issue in SIDH while achieving comparable performance to supervised baseline without ground truth requirements. This makes the method immediately applicable to real-world SIDH systems where clean reference data is unavailable. The approach offers universality as it is independent of specific optical designs and is expected to significantly lower the barrier to practical deployment of high-quality hologram acquisition technologies. While the current validation is performed on simulated data, we expect the framework to demonstrate similar effectiveness on real experimental data from physical SIDH systems.

Acknowledgement

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2019-0-00001, Development of Holo-TV Core Technologies for Hologram Media Services)

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