Online Event-Based Insights into Unsteady Flows with TrackAER

Alexander Rusch[1,*], Thomas Rösgen[1]

1: Institute of Fluid Dynamics, ETH Zurich, Switzerland
*Corresponding author: arusch@ethz.ch

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ABSTRACT

We present a novel event-based quantitative flow visualization system, TrackAER, capable of continuously reconstructing, rendering and recording particle tracks in large test volumes and without limitations on the measurement duration. Multiple event-based cameras are synchronized and calibrated to produce independent and asynchronous, yet temporally co-registered data streams of flow tracers. Subsequently, these data streams are merged into time-resolved 3D particle tracks using photogrammetric techniques. Due to the operating principle of event cameras, the flow scenery is reduced to moving objects only, which effectively compresses the data stream at the camera source. In combination with an efficient data processing pipeline, the measurement system operates online. That is, the investigated flow field is reconstructed and rendered in an interactive 3D viewer without noticeable time lag. The data processing approach follows a "per-event" paradigm and is achieved in real-time, enabling the immediate observation and analysis of both, transient and long duration flow features. Specific issues resulting from event-based, frame-free processing are discussed as well as the advantages and limitations of event cameras. Exemplary results of two different test cases are provided to demonstrate the utility of the TrackAER system in- and outside a wind tunnel, where Lagrangian particle track information is displayed in a virtual scene together with extracted quantitative information such as local flow velocities.

1. Introduction

TrackAER (Rusch & Rösgen, 2021) is our event-based measurement system for large scale flow diagnostics that provides online visual feedback about the flow field under investigation. On the hardware side it builds upon multiple event cameras (ECs) (Lichtsteiner et al., 2008; Posch et al., 2010) that are synchronized and calibrated to enable 3D tracer particle tracking using photogrammetric reconstruction. Due to the functioning principle of ECs, motion information in a scenery is captured in the form of an asynchronous stream of events effectively focusing on moving objects while suppressing static background data. Each event represents a threshold-crossing change in light intensity on the individual pixel level and is defined by its time of occurrence, the location of the "firing" pixel and a binary polarity indicating relative increase or decrease in light intensity. When compared to conventional particle image velocimetry (PIV) or particle tracking velocimetry (PTV) techniques, which capture image frames at high speed, the amount of data generated by ECs is vastly reduced such that online processing of the cameras' data streams becomes viable. With a high temporal registration resolution equivalent to more than 10'000 frames per second, ECs allow to capture even high-speed flow phenomena. However, the advantages of ECs come at a significant cost: The asynchronous data stream is not readily processed with conventional algorithms that typically require images with absolute, frame-like (i.e., quasi-static) intensity information as input. As such, on the software side, we focus on the development of efficient and fast algorithmic pipelines that enable processing of event data under soft real-time constraints. Such algorithms need to be specifically tailored to the asynchronous and sparse nature of the event data stream to fully exploit the potential of ECs for flow diagnostics. While early ECs were severely limited in resolution (Lichtsteiner et al., 2008), recent developments have pushed the number of pixels towards the 1 megapixel mark (Finateu et al., 2020). As a result, we are now able to resolve large measurement volumes on the order of several cubic meters with a spatial accuracy in the lower millimeter/upper sub-millimeter range, comparable to the resolution limit defined by the flow tracer size.

2. Related Work

Event cameras have emerged in the neuromorphic engineering community already in 1991 as an attempt to mimic the function of biological retinae (Mahowald & Mead, 1991). However, only since the 2000s have they evolved from lab prototypes to commercially available cameras (Lichtsteiner et al., 2008). Currently, ECs are heavily researched in the areas of computer vision and robotics in an attempt to accelerate classical image-based computer vision tasks such as feature extraction, simultaneous localization and mapping, segmentation, and pattern recognition, among others. An extensive review of active research areas and applications of event cameras is provided in Gallego et al. (2020). ECs have also been applied to fluid dynamical problems in a few studies already. Drazen et al. (2011) tracked tracers in a pipe flow with a single EC and compared the results to reference measurements with a high-speed frame camera and a commercial particle tracking software. The main objective of their work was to identify and track the tracer particles directly from the event stream. No particle motion or flow field reconstruction was reported and the 2D test section spanned only a few square centimeters. The works of Ni et al. (2012), Berthelon et al. (2017) and Howell et al. (2020) concentrated on the application of ECs to microscopic, hydrodynamic flows seeded with micro beads. These scenarios all featured relatively small 2D observation regions on the order of a few square millimeters or less, captured by a single EC. Previous work that led to our current research was carried out by Borer (2014) and Borer et al. (2017), who used multiple ECs to track and reconstruct the motion of helium-filled soap bubbles (HFSBs) in 3D in a wind tunnel environment. The approach relied heavily on 2D and 3D Kalman filters for tracking, which proved difficult to initialize when new tracer particles entered the field of view of the cameras.

Limited by the comparatively low sensor resolution available at the time, measurement volumes up to about one cubic meter were processed. As their algorithms were implemented in MATLAB, data had to be recorded first and subsequently processed offline. Wang et al. (2020) used a pair of ECs to capture the 3D motion of tracers in a centimeter-sized water tank. To extend the sparse measurement data to a volumetric domain and to correct for measurement errors they performed a constrained optimization on the measurement data enforcing criteria such as incompressibility and temporal consistency in the reconstructed flow field. The extensive optimization runs came at the cost of offline processing durations exceeding several minutes per frame. In more recent developments, Christian Willert and Joachim Klinner have looked into assessing the potential of ECs for PIV-like measurements (two-dimensional, two-components). At the time of writing, their work is under consideration for publication in Experiments in Fluids with the title "Event-Based Imaging Velocimetry – An Assessment Of Event-Based Cameras For The Measurement Of Fluid Flows".

In our previous work (Rusch & Rösgen, 2021) we introduced the TrackAER measurement system to provide true real-time, online analysis of flow fields across a wide range of flow speeds and in observation volumes exceeding several cubic meters. At the time, TrackAER was limited to measurements in 2D. Recent developments extend the system to 3D measurements by means of multiple ECs and add the extraction of velocity information. The measurement system now provides real-time visual feedback in the form of labeled Lagrangian particle tracks of the tracers, visualized both in the individual 2D, single camera views and in a joint interactive 3D viewer.

3. Measurement System

The TrackAER measurement system is a combination of tightly-coupled hardware and software components. Figure 1 provides a schematic overview of the system and its operating principle, considering here an aerodynamic test of a car: Upstream of the test section the flow is seeded with tracers such as HFSBs that are advected by the flow. Multiple ECs are flexibly positioned at the measurement site. After an integrated camera calibration step, they are used to capture the motion of the tracers. It is noteworthy that no laser illumination is needed. Volumetric illumination by, e.g., light-emitting diodes (LEDs) suffices to generate detectable tracer signatures on the ECs. This greatly enhances the practical applicability of the measurement system in various experimental environments (especially in wind tunnels) as laser safety concerns are eliminated. Each camera is connected to a host computer, which runs the front- and back-end software of the TrackAER system. The latter detects and tracks tracers in the individual cameras' data streams, fuses the independent streams and reconstructs the positions of the tracer particles asynchronously. The back-end is complemented by a graphical user interface (GUI) providing means to adjust all algorithmic parameters as well as camera settings while the measurement system is running. Furthermore, the front-end visualizes the reconstructed tracer tracks as 3D path lines that are color-coded with their respective velocity histories or other track features. Thereby, an online feedback is provided to the observer enabling immediate insights even into unsteady or transient flow fields.

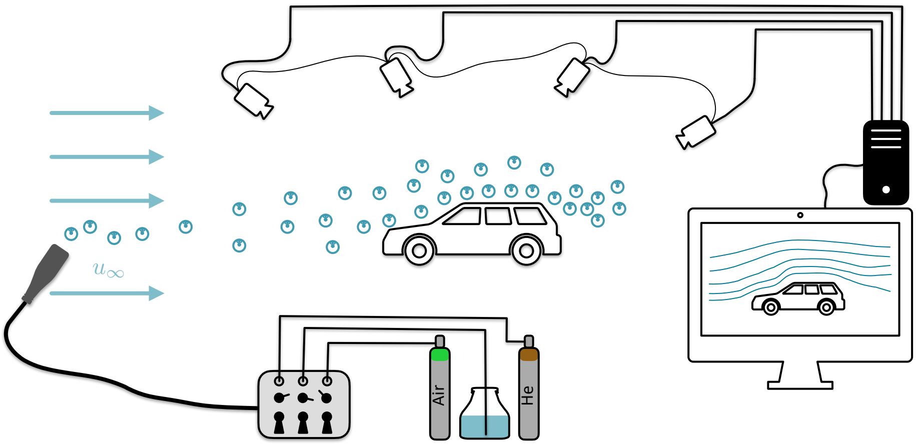


Figure 1. TrackAER measurement system overview.

Algorithmically, TrackAER builds up an asynchronous “per-event” processing chain, starting from the raw event stream of each EC and ending with the rendering of detected tracer streaks in the 3D viewer. At the individual camera level real-time particle detection and tracking is performed utilizing the spatio-temporal coherence of events as they are registered by the sensor. Noise events are effectively suppressed while particles with a coherent visual signature are reliably detected. Prior to each measurement, all cameras are calibrated to retrieve their internal and external camera parameters. We utilize an active, blinking LED target for this task and conveniently employ the same 2D detection and tracking algorithm for target detection that TrackAER also uses for tracer tracking. Once the photogrammetric calibration of the cameras is established, tracer particles are tracked in each camera’s view and temporal coherence and epipolar conditions constrain the 3D correspondence problem. Unambiguous matches are triangulated from multiple camera views, resulting in an asynchronous stream of 3D incremental tracer position changes. Spatio-temporal coherence is again the key to assign the 3D reconstructions to distinct tracer path lines. These discretized path lines are fitted with 3D curves generating continuous streaks of the tracer particles in closed analytical form. Whenever a new 3D reconstruction is assigned to an existing particle track, the 3D curve fit is updated recursively. As a final step, the reconstructed 3D path lines of the tracers are rendered in the TrackAER GUI. Compared to a simple 3D track reconstruction, the availability of both, tracer positions and arrival times, allows for an enhanced labeling of the path lines. In the Lagrangian sense, particle velocities and accelerations are readily available for color coding, but also certain topological features of the tracks could be rendered such as their curvature and torsion, which can be related to vorticity (Braun et al., 2006).

The processing paradigm follows an event-based approach throughout the computational chain. The sequential and asynchronous processing of tracer events facilitates the independent operation of a variable number of cameras. An eventual upper limit is given by the number of cores available on the host computer. Potential buffer over- or underflows are effectively prevented by throttling the complete data pipeline, not only individual processing steps.

A specific challenge arises during the 3D reconstruction step, where event candidates from the different cameras have to be matched. While spatial proximity can be assumed for proper matches via the epipolarity constraint, this does not strictly hold true for the temporal coincidence. The timestamping provided by the EC includes a random latency component that requires the introduction of a temporal acceptance window and, thus, a form of interval search/recursion in the streamed data. To maintain the overall real-time capability, the size of this window has to remain limited, leading to a potential loss of matched events. Note, however, that this does not imply an increasing probability of incorrect matches.

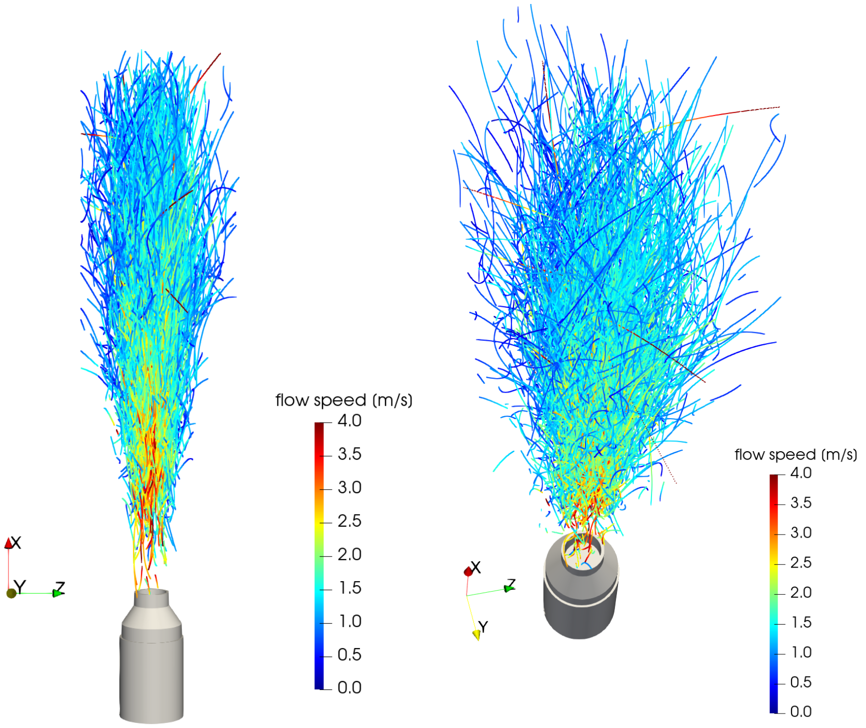
On the analog side of the EC sensor processing, the detection of HFSBs poses some special challenges as well. The very small optical signature of the tracers leads to a speed-dependent decrease in detection efficiency since fast moving tracers create reduced contrast changes in the pixels.

4. Results

As exemplary test cases, in Section 4.1 we investigate the turbulent jet of an air purifier ejecting into quiescent ambient air. Furthermore, we measure and visualize the flow in the wake of a fighter jet wind tunnel model to highlight the detectability of complex vortical structures in Section 4.2.

4.1. Free Jet

The air purifier has a cylindrical shape ingesting air over the entire lateral surface and ejecting upwards through a nozzle along the main axis of the cylinder. To seed the flow, HFSBs are introduced close to the conical exit nozzle of the air purifier device. Subsequently, tracers are entrained in the jet and advected with it. Figure 2 depicts the measurement scenario with the resulting color-coded Lagrangian particle tracks. Note that we show an accumulation of more than 3’000 streaks here as the online, real-time behavior of the measurement system cannot be adequately captured in a still picture. The actual measurement system does, indeed, continuously update the 3D view of the scenery as new tracer reconstructions become available without any limit on the duration of the measurement. Every 3D curve corresponds to a single time-resolved particle track – no spatial binning or temporal averaging is applied. Close to the air purifier exit there are almost no streaks as it takes a certain time for the HFSBs to become entrained in the jet. The chaotic turbulent structure of the jet is clearly visible, as is the decay of the velocity profile with increasing radial distance from the cylindrical axis. Furthermore, the jet speed decays along the cylinder axis with increasing distance from the nozzle exit. The accompanying radial spread of the jet conforms with the observed flow deceleration. The measurement volume covers about 1.0 m^3.



(a) Frontal view.

(b) Tilted view.

Figure 2. Particle track reconstruction of an air purifier ejecting into quiescent ambient air.

4.2. Wake of Delta Wing Airplane Model

A fighter jet wind tunnel model is chosen as another test case due to its delta wing configuration featuring an interesting, yet challenging wake flow field. The model is mounted in the subsonic wind tunnel of the Institute of Fluid Dynamics at ETH Zurich which has a $2 \times 3\ \mathrm{m}^2$ test section. At an angle of attack of 15°, the model is tested at varying bulk flow speeds to investigate the real-time capabilities of the measurement system as well as its transient behavior at different flow speeds. An HFSB seeder injects tracers into the free stream flow upstream of the wind tunnel contraction. The seeder outlet's lateral position is chosen such that the tracers target one half of the model's delta wing. TrackAER is set up around the aircraft model to observe the wake region. At a bulk flow speed of $2.5\ \mathrm{m\ s}^{-1}$, Figure 3 depicts TrackAER's virtual 3D scene of the aircraft model as seen from above with online rendered tracer paths and accompanying color-coded velocity information. The visualized data amounts to a dynamic streak accumulation of 1 s. One clearly recognizes the swirling vortex structure in the aircraft's wake as well as the decreased flow speed towards its center. Note that again, the real-time behavior of the measurement system cannot be delivered in the form of static images. The actual TrackAER measurement was performed continuously for 20 minutes in this case.

Next, the wind tunnel's bulk flow speed is increased to $4.8\ \mathrm{m\ s}^{-1}$. Furthermore, the reconstructed tracers are accumulated for a longer period of time of 20 s to yield a denser, more complete reconstruction of the wake flow field. Figure 4 shows the scenario form three different points of

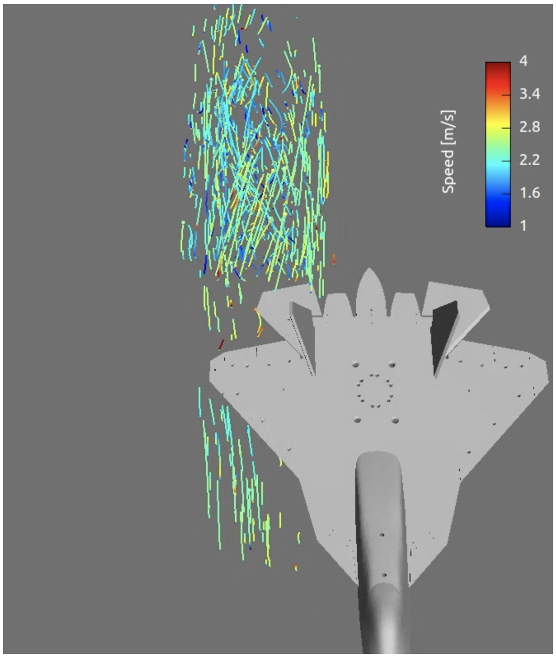
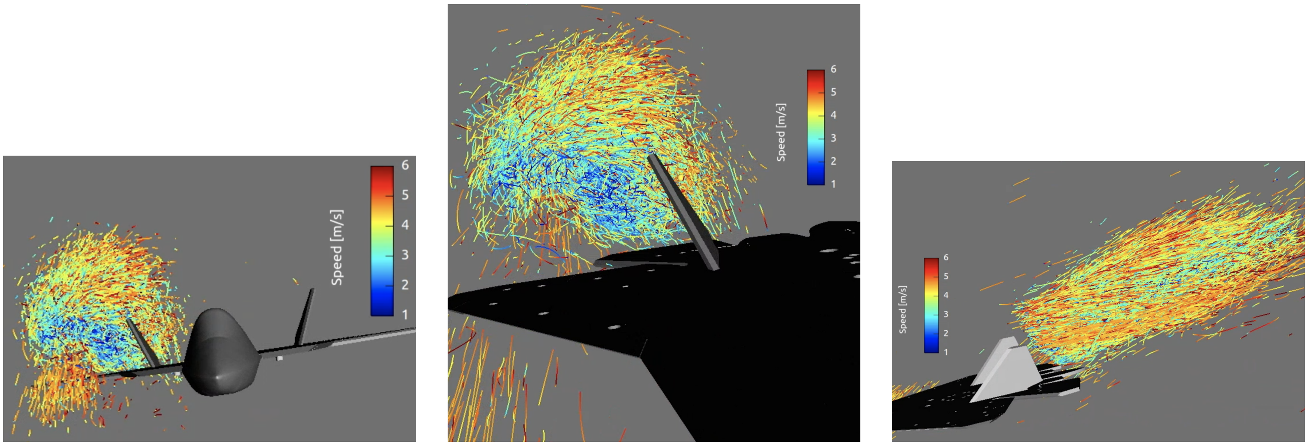


Figure 3. TrackAER view from above onto a fighter jet wind tunnel model at $u_\infty = 2.5$ m s^{-1}. 1 s worth of real-time reconstructed and speed-labeled tracer path lines is visualized.

view: 4(a) shows the entire model from upstream along with the visualization of the vortex system. 4(b) also depicts the situation from upstream, but the view is zoomed in to capture more details of the vortex system. 4(c) depicts the flow field from the side. Looking downstream, on the left-hand side of the large primary delta wing vortex Figures 4(a) and 4(b) additionally reveal a less prominent, secondary vortex that interacts with the primary delta wing vortex downstream of the aircraft. This observation conforms with the two-stage compound delta wing geometry of the airplane model.



(a) View from upstream.

(b) Close-up view.

(c) Side view.

Figure 4. Visualization of the vortex system in the wake of a fighter jet wind tunnel model at $u_\infty = 4.8$ m s^{-1}. The accumulated particle tracks correspond to a sliding time window of 20 s. Local flow speeds are color-coded.

Note that the test cases shown in this section were specifically performed at relatively low flow speeds to generate accompanying video material, in which the tracer movement and online generation of particle tracks is still human-perceivable. We have successfully performed measurements with TrackAER at flow speeds up to 40 $\mathrm{m\,s^{-1}}$ in the subsonic wind tunnel at ETH Zurich. Beyond that speed, fading tracer signals massively reduce the quality of the data and cause reconstruction drop outs.

Further statistical processing of the data, such as the accumulation of track information in certain measurement planes is possible as well. Since this type of post-processing can occur independently of the real-time data stream, however, it is not part of the event-based processing pipeline and is not further elaborated in the present context.

5. Conclusion

We have presented our novel flow measurement system, TrackAER, which uses multiple ECs to reconstruct 3D, time-resolved flow fields in large measurement volumes with real-time visual feedback and analytical capabilities. By efficiently processing the asynchronous event data streams of multiple cameras and subsequently fusing them into 3D information, we are able to visualize the resulting Lagrangian particle tracks with velocity information online in a virtual 3D scene. Two flow scenarios are presented demonstrating the TrackAER capability to accurately capture topological characteristics of the flow fields and to provide insights on the turbulent, unsteady flow structures present. It should be stressed that we cannot fully reproduce the online behavior of the measurement system in the form of still pictures and by providing an accumulation of time-resolved streaks as the final visual result. Our future work will aim at reconstructing even larger flow fields with higher precision and expanded Lagrangian diagnostics. Furthermore, we will extend the application of the system to specific flow field scenarios where other experimental techniques are inapplicable due to storage, bandwidth or speed limitations, such as extremely slow flows or high-speed transient flows.

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