Motion-Resolved Event-Based Holography

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ABSTRACT

Inline holography has enabled twin-image-free complex field reconstruction through advanced differentiable optimization and deep learning techniques. However, under photon-starved or extreme exposure conditions, recorded holograms suffer from a trade-off between motion blur and low signal-to-noise ratio. We demonstrate that event-based holography can overcome these exposure limitations by leveraging the asynchronous and high-dynamic-range sensing of event cameras. Our motion-resolved holographic framework enables robust and high-fidelity reconstruction of dynamic scenes, even under severe illumination constraints. By resolving sub-millisecond motion without sacrificing signal-to-noise ratio, this approach offers a promising solution for ultrafast holographic imaging beyond the limits of conventional frame-based systems.

Keywords: event-based imaging, digital holography, neuromorphic imaging, computational imaging

1. INTRODUCTION

Digital holography (DH) aims to retrieve the complex optical field from target surfaces and faces growing dynamic sensing demands in applications such as cytometric cell sorting, long-term biological monitoring, and fast coherent wavefront sensing. Inline holography, in particular, is attractive for its compact optical layout and the possibility of twin-image-free reconstruction when combined with advanced computational solvers.[1] Single-shot inline DH is inherently ill-posed (twin-image, depth ambiguity), so a physically constrained, differentiable inversion is desirable; recent differentiable holography formulations provide a viable pathway to enforce such physical priors during optimization.[2] Conventional frame-based cameras, however, encounter a fundamental exposure trade-off in dynamic or photon-starved scenarios: long exposures improve signal-to-noise ratio (SNR) but induce motion blur, whereas short exposures avoid blur at the cost of photon starvation. This trade-off limits temporal resolution and often breaks autofocus or sharpness-of-gradient criteria used for depth estimation, rendering holographic inversion more ill-posed for fast-moving or weakly illuminated scenes.

Computational neuromorphic imaging (CNI), which utilizes event sensors and algorithms to process recorded event data directly, is rapidly advancing in optical imaging.[3] CNI is characterized by asynchronous, microsecond-level temporal resolution and very high dynamic range, enabling new imaging modalities under extreme lighting and motion. This capability has inspired time-efficient 3D, high-dynamic-range wavefront sensing and agile defect inspection applications.[4–7] Building on these developments, we investigate reconstructing complex optical fields directly from the event stream rather than from conventional frames.[8]

In summary, we introduce motion-resolved event-based holography, a CNI-assisted framework that fuses asynchronous events with inline holographic physics to overcome the exposure trade-off and enable sub-millisecond, blur-free complex-field reconstruction. Inspired by the event-based Lucas–Kanade tracking framework (EKLT) in the classical event-based sensing community,[9] which leverages event constraints to estimate local motion, we embed a differentiable neuromorphic sensing module into the holographic forward model. Second, we propose a physics-informed, end-to-end differentiable solver that embeds a motion-aware module based on the EKLT formula into the holographic forward model, enabling joint estimation of the complex optical field and the underlying motion trajectory. Finally, we validate the method on dynamic targets under photon-limited conditions, demonstrating superior reconstruction fidelity and robustness compared to conventional frame-based holography.

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2. PRINCIPLE

2.1 Event Sensing and EKLT Modular

Event cameras asynchronously record changes in the logarithmic intensity of the scene at microsecond latency. In NeuroDH, when the log-intensity change at pixel $\mathbf{x}_k = (x_k, y_k)$ exceeds a predefined threshold c at time t_k, an event is triggered with polarity $p_k \in \{-1, +1\}$. Collecting all such events over a short time interval Δt forms a motion-induced cluster $\mathcal{E} \triangleq \{e_k = (\mathbf{x}_k, p_k, t_k)\}_{k=1}^{N_e}$, where N_e denotes the number of events within the interval. Each event encodes the local brightness change and the exact time it occurred, providing a sparse but high-temporal-resolution representation of motion.

The key to motion-resolved reconstruction is the spatio-temporal correspondence inherently captured by the events. For a short Δt, events from the same moving feature satisfy the optical flow constraint, which is the core principle behind the EKLT module. In the log-intensity domain, the instantaneous change ΔL of a pixel is related to the local motion $\mathbf{v}$ via

$$\Delta L(\mathbf{x}) = -\nabla L(\mathbf{x}) \cdot \mathbf{v}, \tag{1}$$

where ∇L is the spatial gradient of the logarithmic intensity, and $\mathbf{v}$ is the solved optimal flow $\mathbf{v}^*$.

2.2 Inline Holography Reparameterization

Inline digital holography models the recorded hologram intensity as an interference between the reference wave and the diffracted object wave. By examining the forward model of in-line holography, the wave propagation from U_0 to $I(\mathbf{x})$ can be determined as a distance-related free-space propagation kernel h_z, i.e.,

$$I(\mathbf{x}) = (U_0 * h_z)(\mathbf{x}) = \mathcal{F}^{-1}\big\{\mathcal{F}\big\{U_0(\mathbf{x})\big\}H_z(\mathbf{f})\big\}, \tag{2}$$

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

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

Consequently, the formulation of Equation 1 and 2 establishes a natural supervision for NeuroDH in Figure 1(c): the event clusters provide precise, localized temporal increments that inform the reconstruction of the latent high-speed intensity dynamics, which are then reparameterized through the holographic forward model. Therefore, it enables motion-resolved complex field recovery under photon-starved and high-speed conditions.

3. EXPERIMENTAL SETUP

We implemented motion-resolved event-based holography using an inline holographic system with coherent illumination from a HeNe laser ($\lambda = 632.8\,\text{nm}$). As shown in Figure 1(a), the object was placed at a distance of several centimeters from the sensor. A DAVIS346 event camera, capable of both frame and event output, was used to capture asynchronous events during high-speed object motion. The system allows a flexible tuning of the inspection stage speed, laser illumination power, and the diffraction distance z.

4. RESULTS

We validated NeuroDH on dynamic samples including a USAF resolution target and biological specimens under photon-starved or extreme illumination conditions, where conventional frame-based holography suffers from motion blur or low SNR. From Figure 2, reconstructions using event data exhibit lower noise and higher contrast due to supervision in the logarithmic feature domain, while effectively eliminating motion blur. Although some residual artifacts remain from the anisotropic log-gradient supervision, they are minor compared to the destructive effects of motion blur and do not compromise the practical quality of the reconstructions, demonstrating the robustness and promise of NeuroDH for high-fidelity, motion-resolved holography.

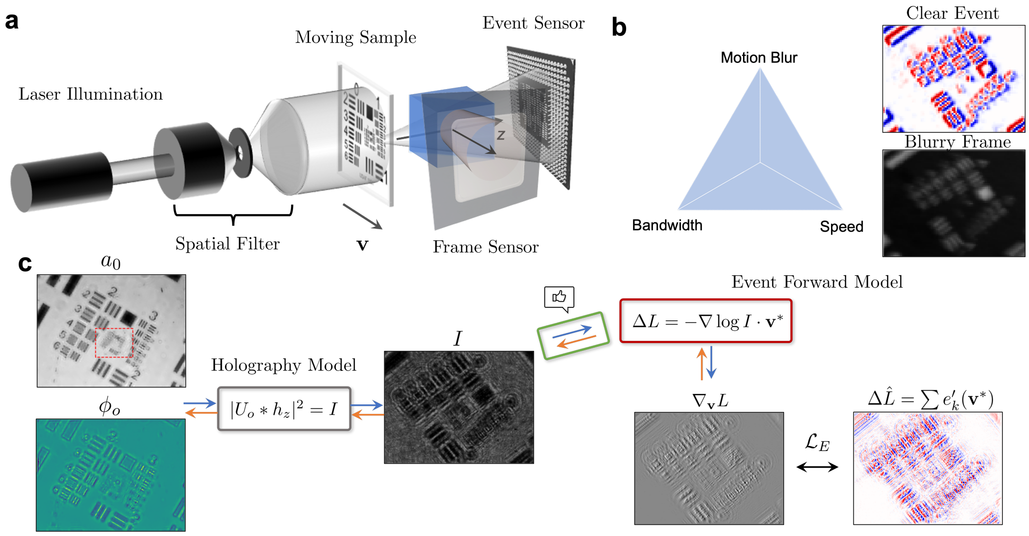

Figure 1. Principle illustration of NeuroDH. (a) Optical configuration of the NeuroDH system. (b) Conventional frame-based sensors suffer from a trade-off between motion blur and low SNR under limited channel capacity—illustrating the "no free lunch" scenario in digital holography. Computational neuromorphic imaging offers a means to overcome this limitation. (c) Differentiable NeuroDH model designed for end-to-end optimization. The "thumb up" symbol highlights our contribution in bridging the computational imaging and event-based vision communities.

5. CONCLUSION

We have presented a motion-resolved holographic framework, namely NeuroDH, that integrates event cameras with inline holography. It demonstrates how CNI can help DH overcome the long-standing "no free lunch" dilemma. Conventional frame-based sensors face an unavoidable trade-off between motion blur and bandwidth, which limits their ability to capture dynamic holographic scenes with high fidelity. By contrast, our approach leverages event-driven motion trajectories to construct an effective blur kernel, embedding it into a differentiable holographic pipeline. This physically grounded formulation enables blind deblurring and robust wavefront recovery under severe motion and photon-limited conditions. More importantly, it establishes a conceptual bridge between the computational imaging and neuromorphic vision communities, showing that event sensing is not merely a data source but a principled way to enrich optical forward models. We believe this framework opens new directions for snapshot holography, offering a pathway toward real-time, interpretable imaging in dynamic biological monitoring, cytometry, and coherent wavefront sensing.

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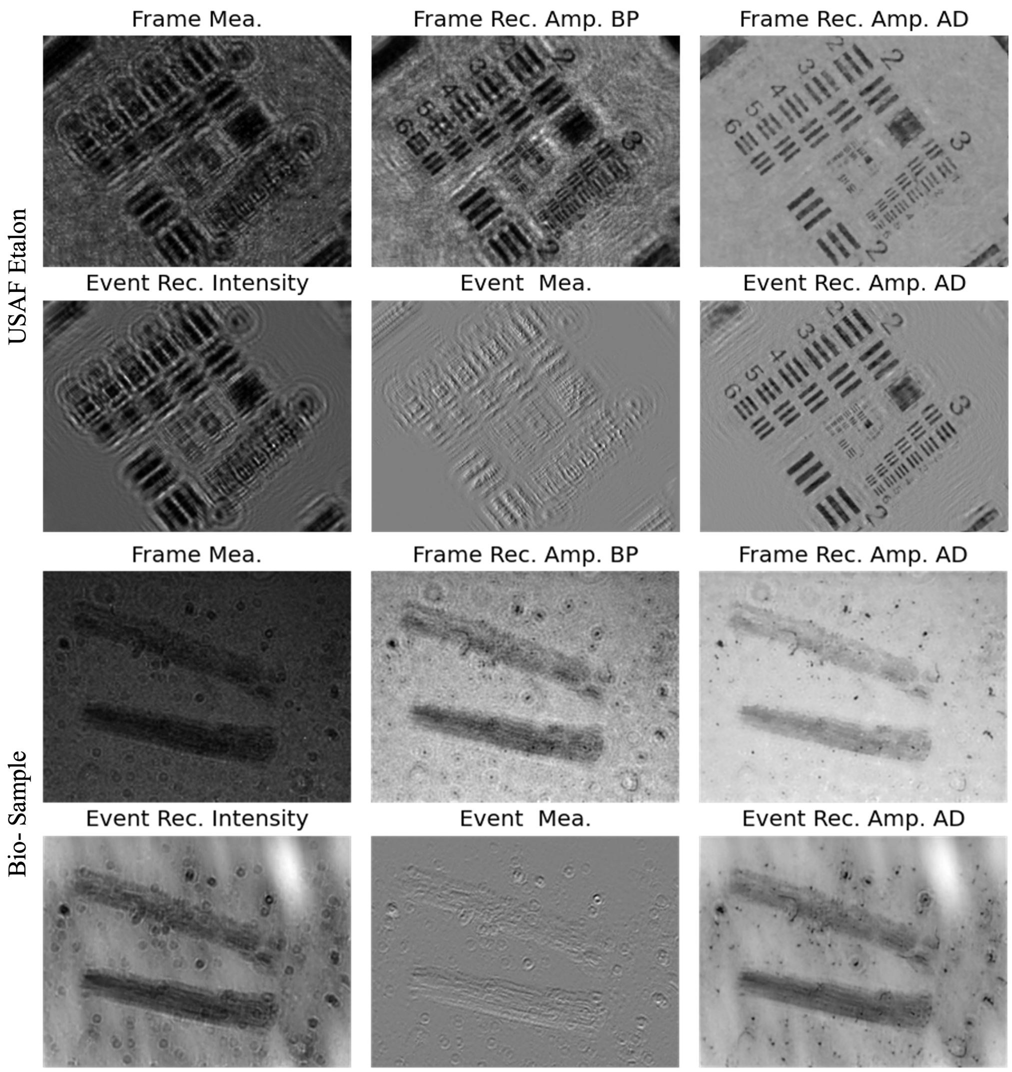

Figure 2. Comparison between frame-based and event-based modalities. Reconstructions using NeuroDH demonstrate lower noise, higher contrast, and effective motion-blur suppression, highlighting the motion-blur-free and HDR advantages.

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