Near-wall Lagrangian particle tracking velocimetry using event-based imaging

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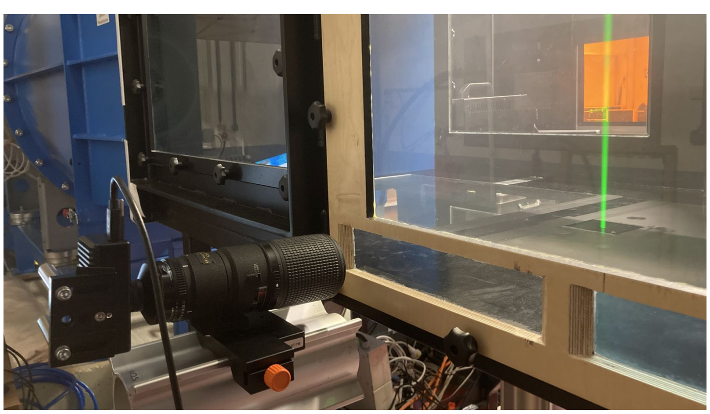
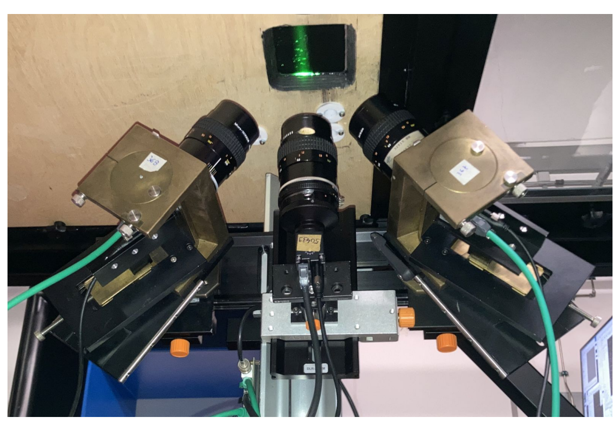
ABSTRACT We describe the implementation of a particle tracking velocimetry (PTV) system based on event-based vision (EBV) and demonstrate its application for the characterization of a turbulent boundary layer (TBL) in air. One configuration uses a single event-camera to image a narrow light sheet extending wall-normal from the wall to obtain the time-resolved velocity profile. In the other configuration a thin light sheet grazes the surface of a glass window illuminating only the viscous sublayer of the turbulent boundary layer. The data simultaneously captured by three synchronized event-cameras is used to reconstruct the 3d particle tracks within a few 100 µm of the wall. Particle movement within the viscous sub-layer permit the estimation of the local, instantaneous wall shear stress under the assumption of linearity between particle velocity and wall shear stress. Thereby 2d distributions of the instantaneous wall shear stress are obtained. PTV tracking algorithms that are orders magnitude faster than correlation-based schemes provide data quality on par with currently used, considerably more expensive, high-speed PIV hardware.

Event-based imaging and its application in particle imaging velocimetry

EBV, dynamic vision sensing (DVS) or neuromorphic imaging describe a rather new sub-field within computer vision, differing considerably from classical frame-based imaging (Gallego et al., 2022). Rather than providing rectangular arrays of exposed sensor pixels, i.e. images, event-cameras provide an asynchronous stream of *events* consisting of pixel coordinates, time stamp and a binary contrast change signal. In this sense, event cameras only record contrast changes on the pixel level, either going from dark to bright (positive event) or bright-to-dark (negative event). Static areas in the scene provide no information. In the context of particle imaging, narrow event streaks are produced in the 2d-space-time domain and can be processed to provide 3D-3C PTV data in either real-time (Rusch and Rösgen, 2021, 2022) or offline (Borer et al., 2017; Drazen et al., 2011; Howell et al., 2020). The recently introduced event-based imaging velocimetry (EBIV) technique combines EBV and light sheet illumination to provide time-resolved, planar (2D-2C) velocity fields (Willert and Klinner, 2022; Willert, 2023). In the proposed contribution, we first introduce the use of event-based imaging to obtain profiles of turbulent quantities in analogy to profile-PIV technique (Willert, 2015), hereafter referred to as *event-based profile imaging velocimetry* or just *profile-EBIV*. The second part is devoted to the extension of EBIV to 3D-3C PTV to capture the particle motion within the viscous sublayer.



(a)



(b)

Figure 1: *(a): velocity profile measurement setup using a single event-camera at the 1 m wind tunnel of DLR in Göttingen; (b): triple event-camera setup for particle tracking in the viscous sublayer of a TBL.*

Profile-EBIV on a turbulent boundary layer

The profile-PIV technique as introduced by Willert (2015) has been extensively used to obtain both detailed velocity statistics as well as time-resolved data of turbulent flows in a variety of applications Cuvier et al. (2017); Willert et al. (2017, 2018, 2021). For *profile-EBIV* an event-camera is used in place of the high-speed camera and images a narrow field of view in the wall-normal direction (Fig. 1(a)). Seeding is equivalent to the 1 µm aerosol tracers used for conventional PIV in air. Measurements are performed in the 1 m windtunnel of DLR in Göttingen at free stream velocities of $U_\infty = 5-10$ m/s. Figure 2 provides exemplary velocity profile statistics obtained through the analysis of event recordings of 10 s duration and a laser pulsing rate of 10 kHz. The data shown in the left column is obtained by a multi-frame, pyramid-based cross-correlation scheme originally designed for PIV data processing. Preliminary results obtained using a pure particle tracking scheme are provided in the right column. Each data point represents bin-average statistics with a bin-size of $\Delta y = 50\,\mu$m ($\approx 0.8^+$). Both data sets show near perfect agreement with both corresponding DNS data as well as conventional PIV measurement data (not shown here), thereby documenting the viability of the proposed measurement technique.

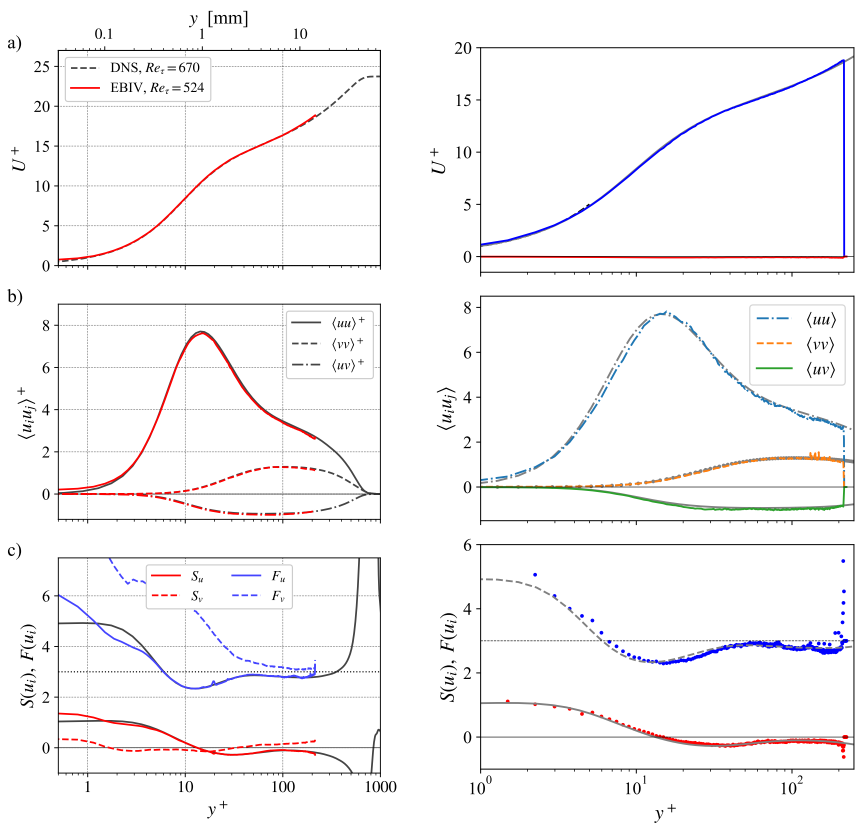


Figure 2: Exemplary velocity profiles in viscous scaling obtained with profile-EBIV records of 10 s duration for $Re_\tau = 585$ using multi-frame correlation processing (left column) and 2d particle tracking (right column), both compared to DNS from Schlatter and Örlü (2010). PTV statistics are based on bin-averaging using bin a size of $\Delta y = 50\,\mu$m.

Event-based particle tracking of the viscous sublayer

A second EBIV configuration captures the flow in the viscous sublayer of a TBL using a thin, wall-parallel light sheet of <0.5 mm thickness that is imaged by three synchronized event-cameras (see Fig. 1(b)). The dynamics of the near wall flow can already be visualized in the raw event data for which two examples are given in Fig. 3, although the static imagery can only partially reveal the true particle motion. Extreme events such as high-speed sweeps, strong spanwise motions or reverse-flow areas can be readily observed in a simple manner by scrolling through the recordings. After careful camera calibration using a y-translated target, 3D particle tracks can be reconstructed from the three event streams. With both the particle's wall-distance Δy and velocity $\mathbf{u}$ known, the corresponding wall shear stress can be estimated from $\tau_w = \mu \frac{du}{dy} \approx \mu \frac{\mathbf{u}}{\Delta y}$ with the assumption that the particle is located in the viscous sublayer (i.e. $y \lessapprox 4^+$). Two examples of preliminary (unfiltered) wall shear stress distributions are provided in Fig. 4, and, for instance, show the footprint streamwise streaks. The proposed contribution will provide details on the procedure for reconstruction of the 3D particle tracks from the event data records. Time-resolved 2d maps of both components of the wall shear stress are obtained from records of up to 1 minute duration, which, to best of the authors' knowledge, is not possible with currently available conventional imaging.

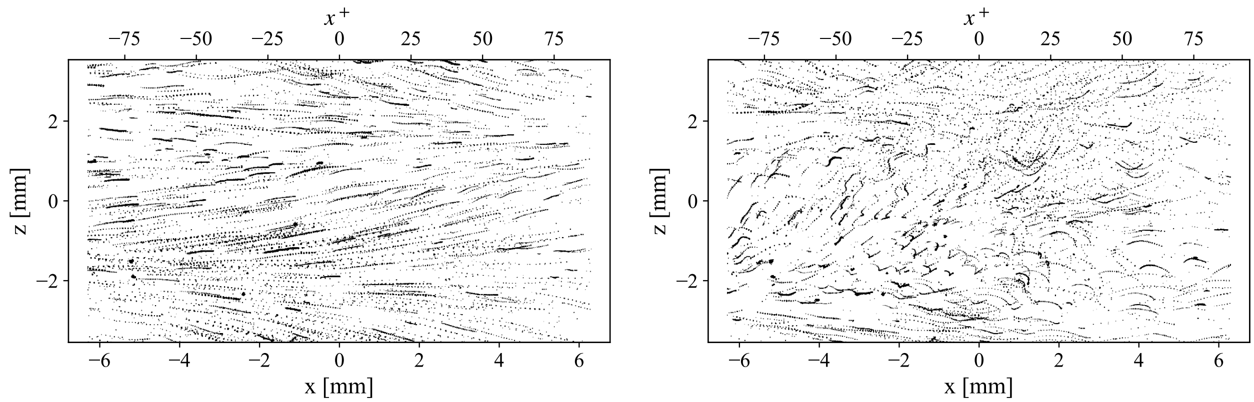


Figure 3: *Visualizations of the near wall flow ($y^+ < 8$) with mean flow left-to-right; (a) sweep event at $z = -2$ mm, (b) streaklines produced by a reverse flow event near the lower center (particles briefly moving upstream, best observed if animated).*

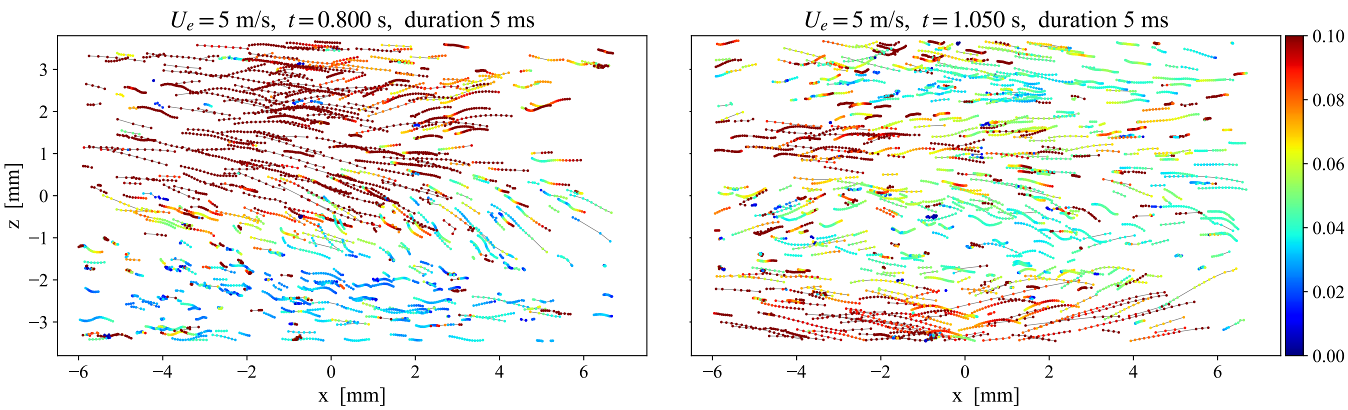


Figure 4: *Preliminary distributions of the wall shear stress magnitude obtained by estimating the velocity gradient experienced by particles moving within the viscous shear layer. The mean flow is from left to right.*

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