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Continuous-Time Trajectory Estimation for Event-based Vision Sensors

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1. Introduction

Event-based vision sensors, such as the Dynamic Vision Sensor (DVS [2]), do not output a sequence of video frames like standard cameras, but a stream of asynchronous events (see Fig. 1).

- An event is triggered when a pixel detects a change of brightness.
- An event contains the location, sign, and timestamp of the change.

The high dynamic range and temporal resolution of the DVS, which is in the order of micro-seconds, make this a very promising sensor for high-speed applications, such as robotics and wearable computing. However, due to the fundamentally different structure of the sensor's output, new algorithms are required.

Here, we address ego-motion estimation for an event-based vision sensor using a continuous-time framework [1] to directly integrate the information conveyed by the sensor. The DVS pose trajectory is approximated by a smooth curve in the space of rigid-body motions using cubic splines and it is optimized according to the observed events.

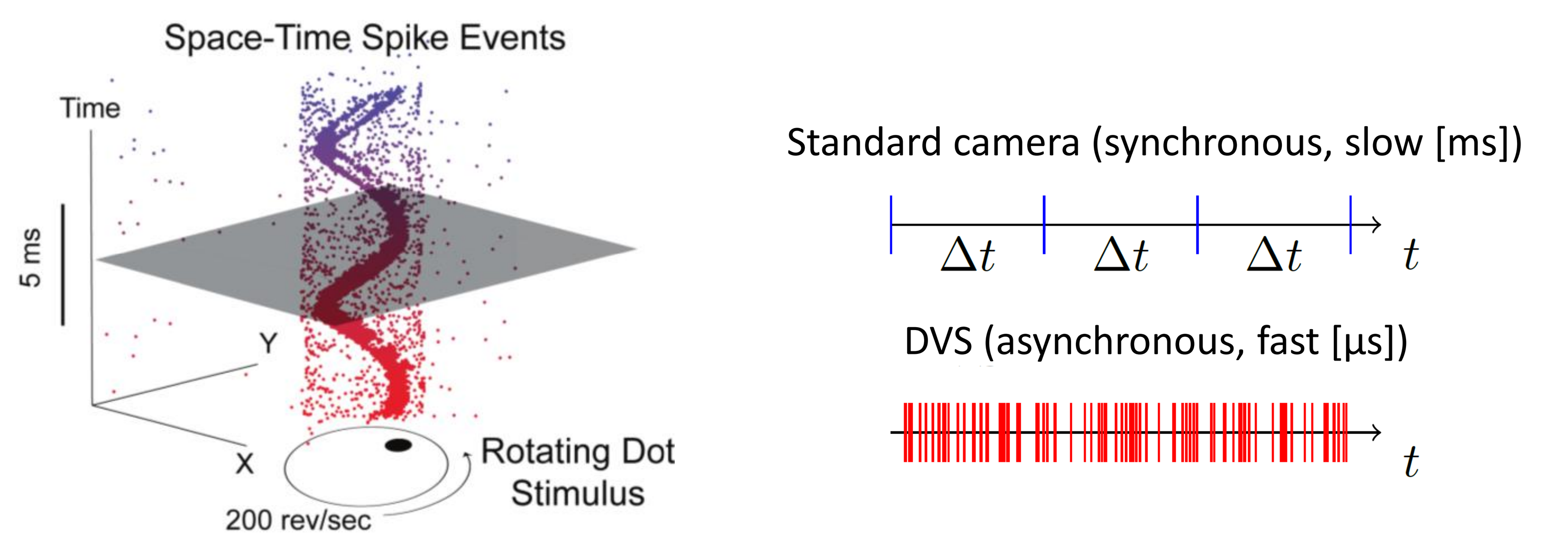
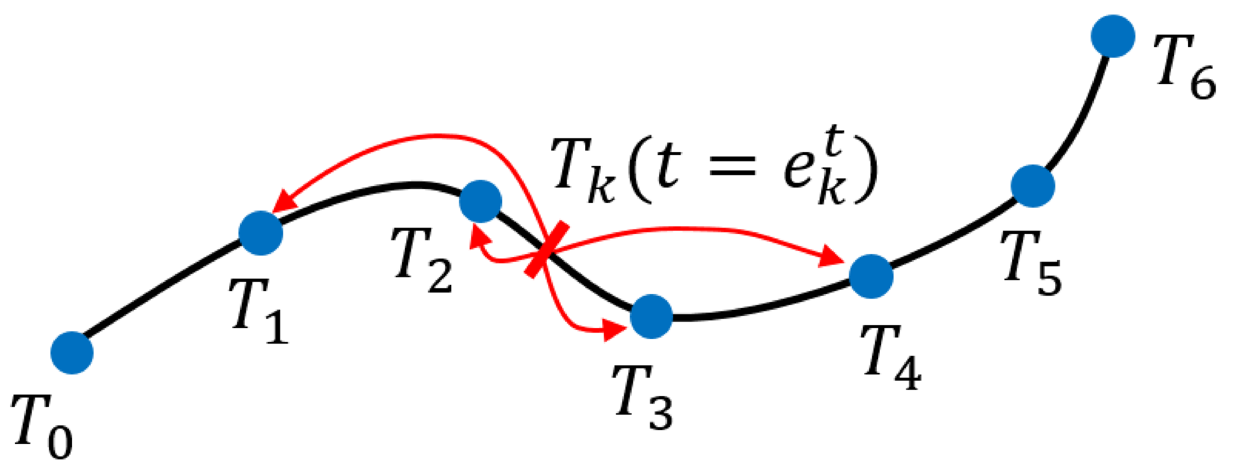


Fig. 1: The output of a DVS is fundamentally different to that of standard cameras.

2. Continuous-Time Trajectories

Following the approach in [1], we use a continuous trajectory representation given by cubic splines since they have desirable properties:

- local dependency of the trajectory with respect to the control points,
- simple analytical derivatives and integrals,
- the possibility of having C^2 continuity.



We adopt cumulative B-spline basis functions formed using the Lie algebra, which produce smooth trajectories in the manifold of rigid-body motions SE(3). We can evaluate the pose at any time along the trajectory, specifically for every time an event was triggered. Therefore, we can both incorporate the asynchronous nature of the events in a natural way and exploit their very high temporal resolution.

We search for the set of control poses (blue) such that the reprojection error of all events is minimized. The pose of each event is only dependent on the closest 4 control poses. This optimization is done in batch mode. Only few control poses are needed to incorporate many events: dozens of control poses for tens of thousands of events suffice.

3. Experiments

We tested our algorithm with sensor-in-the-loop simulation and quadrotor flip experiments (see Fig. 2). During these flips, rotational speeds of up to 1200°/s were measured. We compared our results to an event-based ICP approach [3] and showed that the continuous-time approach yields better results in both experiments (see Fig. 3).

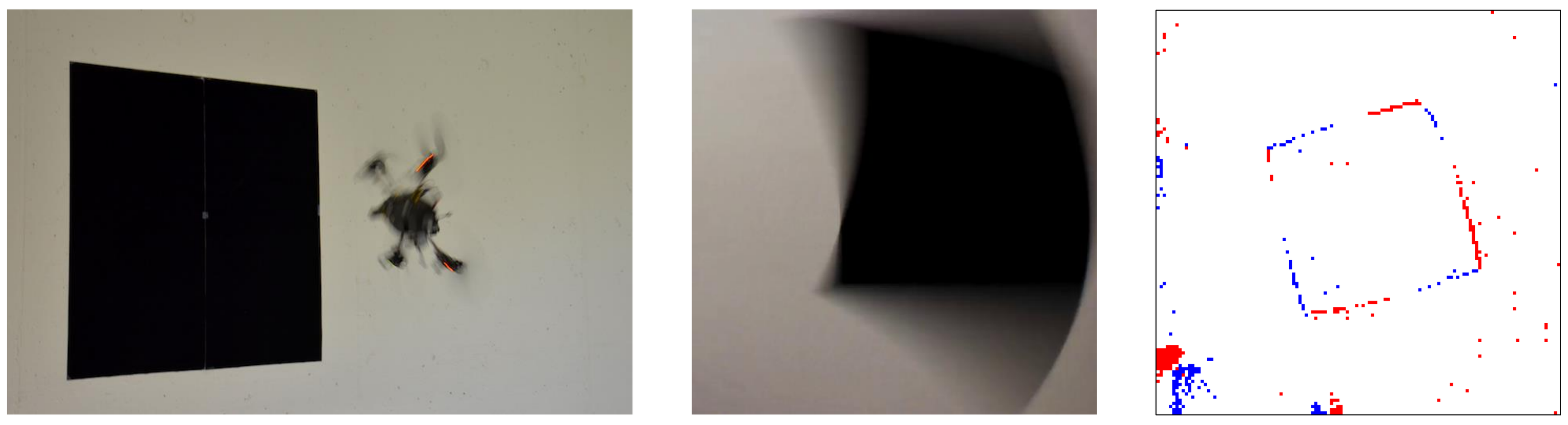


Fig. 2: Quadrotor performing a flip: image of a standard camera compared to a rendering of the DVS' events.

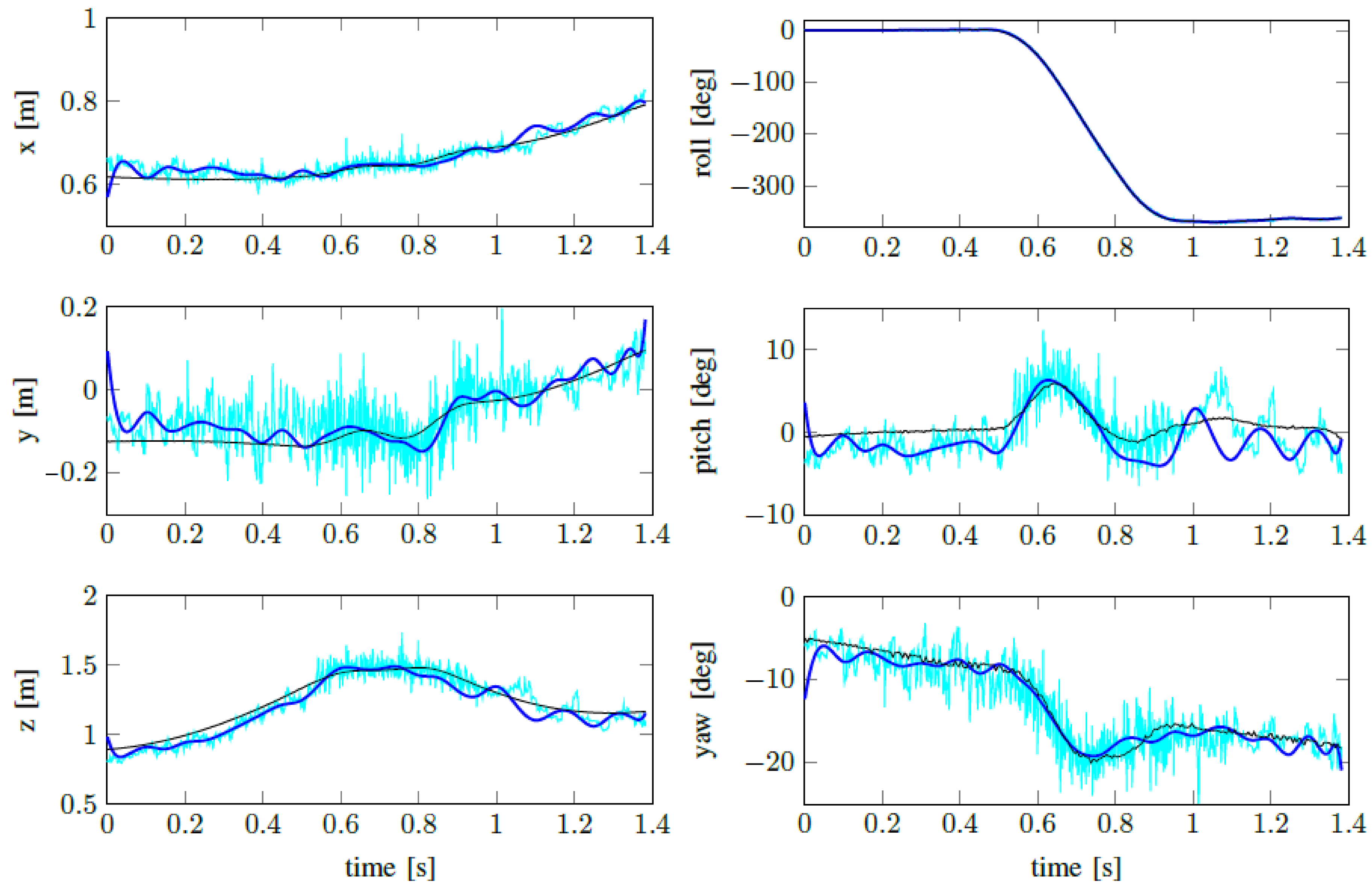


Fig. 3: Tracking comparison of the continuous-time approach (blue) with an ICP-based approach [3] (cyan) for all 6 DOF with ground truth (black).

Conclusion

The continuous-time framework can incorporate the high temporal resolution and asynchronous nature of event-based vision sensors

- Camera pose can be evaluated at *any* time
- A geometrically meaningful error for each event is optimized that has a probabilistic justification
- Optimization problem has few parameters (the control poses)

References

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[2] P. Lichtsteiner, C. Posch, and T. Delbruck. A 128x128 120 dB 15μs latency asynchronous temporal contrast vision sensor. IEEE J. of Solid-State Circuits, 43(2): 566–576, 2008.

[3] E. Mueggler, B. Huber, and D. Scaramuzza. Event-based, 6-DOF pose tracking for high-speed maneuvers. In IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), 2014.

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