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Surpassing the Wavefront Sensor Dynamic Range with Neuromorphic Temporal Diversity Measurements

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Abstract: We demonstrate the utilization of the computational neuromorphic imaging paradigm to acquire temporal diversity measurements, which proves advantageous in overcoming the dynamic range limitations of Shack-Hartmann wavefront sensors for ultra-fast large-gradient turbulence diagnosis.

1. Introduction

Despite being a classical approach, the Shack-Hartmann wavefront sensor (SHWFS) remains the most widely utilized wavefront sensor in contemporary adaptive optics (AO) systems, owing to its robustness and high optical efficiency. However, the wavefront sensor dynamic range (WFS-DR) in SHWFS remains a challenge for high-resolution turbulence characterization. This is due to the utilized microlens array (MLA) with a rigid focal length and a fixed lenslet pitch [1]. Diversity measurement is one kind of solution that involves leveraging additional information from multiple channels to surpass the WFS-DR limitation without complicating the optical configuration. The conventional axial diversity scheme, which includes techniques such as phase diversity [2] or the curvature wavefront sensor and defocused SHWFS [3], utilizes multiple measurements along the z-axis to improve the accuracy of phase retrieval by regularizing the solution. However, implementing an axial-scanning scheme with conventional active pixel sensors (APS) entails sacrifices in terms of time. This greatly restricts the application of diversity measurements in dynamic turbulence scenes in recent advanced AO systems.

The computational neuromorphic imaging (CNI) paradigm utilizes a dynamic vision sensor (DVS) and computational algorithms to enable ultra-fast visualization for dynamic scenes with a high dynamic range. The acquired asynchronous dense event stream in a scale of microseconds provides superior properties for imaging and sensing enhancement in spatiotemporal dimensions. Quite a number of optical applications, such as auto-focusing [4], wavefront sensing [5], non-line-of-sight imaging [6], and denoised dynamic imaging [7], etc., have been investigated based on the CNI paradigm [8]. In this work, we propose a novel scheme to enlarge the WFS-DR by utilizing highly efficient temporal diversity measurements within the CNI paradigm.

2. Methods

The classical SHWFS enables direct sensing of the incident wavefront W by recording its local gradient ∇W as the lateral displacement vector $\Delta \mathbf{r}$ on the sensor plane. This sensor plane is positioned at a distance of focal length f from the MLA, as depicted in Fig. 1(a). However, conventional spot extraction methods encounter limitations when the spot displacement moves beyond the lenslet boundary Ω or overlaps with adjacent spots, thereby restricting the WFS-DR. To overcome these limitations, the temporal diversity scheme is designed to directly perceive the high-dimensional wave normal by recovering its time partial derivative, *i.e.*,

$$\mathbf{v} = f \frac{\partial \nabla W}{\partial t}, \tag{1}$$

where $\mathbf{v}$ represents the instantaneous optical flow of the varying Hartmanngram.

Fig.1(b) compares the data recorded using the conventional frame-based imaging paradigm with that obtained using the bio-mimic CNI paradigm, showcasing the temporal diversity measurements in Fig.1(c). It is evident that the frame stack acquired from the conventional APS is highly redundant, while the DVS asynchronously triggers a continuous spatiotemporal event stream, even providing an impressive visualization of the wave normal. The working mechanism of the diversity measurements is illustrated in Fig. 1(d). As a result, the high-dimensional temporal wave normal can be directly perceived as motion trajectories embedded within the event stream.

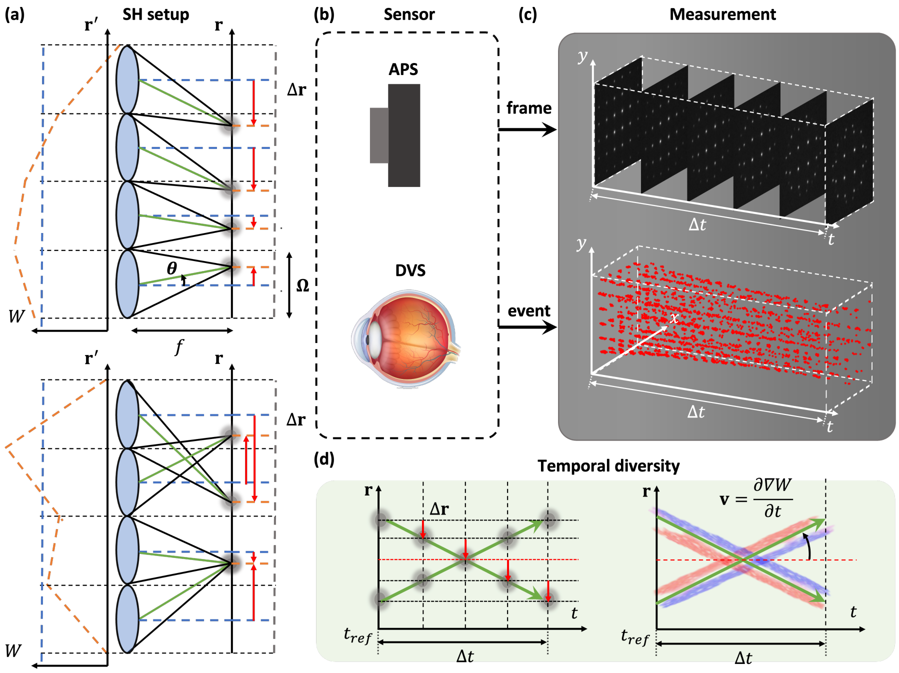

Fig. 1. The principle of illustration of the neuromorphic temporal diversity scheme is as follows: (a) The basic working mechanism of a classical SHWFS imposes limitations on WFS-DR due to the detectability of the displacement vector. (b) The choice between using a conventional APS or a DVS as the data acquisition hardware results in different temporal measurements. (c) The former records a frame stack (upper), while the latter triggers an asynchronous event stream (lower). (d) The proposed temporal diversity scheme resolves the issue of displacement overlapping by extracting the temporal partial derivative of the wavefront gradient.

3. Conclusion

In conclusion, the suggested neuromorphic temporal diversity scheme effectively resolves the inherent ambiguity that limits the SHWFS-DR, demonstrating its potential for seamless integration into advanced CNI-based AO systems.

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References

1. V. Akondi and A. Dubra, "Shack-Hartmann wavefront sensor optical dynamic range," *Optics Express*, vol. 29, no. 6, pp. 8417–8429, 2021.
2. R. A. Gonsalves, "Phase diversity: math, methods and prospects, including sequential diversity imaging," in *Unconventional Optical Imaging*, vol. 10677 of Proceedings of the SPIE, 2018, pp. 335–345.
3. C. Li, B. Li, and S. Zhang, "Phase retrieval using a modified Shack–Hartmann wavefront sensor with defocus," *Applied optics*, vol. 53, no. 4, pp. 618–624, 2014.
4. Z. Ge, H. Wei, F. Xu, Y. Gao, Z. Chu, H. K.-H. So, and E. Y. Lam, "Millisecond autofocusing microscopy using neuromorphic event sensing," *Optics and Lasers in Engineering*, vol. 160, p. 107247, 2023.
5. C. Wang, Z. Ge, S. Zhu, P. Zhang, and E. Y. Lam, "Tracking the Shack-Hartmann spots using neuromorphic motion compensation," in *Computational Optical Sensing and Imaging*, 2023, pp. CTu2B–5.
6. S. Zhu, Z. Ge, C. Wang, J. Han, and E. Y. Lam, "Removing wall redundancy in non-line-of-sight object-tracking using neuromorphic imaging," in *Computational Optical Sensing and Imaging*, 2023, pp. CTu2B–6.
7. P. Zhang, C. Wang, and E. Y. Lam, "Neuromorphic imaging and classification with graph learning," *Neurocomputing*, vol. 565, p. 127010, 2024.
8. 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.