Low-latency object tracking through scattering media with event camera

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Abstract: We use an event camera to track objects through scattering media, achieving enhanced robustness with lower latency than frame-based systems. This method paves the way for high-speed, low-power sensing in complex environments. © 2025 The Author(s)

1. Introduction

Non-invasive imaging and tracking of moving objects hidden behind scattering media is critical for biomedical diagnostics, autonomous vehicle navigation in fog or smoke, and security screening. Direct imaging through scattering layers is difficult due to light distortion from inhomogeneous media. Indirect methods, such as speckle autocorrelation (SA), can infer object geometry from speckle patterns [1], but real-time tracking with ultra-low latency remains a major challenge, especially in dynamic environments. Tracking moving objects in such scenes requires sub-millisecond temporal resolution to prevent trajectory distortion in biomedical imaging [2] or delayed hazard recognition in autonomous systems [3]. Conventional frame-based cameras are fundamentally limited by fixed exposure intervals, resulting in temporal gaps that undersample rapid motions. Even high-frame-rate systems struggle to resolve small displacements due to insufficient tracking cues between frames. Event cameras overcome these limitations by asynchronously encoding spatiotemporal intensity changes, bypassing fixed exposure windows to enable low-latency tracking [4, 5]. This capability is transformative for scenarios requiring real-time monitoring, such as tracking cellular dynamics in turbid fluids or detecting obstacles through fog.

2. Experimental setup and methods

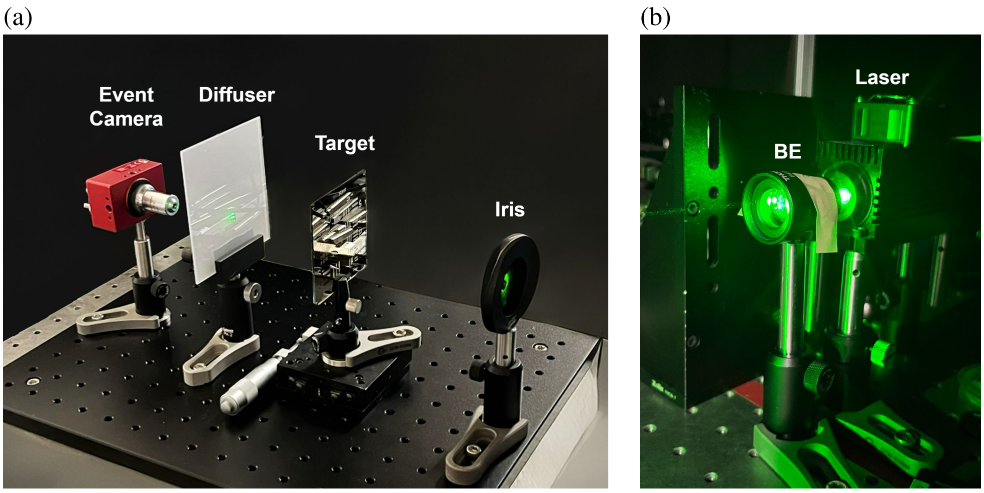

Fig. 1. Experimental setup of the event-based tracking system. (a) The event camera captures the illuminated target hidden behind a ground glass diffuser. (b) The illumination source for the system.

The system (Fig. 1) uses an event camera (iniVation, Davis346, 346 × 260 pixels) to simultaneously record both frame and event data, enabling direct comparison. A hidden target is illuminated by a 532 nm laser (CivilLaser) with a 2x beam expander (Thorlabs BE02M-A) behind a diffuser (100 × 100 mm, 220-grit), generating speckle patterns. These patterns are governed by the optical memory effect (OME), where the system isoplanatic response remains linear and space-invariant within a defined range [1]. Both frame-based and event-based systems utilize SA for motion tracking. However, the key difference lies in their sensing mechanisms: frame-based systems synchronously capture intensity frames, while event-based systems asynchronously detect intensity changes and output binary signals at the pixel level, which are accumulated before applying SA. This allows event-based systems to resolve motion-induced speckle shifts at microsecond resolution, making them effective for low-latency tracking. For an object moving at velocity v under optical magnification m, the displacement Δx is related to the observed pixel shift Δp by $\Delta x = m \cdot \Delta p$. Since displacement also follows $\Delta x = v \cdot \Delta t$, we derive $\Delta p = \frac{v}{m} \cdot \Delta t$, indicating that shorter time intervals Δt result in smaller pixel shifts. Thus, achieving low-latency tracking requires the system to detect small Δp values between successive time points. If temporal resolution is insufficient, subtle displacements are undetectable, forcing an increase in Δt to resolve larger shifts, introducing additional latency.

3. Results and Conclusions

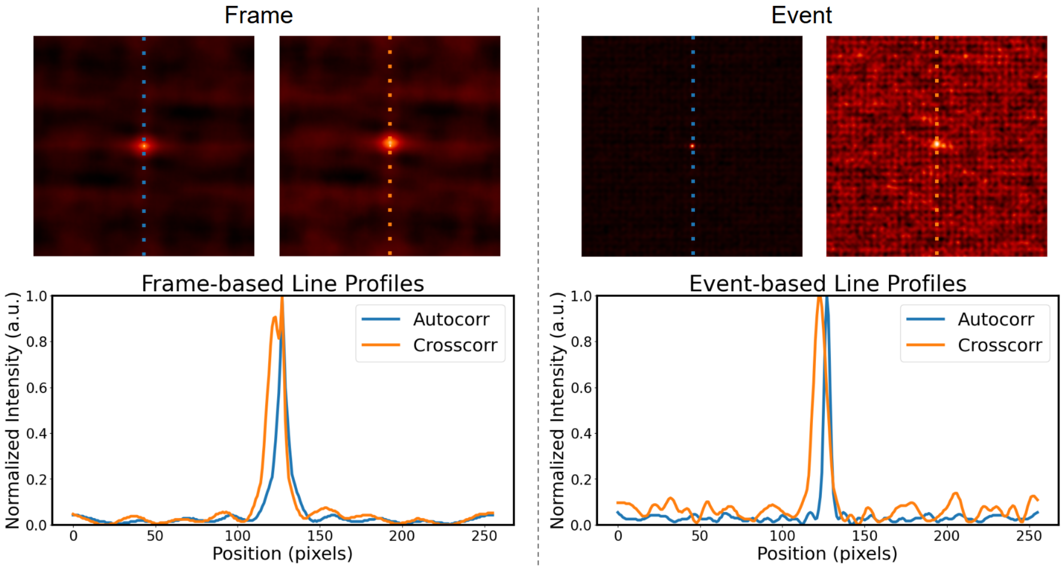

Fig. 2. Tracking results of frame-based and event-based systems. The first row presents the speckle autocorrelation and crosscorrelation at consecutive time steps. The second row shows the normalized intensity profile for the central column of the first row.

Figure 2 compares the tracking performance of event-based and frame-based systems based on SA. The top row shows the speckle autocorrelation at the initial time step and the crosscorrelation between the initial and subsequent time steps. The second row presents the corresponding intensity profiles along the centroid line of each correlation map. The blue curve represents the autocorrelation as a reference, while the orange curve represents the crosscorrelation, capturing positional shifts over time. In the frame-based system, the crosscorrelation peak remains nearly aligned with the autocorrelation peak, indicating minimal detectable displacement. As a result, small pixel shifts Δp cannot be resolved unless a longer time interval Δt is introduced, which increases latency and diminishes the system responsiveness in rapidly changing environments. In contrast, the event-based system exhibits a distinguished shift in the crosscorrelation peak. This indicates its ability to detect fine motion with high temporal resolution. By resolving smaller Δp without extending Δt, the event camera achieves significantly lower latency, allowing real-time tracking with immediate feedback and high-speed decision-making.

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References

1. J. W. Goodman, *Speckle Phenomena in Optics: Theory and applications* (Roberts and Company Publishers, 2007).
2. J. Fan, J. Suo, J. Wu, H. Xie, Y. Shen, F. Chen, G. Wang, L. Cao, G. Jin, Q. He *et al.*, "Video-rate imaging of biological dynamics at centimetre scale and micrometre resolution," Nat. Photonics **13**, 809–816 (2019).
3. D. Gehrig and D. Scaramuzza, "Low-latency automotive vision with event cameras," Nature **629**, 1034–1040 (2024).
4. 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 (SPIE, 2024), pp. 4–10.
5. S. Zhu, Z. Ge, C. Wang, J. Han, and E. Y. Lam, "Efficient non-line-of-sight tracking with computational neuromorphic imaging," Opt. Lett. **49**, 3584–3587 (2024).