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Event-based reconstructions in Computational Microscopy

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Abstract. We present a maximum-likelihood estimation (MLE) framework tailored to event-driven detectors to perform computational image reconstruction and phase retrieval. Using Poissonian photon statistics, we built an event-based loss function that maximizes the probability of having the set of events and non-events given the initial parameters. Our loss function can be utilized in both optical and electron ptychography. We demonstrate experimental reconstructions using data acquired with a Timepix3 detector.

1 Introduction

Ptychography is a well-established lensless imaging technique that enables the retrieval of both an object's amplitude and phase. In a conventional setup, a probe beam illuminates the sample at multiple positions, and the resulting diffraction patterns are recorded after propagating to a detector. Traditionally, this detection is frame-based, integrating photon arrivals over a fixed exposure time. In this work, we extend ptychography to event-driven detection modes. One of the primary limitations of conventional ptychography is its long scanning time, largely limited by the start-and-stop scanning approach and the need to accumulate sufficient flux at each stationary scan position. Fly-scan ptychography [1] enables continuous scanning, but requires computational motion-blur correction. By leveraging the capabilities offered by modern event-counting detectors with nanosecond time resolution (SPAD arrays, Timepix3, Dectris ELA, etc.) [2], a ptychography concept can be developed based on continuous high-speed scanning combined with a forward model based on event-detection and accurate noise-statistics modeling [3]. We show that our approach enables high-quality ptychographic reconstructions from event-triggered data.

2 Event-Driven reconstructions

We present experimental ptychographic reconstructions from a Timepix3 camera by means of our maximum-likelihood (ML) event-driven loss function:

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$$\ell(\boldsymbol{\theta}) = \sum_{k\in\{\text{events}\}} \log[1 - F_k(T_k; \boldsymbol{\theta})] + \sum_{k\in\{\text{non-events}\}} \log[F_k(T_k; \boldsymbol{\theta})]. \quad (1)$$

where $I_k(\boldsymbol{\theta})$ is the intensity predicted in pixel k for the model parameters $\boldsymbol{\theta}$, F_k is the Poisson cumulative distribution function and the probability of detecting more photons than the threshold T_k is $1 - F_k(T_k; \boldsymbol{\theta})$. Using $-\ell(\boldsymbol{\theta})$ as our loss function and minimizing with automatic differentiation and gradient descent, we can reconstruct the complex object and probe as a result of the maximum likelihood. The experimental setup is shown in Figure 1 (a) and experimental reconstructions using a Timepix3 detector are shown in Figure 1 (b).

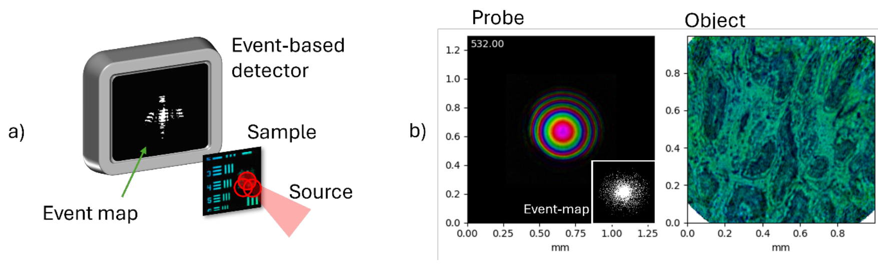

Figure 1. (a) Schematic of the ptychographic setup utilizing a hybrid detector in event-detection mode. (b) Experimental reconstructions showing a Gaussian beam as the probe and a biological sample slice obtained using the event-driven loss function.

The advantages of event-driven ptychography, combined with maximum-likelihood estimation, can be extended to electron ptychography [4]. Our loss function effectively reconstructs electron ptychography data within this framework. By leveraging event-driven cameras, which are highly sensitive to single-particle detection, this approach provides an optimal tool for event-driven electron ptychography.

3 Conclusion and Outlook

We present experimental results demonstrating the extension of maximum-likelihood phase retrieval in ptychography to detectors capable of timestamping photon events. Future work could explore the integration of fast scanning strategies, such as Fly-scan, to enable real-time reconstruction of dynamic processes by leveraging time-of-arrival information in particle detection for both photons and electrons.

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