Differentiable Event-based Holography

Chutian Wang, Shuo Zhu, Jingqian Wu, Ni Chen and Edmund Y. Lam *

Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong SAR, China

**elam@eee.hku.hk*

Abstract: We present an event-based computational holographic imaging technology utilizing automatic differentiation. Our end-to-end paradigm, Ev-Holo, shows promising results that could advance the field and enable new applications.

1. Introduction

Computational neuromorphic imaging (CNI), which utilizes event sensors and algorithms to process recorded event data directly, is rapidly advancing in the field of optical imaging, characterized by its impressive asynchronous ultra-fast response at the microsecond level [1]. This innovation inspires advanced imaging applications, such as time-efficient 3D reconstruction [2]. Digital holography (DH), a computational imaging technology, aims to retrieve the complex optical field emitted from target surfaces and has growing dynamic sensing requirements across various applications, such as cytometric cell sorting, long-term biological event monitoring, and instant coherent wavefront sensing [3]. The integration of digital holography with event-based sensing has already yielded promising results in holographic particle tracking [4]. In this letter, we will further investigate the optical field reconstruction algorithm directly from the captured event stream.

Based on our experience, a significant challenge in integrating event sensors into inline DH setups via CNI is the asynchronous nature of the data modality. The event sensor measures only temporal increments at each pixel, lacking global information about the hologram distribution. Consequently, we cannot simply count the events within a spatio-temporal neighborhood along the t-axis, treating it as a proxy for the frame modality, and then backpropagate the event histogram to the corresponding depth. Moreover, directly employing supervised learning-based approaches compromises interpretability. Achieving digital holography with an event sensor also necessitates a single-shot approach, which involves addressing typical ill-posed problems in single-shot inline holography setups, such as the well-known twin-image artifact. State-of-the-art differentiable holography emerges as a viable solution for this challenge [5]. Therefore, we propose differentiable event-based holography (Ev-Holo), a physically informed paradigm that enables ultra-fast optical field reconstruction in a classical inline holographic setup while maintaining a high degree of interpretability.

2. Principle

Figure 1 illustrates the principle of Ev-Holo. As shown in Figure 1(a), a HeNe laser (Thorlabs, HNL100L) with a wavelength of 632.8 nm is collimated using a custom-built $4f$ system, serving as the spatial filter. This setup ultimately illuminates the resolution target sample (USAF 1951, Silverfast) following collimation. The sample is mounted on a translation stage (WN262TA20, 2 µm repeatability precision) to simulate rapid and robust movement with known ground truth velocity. An event sensor (IniVation, DAVIS 346) with a resolution of 346×260 pixels is employed to capture the triggered events during this fast movement.

Figure 1(b) illustrates the designed differentiable model of Ev-Holo for end-to-end optimization implementation. When the logarithmic intensity change exceeds a predetermined threshold c at timestamp t_k during a sweep, the motion-induced cluster can be defined as $\mathcal{E} \triangleq \{e_k\}_{k=1}^{N_e}$, where k represents the index of all counted N_e events. In this cluster, each event triggered at the spatial pixelated location $\mathbf{x}_k = (x_k, y_k)$ is denoted as $e_k = (\mathbf{x}_k, p_k, t_k)$. The event polarity $p_k \in \{-1, +1\}$ indicates whether there is a positive (red) or negative (blue) change. The cluster of events corresponds to the pixels it traverses within Δt. For a short Δt, the resulting event cluster $\mathcal{E}$ will exhibit spatio-temporal correspondence due to the basic optical flow constraint, yielding the supervision in Ev-Holo, *i.e.*,

$$\mathcal{L}(u_0, z; \mathbf{v}) = \|\Delta L_z(\mathbf{x}) + \nabla L_z(\mathbf{x}) \cdot \mathbf{v}\Delta t\|_2^2 + \kappa(u_0)\mathcal{R}(u_0), \tag{1}$$

where $\Delta L_z(\mathbf{x})$ represents the recorded temporal increment of the logarithmic hologram in a short Δt, I_z and $L_z \triangleq \log I_z$ denote the intensity and logarithmic hologram at distance z. Herein, $\mathbf{v}$ indicates the uniform optical flow representing the sample motion and can be pre-registered from the motion configuration of the translation stage. $\nabla L(\mathbf{x}) \cdot \mathbf{v}$ denotes the spatial gradient of the logarithmic hologram along the motion direction. The total loss $\mathcal{L}$ is composed of a regularizer term $\mathcal{R}$ for twin-image suppression, where κ represents the corresponding weight.

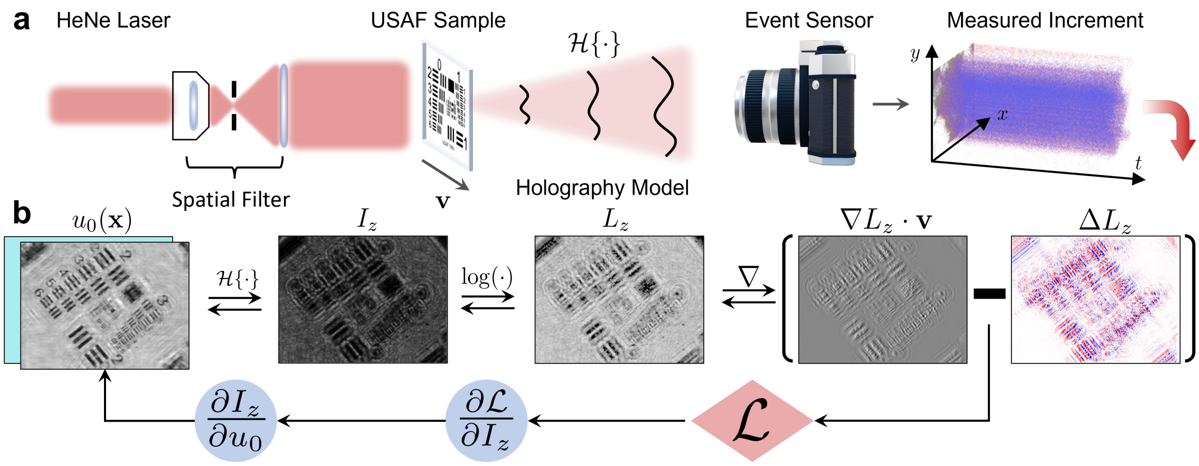

Fig. 1. Pipeline of Ev-Holo. (a) Optical configuration of Ev-Holo. (b) The designed differentiable model of Ev-Holo for end-to-end optimization implementation.

Subsequently, by examining the forward model of in-line holography, the wave propagation from u_0 to $I_z(\mathbf{x})$ can be determined as a holography operator $\mathcal{H}$, *i.e.*,

$$I_z(\mathbf{x}) = \mathcal{H}\{u_0, z\} = \mathcal{F}^{-1}\{\mathcal{F}\{u_0(\mathbf{x})\}H_z(\mathbf{f})\}, \tag{2}$$

where $\mathcal{F}$ refers to the Fourier operator and $\mathbf{f} = (f_x, f_y)$ represents the spatial frequency coordinates, and H_z is the transfer function at distance z, which can be written as

$$H_z(\mathbf{f}) = \begin{cases} \exp\left(-i\frac{2\pi z}{\lambda}\sqrt{1-\lambda^2\mathbf{f}^2}\right) & |\mathbf{f}| < \frac{1}{\lambda} \\ 0 & \text{otherwise} \end{cases}. \tag{3}$$

Consequently, by effectively reparameterizing the recorded event stream as the temporal increment of the logarithmic diffraction pattern of the original object complex field u_0, combined with the regularizer term applied on u_0, we formalize the neuromorphic holohgraphy as a linear inverse problem in Ev-Holo. As illustrated in Figure 1(b), the reconstruction outcome of the amplitude has already demonstrated the feasibility of solving the optimal u_0 and distance z iteratively, using the automatic differentiation technology outlined in [5].

3. Conclusion

In conclusion, the proposed Ev-Holo scheme effectively bridges the gap between event-based vision and digital holography reconstruction algorithms. By accurately modeling the optical field, Ev-Holo enables ultra-fast imaging while preserving interpretability, showcasing its potential to advance real-time applications in various fields.

Acknowledgements: The work is supported by the Research Grants Council of Hong Kong (GRF 17201822), Hong Kong SAR.

References

1. S. Zhu, C. Wang, H. Liu, P. Zhang, and E. Y. Lam, "Computational neuromorphic imaging: principles and applications," in *Computational Optical Imaging and Artificial Intelligence in Biomedical Sciences,* vol. 12857 of Proceedings of the SPIE (2024), pp. 4–10.
2. J. Wu, S. Zhu, C. Wang, and E. Y. Lam, "Ev-GS: Event-based gaussian splatting for efficient and accurate radiance field rendering," in *2024 IEEE 34th International Workshop on Machine Learning for Signal Processing (MLSP),* (2024), pp. 1–6.
3. C. Wang, S. Zhu, P. Zhang, K. Wang, J. Huang, and E. Y. Lam, "Angle-based neuromorphic wave normal sensing," Laser & Photonics Rev. **19**, 2400647 (2025).
4. Z. Ge, C. Wang, J. Huang, and E. Y. Lam, "Event-driven neuromorphic holography for dynamic particle imaging," Opt. Lett. **50**, 1496–1499 (2025).
5. N. Chen, C. Wang, and W. Heidrich, "∂H: Differentiable holography," Laser & Photonics Rev. **17**, 2200828 (2023).