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LETTER

Toward real-time particle tracking using an event-based dynamic vision sensor

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Abstract Optically based measurements in high Reynolds number fluid flows often require high-speed imaging techniques. These cameras typically record data internally and thus are limited by the amount of onboard memory available. A novel camera technology for use in particle tracking velocimetry is presented in this paper. This technology consists of a dynamic vision sensor in which pixels operate in parallel, transmitting asynchronous events only when relative changes in intensity of approximately 10% are encountered with a temporal resolution of 1 μs. This results in a recording system whose data storage and bandwidth requirements are about 100 times smaller than a typical high-speed image sensor. Post-processing times of data collected from this sensor also increase to about 10 times faster than real time. We present a proof-of-concept study comparing this novel sensor with a high-speed CMOS camera capable of recording up to 2,000 fps at 1,024 × 1,024 pixels. Comparisons are made in the ability of each system to track dense ($\rho > 1$ g/cm^3) particles in a solid–liquid two-phase pipe flow. Reynolds numbers based on the bulk velocity and pipe diameter up to 100,000 are investigated.

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1 Introduction

In experimental fluid mechanics, the kinematics of the flow can be measured non-intrusively using optical methods such as particle image velocimetry (PIV) and particle tracking velocimetry (PTV), (see Sveen and Cowen 2004; Cowen and Monismith 1997; Raffel et al. 1998; Adrian 1991). PIV is a pattern matching technique that cross-correlates similar regions in a pair of images to track the motion of a group of particles. PTV is a method where particles are found in a image, tracked in time, and the velocity calculated from the measured particle positions and the time separation between a pair of images.

Advances in digital camera technology toward higher frame rates has yielded the ability to better resolve high-speed flows in a method called time-resolved PIV (TR-PIV). Data rates from traditional PIV are limited by the frame rate of the camera, typically on the order of 30 fps. With the temporal resolution of the measurements of TR-PIV increasing to O(1 ms), turbulence quantities of the fluid can also be resolved in high-speed or rapidly evolving flows. One main drawback of TR-PIV is the storage requirement of the collected images (a rate of $\approx$2GB/s) along with the subsequent lengthy data analysis.

Alternatives to traditional PIV also exist. Holography (Tao et al. 2000) and ultrasonic transducers (Mordant et al. 2005) have been used to track particles in 3-D space. Voth et al. (1998) used a position sensitive photodiode to record particle tracks between a pair of counter-rotating disks. Voth et al. (2001) used silicon strip detectors designed for high-energy physics experiments to track particles in a turbulent flow and was able to record particle position data at 70 kHz, with an accuracy of 0.08 pixels.

The application of a novel camera technology for PTV is presented here. While PTV is the focus of this letter, the technique could be extended to techniques such as optical flow. This novel sensor is termed a dynamic vision sensor (DVS) and is an address-event representation (AER) camera. AER cameras differ from traditional camera technology in that they are frame-free, i.e., no complete image is recorded and conveyed at a regular frame rate. Instead, the addresses of pixels are asynchronously read out as events only when a relative change in log intensity of 10% is observed in that pixel (Lichtsteiner et al. 2008). In our experimental setup only a few pixels will register changes at any one time, so the bandwidth and subsequent storage and processing requirements are greatly reduced. Images and frames can, of course, still be reconstructed from the asynchronous event stream, but the equivalent frame rate is a post-processing choice that is independent of the actual sensor data.

This paper presents a proof of concept that reliable real-time high-speed PTV can be implemented using a dynamic vision sensor. Such a sensor will provide low-cost, high temporal resolution particle tracking with minimal data storage requirements when compared with conventional techniques. The test case consists of a solid–liquid two-phase pipe flow, where dense (ρ_p >1 g cm^{-3}) particles are dispersed in a flow with bulk Reynolds numbers ranging from approximately 10,000 to 100,000.

2 Experimental setup

Experiments were conducted to quantify the performance of the DVS-based system using the results of a Photron camera–based PTV system as a reference. This has the drawback that the comparison is only as accurate as the Photron measurements. It should be noted that using well-characterized movie sequences is an unviable alternative as the DVS sensor is dependent on continuous observation of the particles for optimal performance. Playing back a sequence of frames recorded at discrete intervals would prevent the DVS system from performing optimally from the outset. It is therefore dependent on a real-world stimulus for proper characterization of the sensor.

The experiments described here were conducted in the hydrodynamics laboratory at the University of Oslo. A brief overview of the experiments will be given here, but a more in-depth discussion is provided in Drazen and Jensen (2007).

The test facility is a 5-cm ID perspex pipe controlled via a pump driven by a variable frequency drive. Bulk properties of the flow such as density, temperature, and flowrate are measured during each run. The measurement region is 27.5 m downstream of the particle inlet and consists of a perspex box filled with Isopar M that encloses the pipe. A series of eight runs were conducted where the bulk velocity in the pipe and the Photron camera's frame rate were varied (Table 1).

The field of view is illuminated using a 5-W Innova 300 C multiline argon-ion laser. The laser light was delivered to the measurement region via a fiber optic cable and passes through a collimator before entering the light sheet optics. A set of optics with a 30° divergence angle was used to create a 3-mm lightsheet spanning the camera's field of view (6 cm^2) along the centerline of the pipe.

We used 950-µm polystyrene particles ($\rho = 1.02$ g/cm^3) dispersed in water to test the tracking ability of the DVS. At the beginning of a run, the particles were introduced into the pipe and recording began once they arrived at the measurement region. For the purposes of this study, the particles needed to be larger than a pixel. The particle diameter is approximately 20 pixels for the Photron system and 3 pixels for the DVS system.

For the reference data, we used a Photron Ultima APX, a 1 megapixel CMOS camera capable of recording up to 2,000 fps at full resolution. The camera has sufficient memory to record approximately 3 s of data at full-spatial and temporal resolution. A lens aperture of f1.2 provided sufficient illumination for particle tracking, but a shutter speed equal to 1/frame rate was not enough to freeze the motion of the dispersed phase, so there is some blurring of the particle images. The centroid of the particle image is tracked, so this uncertainty is not expected to introduce any significant errors in the analysis. The entire optical system is calibrated before and after the set of experiments using a grid with 1-mm holes spaced every 5 mm within the measurement region.

The camera's internal clock was synced to an external TTL signal, and after initiating recording, a sync signal was sent to the DVS. This reset the timestamp and allowed for subsequent alignment of the data from each camera.

Post-processing of the images for particle tracking was performed using a commercially available software package called Digiflow (http://www.dalzielresearch.com/). The particle tracking algorithms used in Digiflow are based on those described in Dalziel (1992).

The DVS was placed on the opposite side of the pipe from the Photron camera at a distance of approximately 20 cm to have the same approximate field of view. It was calibrated with the same calibration grid as the Photron system. A USB cable connected it to a laptop where it recorded directly to disk with several hours of recording capacity.

The DVS has a spatial resolution of 128 × 128 pixels and a temporal resolution of 1 µs. Pixels are asynchronous emitters of events, and these events are encoded using the pixel coordinates combined with a timestamp. Arbitrated

Table 1 Experimental conditions used for the comparison

Run #	Frame rate (Hz)	Bulk velocity (m s^{-1})	*Re*
1	1,000	0.47	23,618
2	1,000	0.75	39,880
3	1,000	1.20	65,534
4	2,000	1.29	71,071
5	1,000	0.22	11,950
6	1,000	0.90	47,850
7	2,000	2.04	108,780
8	1,000	1.14	60,921

Reynolds number is based on the pipe diameter and bulk velocity

access to the communication bus prevents collisions between events but can introduce delays to event timing. The sensor has a peak bandwidth of about 2 million events/s, so several events can receive the same timestamp. Each event is the result of a relative change in photocurrent/illuminance, typically about 10% for the settings used in these experiments. The sign of that change (positive or negative) is recorded as an extra bit in the pixel address. A short burst of events with positive sign will be generated as the particle enters the pixel and a short burst of negative events as the particle leaves, see Fig. 1.

3 DVS particle tracking method

Particles are identified as a coherent event activity of neighboring pixels within a time window T. If the event flow is slow enough (on the order of a few kEvents/s or keps), the computations for reconstruction of position and

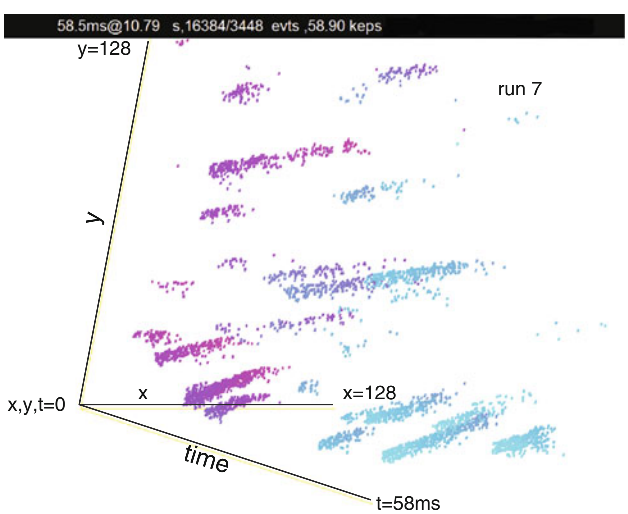

Fig. 1 Sample DVS event data of 58-ms duration taken from Run 7 shown as space-time 3-D *plot*. Each *dot* represents one pixel event. Moving particles create linear tracks in space-time. *Color* indicates relative time during this 58-ms slice

speed can be executed on a laptop faster than real time. The algorithm is open-sourced as the jAER project (Delbrück 2007, http://www.jaer.wiki.sourceforge.net/) as the class ParticleTracker and is as follows:

For every new event:

- Check all 24 nearest and second nearest neighboring pixels for events that are no older than T µs. $T = 2$ ms for the experiments reported here.
- If there are no nearby recent events:
  - Create a new particle (add to internal particle list).
  - Assign this particle the location of the event, **e**, and set the particle 'mass' $m = 1$. The mass is a measure of the particle's size and recent activity.
- Else if there are one or several nearby recent events:
  - If these events belong to different particles: merge these particles in the list.
  - Assign the event to the corresponding particle.
  - Update the position of that particle with the new event.

A particle's position is updated when a new event with event coordinates **e** is assigned to that particle in the following manner:

- The particle's 'mass' m is multiplied by $e^{\frac{-t}{T}}$ and then incremented by 1, where t is the time interval since the last particle event. (Only particles with a minimal mass M are considered alive. M has been set to 5 for the experiments shown here.)
- The new position $\mathbf{p_n}$ is computed as the weighted vector sum of the new event's position **e** and the old position $\mathbf{p_o}$ as $\mathbf{p_n} = \frac{1}{m}\mathbf{e} + \frac{m-1}{m}\mathbf{p_o}$

If a new event connects two previously separate particles (e.g., if their trajectories cross each other), the particles are merged in the particle list. The new particle's mass m is the sum of the individual masses, and the position is the average of the individual positions weighted with their individual masses. Note that merging happens continuously whenever an event connects two activity 'blobs'.

On the other hand, a 'blob' separating into two or more particles (e.g., two particles having crossed trajectories) is not as easily detected. To address this, an extra processing step is introduced at regular intervals that 'cleans up' the particle list. This constitutes an exception from the event-driven processing. For the experiments described here, this interval was 20 ms and the following algorithm is applied:

- The whole pixel array is parsed and all pixels are checked for events that are no older than T. These pixels are tagged as being alive.
- Areas of coherently connected, alive pixels are defined as new particles in a new particle list.

- If but one single new particle has overlapping pixels with a single particle in the old list, it inherits the old one's mass and position.
- If several new particles have overlapping pixels with the same single particle in the old list (due to a separated 'blob'), the new particle with the largest connected area inherits the mass and position of the old particle. The other new particles are spawned with zero mass and an undefined position such that the first new event of this particle will establish its position.

The tracking algorithm executes two more functions at regular intervals:

- At intervals of 20 ms, the particles with a mass exceeding a threshold M are displayed as an overlay onto the reconstructed images on the computer screen.
- At intervals of 1 ms or 0.5 ms (corresponding to the Photron frame rate for particular test runs), the particle list of particles with a mass exceeding M is written into a log-file.

4 Results

The example frame in Fig. 2 illustrates the generally higher detection threshold of the DVS system: low contrast particles that were only touching the light sheet did not create enough events. Also, particles on different sides of the sheet led sometimes to the detection of different particles.

For each particle of the DVS system, the closest particle of the Photron system was considered to be the matching particle. Scatter plots of the (x, y) position of the matching particles are shown in Fig. 3. The title of each subfigure is the correlation coefficient between the two datasets. When the DVS system particles reach the edge of the field of view, they do not disappear instantly. Instead, they slowly lose "mass", and this appears predominately in Fig. 3a–c as a horizontal line near $X_d = 0.02$. Not surprisingly, the particles tend to congregate in the lower half of the pipe for the lower Reynolds numbers, while they are more dispersed vertically at the higher Reynolds numbers. Despite the broad nature of the distributions, there is a fair amount of correlation between the two datasets.

Run 8 was conducted using a standard incandescent bulb as the light source, illuminating the entire pipe volume instead of just a thin sheet. Consequently, particles at unknown distance from the two cameras on opposite sides of the pipe cannot be matched with any confidence. Despite this, we wanted to get an indication of the respective performances, as the DVS system with its logarithmic sensitivity is not strongly dependent on strong illumination. As

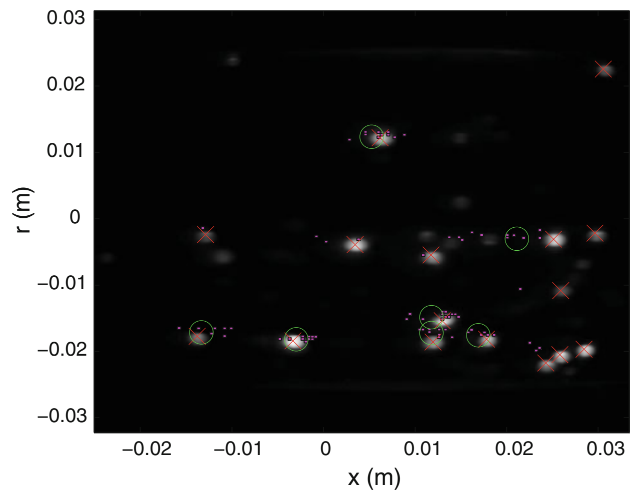

Fig. 2 Particle positions found from the Photron *image* and a subset of the DVS data in Fig. 1 (corresponding to the image's exposure time), overlaid on the original Photron image. DVS events are *purple dots*, the particles found by the DVS tracker are shown as *green circles*, and the particles from the Photron image as *red* X's

expected, a larger number of particles were detected by the DVS system. Future work should include using an incandescent light sheet to minimize the error caused by projection of out of plane motion. Alternatively, a stereoscopic

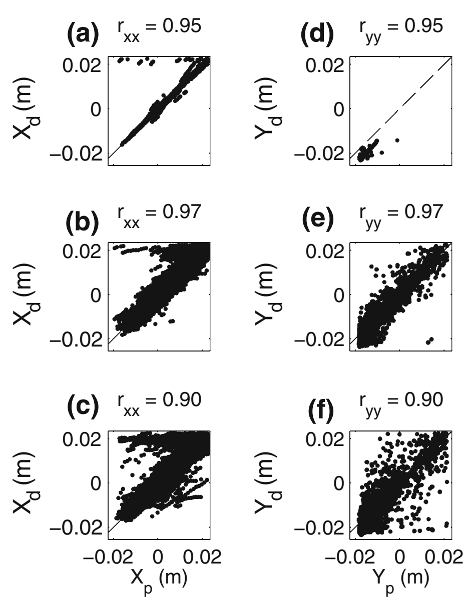

Fig. 3 Scatter *plots* of *horizontal* and *vertical* particle positions as determined by the Photron camera, (X_p, Y_p), and the DVS system, (X_d, Y_d) for **a** Run 1 − X, **b** Run 4 − X, **c** Run 7 − X, **d** Run 1 − Y, **e** Run 4 − Y, **f** Run 7 − Y. The title of each *figure* shows the correlation coefficient between the two datasets. If the correlation were perfect, the data would lie along a 45° *line*. Particles appearing to be "stuck" at the DVS system boundary are an artifact of the processing, as particles that have *left* the frame are no longer updated by events but will survive in the particle list for some time

system using an incandescent lighting system would also allow for the tracking of particles in 3-D space.

For all other runs, the Photron camera found a larger number of particles per frame as compared to the DVS system. While the DVS system is more sensitive to changes in photocurrent, the number of events returned per particle is still small as shown in Fig. 2. Having enough events that last long enough to qualify as a particle is difficult at the resolution used in these experiments. The goal of these experiments, however, was to demonstrate the use of this novel camera technology for particle tracking. Next-generation DVS cameras with higher-resolution sensors will only improve in their particle tracking capability. Even at the low resolution of the current DVS camera, significant improvements on processing speed have been realized.

The Particle Tracker class in the jAER software processes events at a rate of 500–1,200 keps on a 3.33-GHz Core i7 975 Windows 7 processor running Java 1.6. Since the average rate of events during the experimental runs is only about 50 keps, the processing runs about 10 times faster than real time. Running Digiflow on 6143 images (3 s at 2,000 fps) takes 144 min on a dual 2.67-GHz Quadcore machine running Windows XP, nearly 2,900 times slower than real time.

5 Conclusion

In this paper, we have presented a proof-of-concept study examining the utility of using a novel sensor for particle tracking measurements. One of the shortcomings of methods used in traditional optical fluid dynamics measurements is the time lag of the results. A TR-PIV setup has data rates of several kHz and often requires a high-energy laser sheet to achieve proper particle illumination due to the short exposure times. High frame rates require a huge data bandwidth, often only possible with a local buffer in the camera. In the direct comparison in this paper, particles were observed flowing through a pipe for 6 seconds. This required 8 GB of memory on the high-speed camera. With the same resolution as the DVS circuit (128 $\times$ 128 pixels), it would still have needed 120 MB, while the DVS sensor used only 840 kB to record the same sequence.

Due to its frame-free, asynchronous pixel event nature, the DVS vision sensor is able to observe a moving small particle seamlessly from one pixel to the next over a range of speeds, limited only by bandwidth. Its large logarithmic dynamic range does not require uniform bright illumination of a scene to accomplish this high temporal resolution. Data are conveniently streamed via a USB interface to a computer, allowing for long continuous data records. Processing of the data on a computer is simple enough to be executed faster than real time, allowing quick adjustments to an experimental setup, which may be essential in field experiments with test platforms such as a helicopters or underwater vehicles.

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