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Tracking the Shack-Hartmann Spots Using Neuromorphic Motion Compensation

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Abstract:
The essential part of Shack-Hartmann (SH) wavefront sensing is the fast and precise estimation of spot displacement. We report a neuromorphic motion compensation technique to track the motion of SH spots directly from spatio-temporal event streams.

1. Introduction

Nowadays, high-contrast imagers in astronomy pose a challenge to advanced adaptive optics (AO) technologies that requires an ultra-fast ($1 \sim 2$ kHz) wavefront sensing. For example, SAXO [1], the SPHERE extreme AO system, uses a 1.2 kHz electron Multiplying CCD (EMCCD) and 41×41 actuators in its deformable mirror, such that the servo-loop frequency can be up to 1.5 kHz.

Neuromorphic sensors encode the pixel-wise intensity changes as an asynchronous event stream with microsecond temporal resolution, low latency, high dynamic range, and low data redundancy reduction. The neuromorphic imaging technology has been used in many applications like autofocusing microscopy [2] and laser speckle imaging [3], meanwhile, its applicability in the field of Shack-Hartmann (SH) wavefront sensing is also validated [4]. To further explore the feasibility of the potential embedding in advanced AO systems, we analyze its embedding in the SH setup from the perceived spatio-temporal event streams. The outcome of this work illustrates how a changing wavefront trigger events in the SH setup in neuromorphic imaging and shows that the displacement of SH spots can be estimated by adopting the theory of motion compensation in neuromorphic imaging [5].

2. Methods

In the SH setup, the input turbulence will introduce a linear deviation within the section corresponding to each sub-aperture of the microlens array (MLA) if only the first order of the Taylor expansion is preserved. This linear geometry relates the lateral displacement $\Delta\mathbf{r} = (\Delta x, \Delta y)$ to the changing wavefront gradient $\nabla\mathbf{W}(\mathbf{r})$:

$$\Delta\mathbf{r} = \frac{\lambda f}{2\pi}\Delta(\nabla\mathbf{W}), \tag{1}$$

where λ is the wavelength of the incident optical wave, and f is the focal length of the MLA used in the classic SH wavefront sensor.

In neuromorphic imaging, an event $\mathbf{e}_k = (\mathbf{r}_k, p_k, t_k)$ is triggered at a pixel $\mathbf{r}_k = (x_k, y_k)$ at the timestamp t_k if the log intensity change is larger than a threshold T, i.e., $\Delta L(\mathbf{r}_k, t_k) = L(\mathbf{r}_k, t_{k+1}) - L(\mathbf{r}_k, t_k) \triangleq p_k T$, where $L(\mathbf{r}_k, t_k)$ is the log intensity, and $p_k \in \{-1, 1\}$ is the event polarity that responds to the sign of the changing. The theory of motion compensation for SH spot tracking is as follows: a moving spot will trigger events on the pixels it passes through when the SH setup senses turbulence. If the triggered events in a short time window can be warped to maximize their alignment, then the motion of SH spots can be estimated [5]. Specifically, the events are separated into different clusters, with each cluster containing N_{sub} number of event points that are triggered by the spot trajectory of each sub-aperture. The events are then warped through an affine transformation $\mathbf{e}_k = (\mathbf{r}_k, t_k) \mapsto \mathbf{e}'_k = (\mathbf{r}'_k(\theta), t_k)$, where $\mathbf{r}'_k(\theta)$ denotes the warped coordinates according to the induced affine parameter θ. This will result in a weighted image of warped events (IWE), denoted as $H(\mathbf{r};\theta)$, yielding an image of the motion compensation

$$H(\mathbf{r};\theta) = \sum_{k=1}^{N_{sub}} p_k \delta(\mathbf{r} - \mathbf{r}'_k(\theta)), \tag{2}$$

where δ is the Kronecker delta function. If we set the optimization parameter θ as the spot motion velocity for each cluster, the corresponding IWE at the optimal velocity that tracks the maximized alignment is definitely the motion-compensated increment we pursue.

3. Simulation experiment

Fig.1 (a) illustrates the design to simulate SH wavefront sensing using a neuromorphic sensor. To be specific, the simulation utilizes a collimated 632*nm* laser as the illumination and a 3×3 MLA that is configured at its focal distance in front of the neuromorphic sensor. The rays illustrate the working mechanism of the SH wavefront sensor, with the blue and the yellow color referring to a referenced wavefront and the added distorted turbulence, respectively. The input wavefront aberration is set as the type of defocus, i.e., the fourth order of Zernike polynomials, with the amplitude change ranging from 0 to λ. In AO, the process of sensing and correction is performed within a fixed time window Δt that relates to the servo-loop frequency of the actuators.

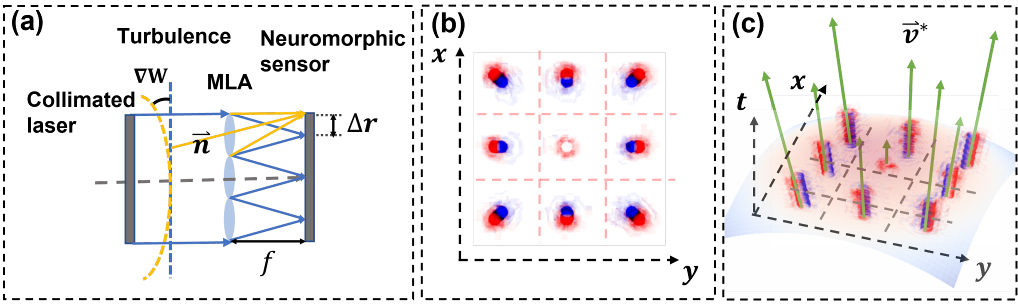

Fig. 1. Visualization of the simulation experiment of the Shack-Hartmann wavefront sensing using neuromorphic imaging. (a) The optical configuration used in SH wavefront sensing. (b) The vertical view of the triggered events on the sensor plane. (c) The estimated 3D motion trajectory vector $\vec{\mathbf{v}}^*$ of the SH spots by motion compensation. In (b) and (c), the red and blue point clouds refer to the positive and negative events, respectively.

Fig. 1 (b) illustrates the vertical view of the triggered events on the sensor plane. By summing the producing IWE through this view angle, i.e., $H(\mathbf{r};\theta = 0)$, neuromorphic SH spot tracking will degrade to a resemble frame-based centroiding method since no motion is compensated.

To perform motion compensation we adopt a three-dimensional (3D) perspective, that is, the two-dimensional measurement of the lateral moved SH spots is sampled as the spatial and time-dependent trajectories using the property of high temporal resolution in neuromorphic imaging, as shown in Fig. 1 (c). In which, the 3D motion trajectory vector of each SH spot $\vec{v}^*$ can be further estimated through the constructed space-time dependent implicit equations using the neuromorphic spatio-temporal neighbourhood, and therefore the optimal velocity is explicated.

4. Conclusion

The neuromorphic imaging technique enables the SH setup to track the motion of spots directly through the resulting trajectories from a perceived spatio-temporal event stream. By leveraging the idea of motion compensation, the neuromorphic imaging samples the motion of SH spots from a 3D perspective with both high speed and high precision, thus paving the way for the development of advanced AO.

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