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A 5-Point Minimal Solver for Event Camera Relative Motion Estimation

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MPL RPG

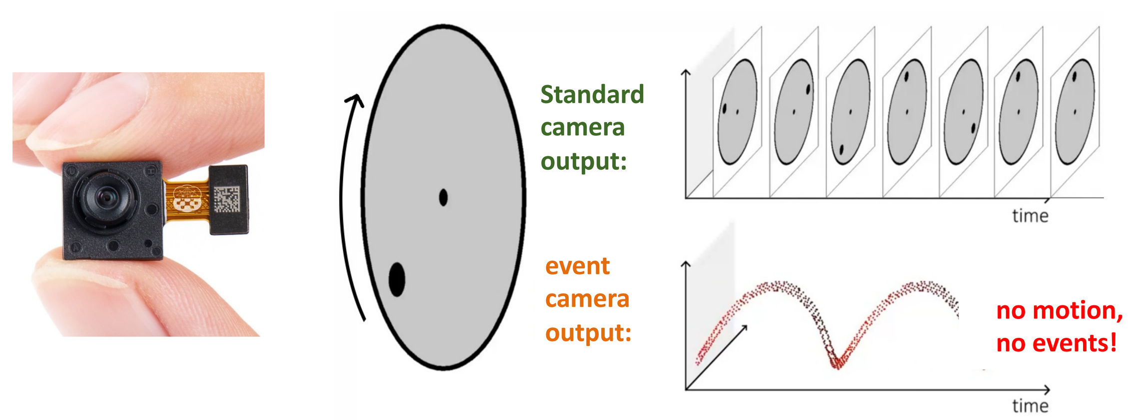
Motivation:

In the line-based motion estimation with event cameras, events generated by a single line are typically modelled as **simple, yet incorrect** spatio-temporal planes.

Contribution:

1. Parametrization of the **non-linear manifold** of events generated by a line observed under locally constant speed;
2. Minimal solver of the manifold parameters: **3D line,** and **partial camera velocity**;
3. Fusion of multiple partial camera velocity measurements into a single, averaged velocity.

What is an event camera?



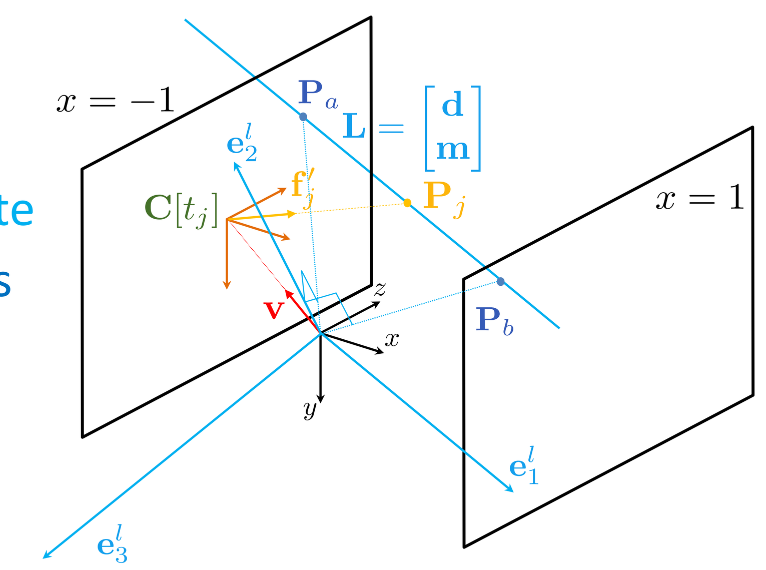
- Only transmits **brightness changes**
- Output is a stream of **asynchronous** events
- **Advantages:** high temporal resolution, reduced motion blur, low power consumption, high pixel bandwidth, HDR

Method:

Events from temporal slice → Extracting eventail manifold → Averaging partial velocity results → Camera Velocity

Geometric view of the incidence relationship

- Plücker coordinate
- 3D line endpoints
- Event ray
- Camera velocity
- Camera position



- We use the **Plücker coordinates** to define a 3D line and an event ray, and their **incidence relationship**
- Only **partial** velocity can be observed by a single eventail solver (**aperture problem**)
- Solve for unknowns $\mathbf{P}_a, \mathbf{P}_b$ and $\mathbf{v}_l$ with Gröbner-basis theory under scale sconstraint: $(\mathbf{R}_l\mathbf{v}_l)^\mathrm{T}\cdot(\mathbf{R}_l\mathbf{v}_l)-1=0$
- Problem has 6 – 1 = 5 unknowns (**scale is unobservable**) --> five events are needed for a minimal solution

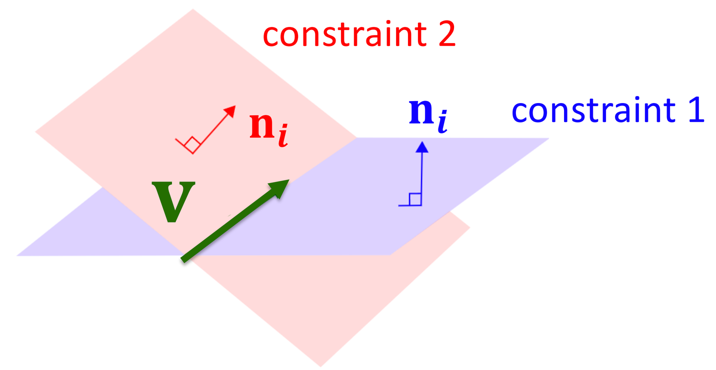
Incidence relation equation: $t_j'(\mathbf{P}_b-\mathbf{P}_a)^\mathrm{T}\left((\mathbf{R}_l\mathbf{v}_l)\times\mathbf{f}_j'\right)-\mathbf{f}_j'^\mathrm{T}(\mathbf{P}_b\times\mathbf{P}_a)=0$

Velocity Averaging Scheme

Linear velocity constraint

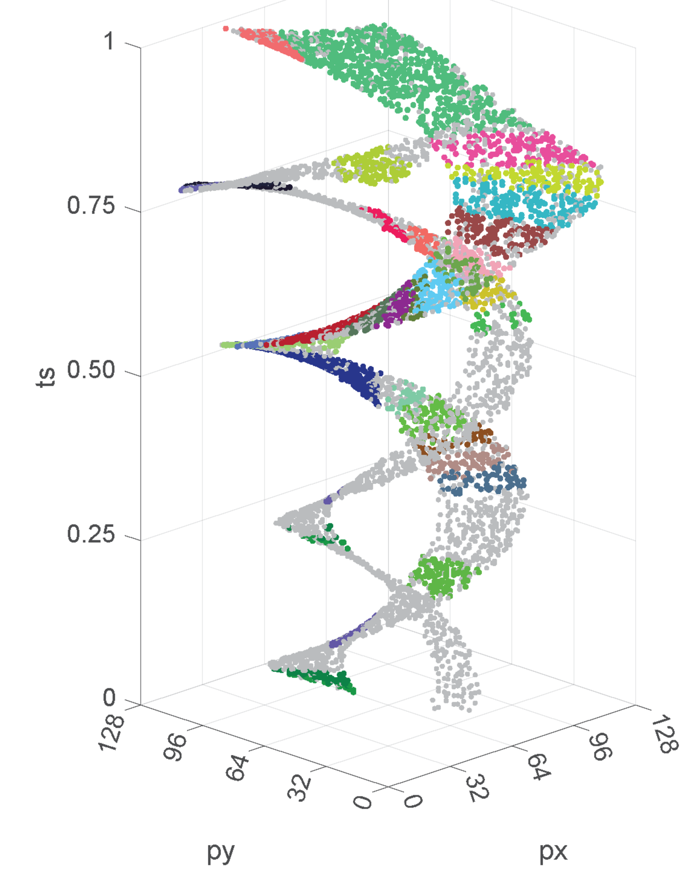
$$\mathbf{v}^\mathrm{T}\underbrace{\left(\left\|\mathbf{e}_{3i}^l\right\|^2\mathbf{e}_{2i}^l v_{zi}^l-\left\|\mathbf{e}_{2i}^l\right\|^2\mathbf{e}_{3i}^l v_{yi}^l\right)}_{\mathbf{n}_i}=0$$

- Each manifold imposes a linear constraint on the camera velocity
- Recover camera velocity by stacking multiple constraints.

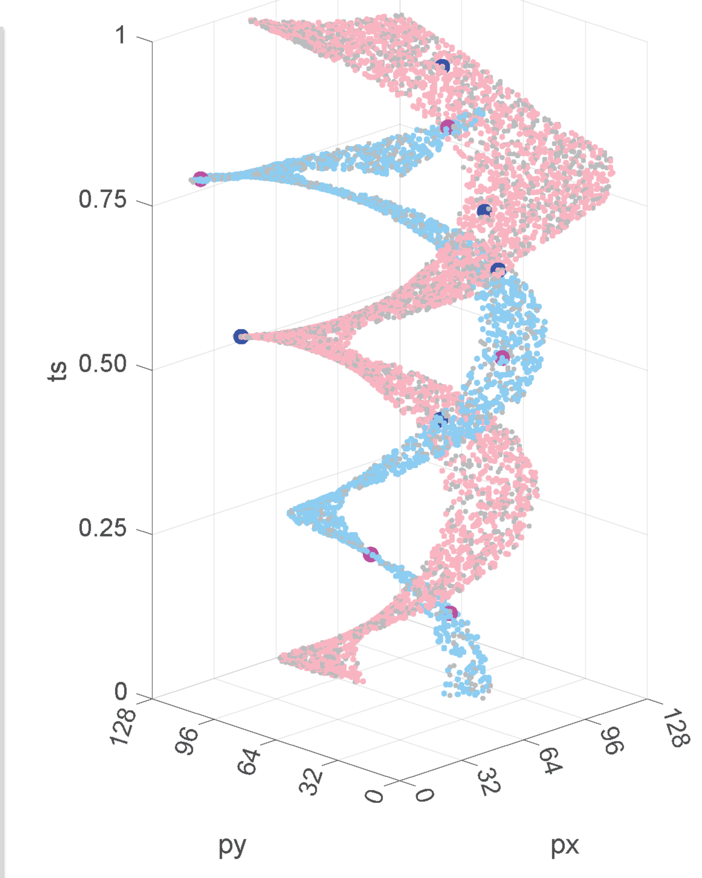


Qualitative Results:

An event camera observing two lines and moving with constant linear and angular velocity triggers events lying on a manifold.



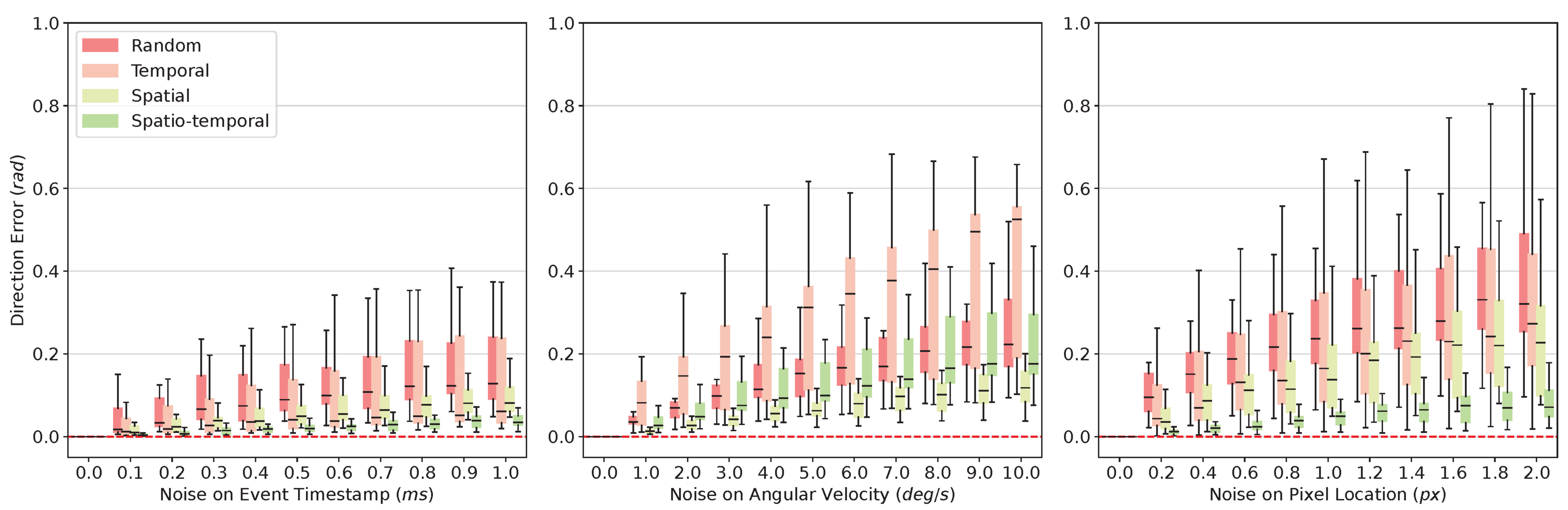
Clustering these events based on spatio-temporal planes [2] generates many spurious clusters (colorful points) and outliers (grey points).



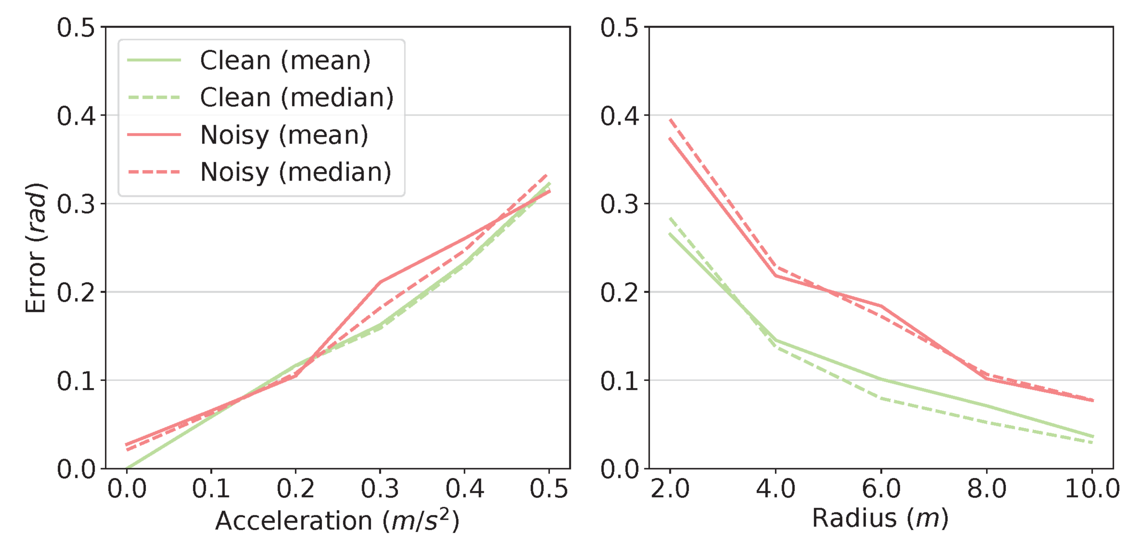
Non-linear manifold clustering generates two large clusters with fewer outliers. Our minimal 5-point solver recovers the parameters for each manifold.

Quantitative Analysis:

Noise resilience of the minimal solver



Validity of motion model from multiple eventails



References:
[1] L. Gao, et. al. VECtor: A versatile event-centric benchmark for multi-sensor SLAM. RAL 2022.
[2] X. Peng, et. al. Continuous event-line constraint for closed-form velocity initialization. BMVC 2021.

Comparison with another closed-form solver on real data

Sequences [1]	CELC+opt [2]			Ours				
	ϕ^*_{mean}	ϕ^*_{median}	Success	ϕ^*_{mean}	ϕ^*_{median}	ϕ_{mean}	ϕ_{median}	Success
board-slow	0.451	0.434	65.69 %	**0.429**	**0.385**	0.484	0.416	100 %
mountain-normal	**0.483**	**0.512**	56.70 %	0.542	0.528	0.584	0.586	100 %
desk-normal	0.464	**0.464**	69.86 %	**0.461**	0.474	0.461	0.466	100 %
sofa-normal	**0.419**	0.455	23.16 %	0.532	**0.438**	0.550	0.514	100 %

* subset where CELC+opt [2] does not fail

Direction Error (ϕ): the angle between the estimated and the ground truth velocity
Success Rate: the percentage of seq. where the algorithm outputs reasonable results

Project Webpage

https://mgaoling.github.io/eventail/

Sponsors

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