ETH zürich V4RL VISION FOR ROBOTICS LAB

Towards Asynchronous SLAM with Event Cameras

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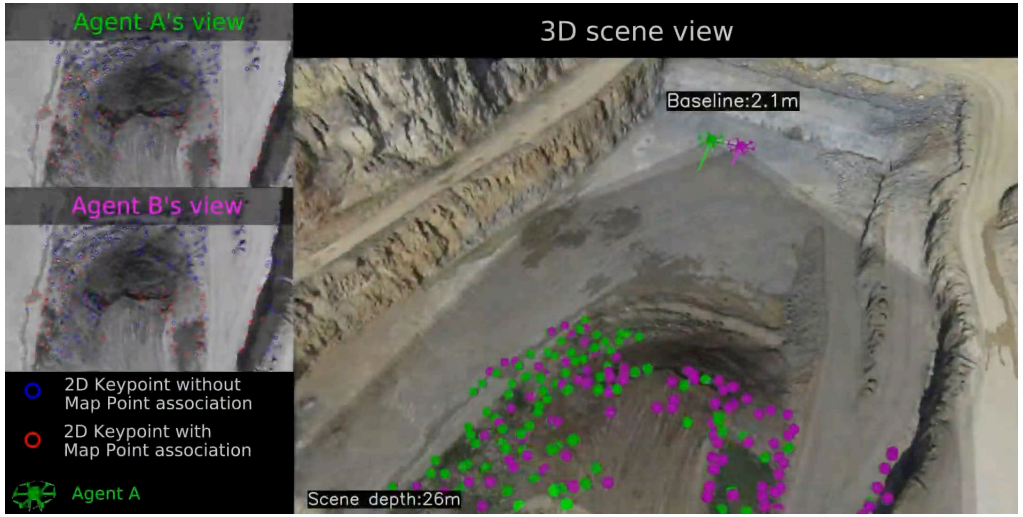
Vision for Robotics Lab, ETH Zurich

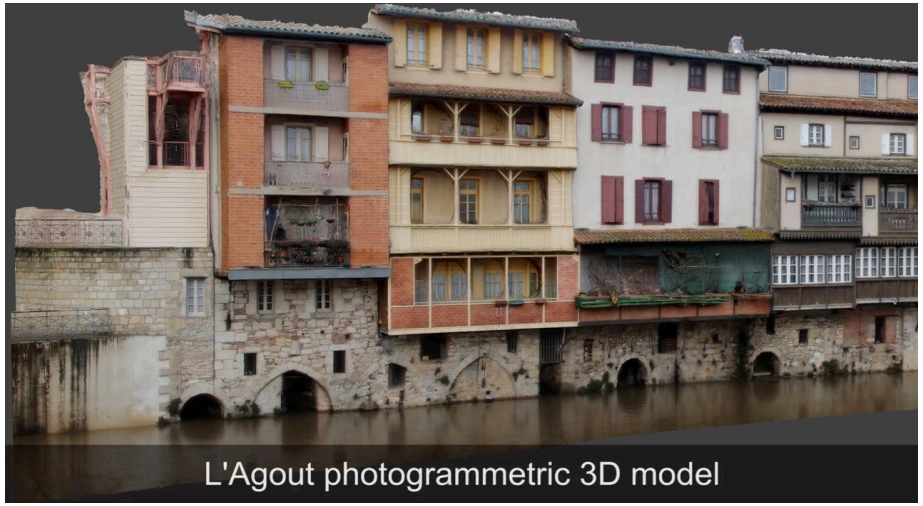
CVPRW 2021

Research @ Vision For Robotics Lab



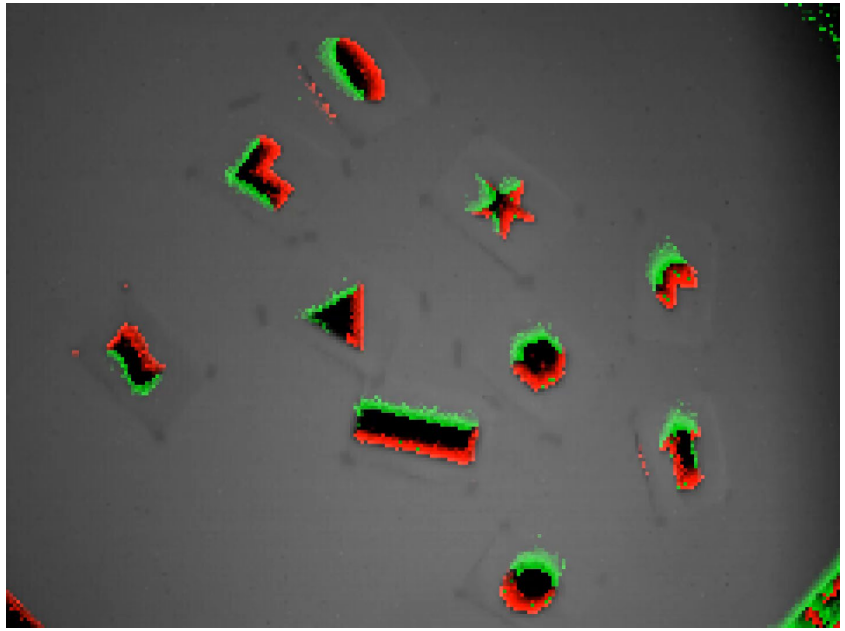
Robust Perception for Robotics:

- Multi-Agent Visual SLAM
- Vision-based Navigation & Manipulation
- Viewpoint-tolerant Place Recognition

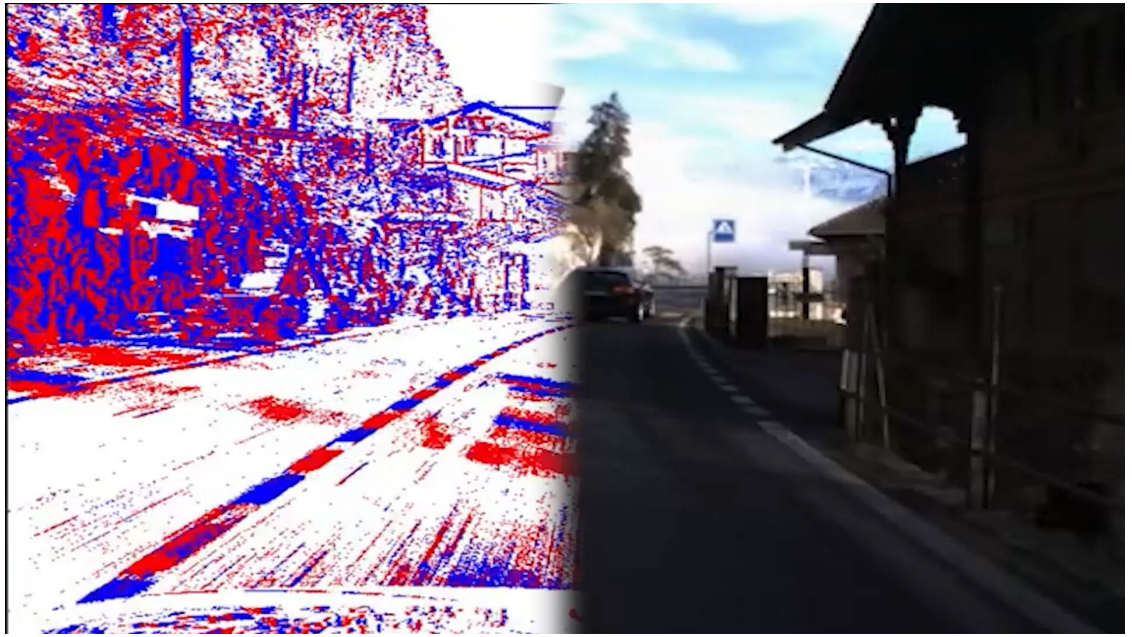


Event Cameras in Robotics Application

Dataset* [Mueggler *et al.*, IJRR'17]



Dataset [Gehrig *et al.*, RAL'21]



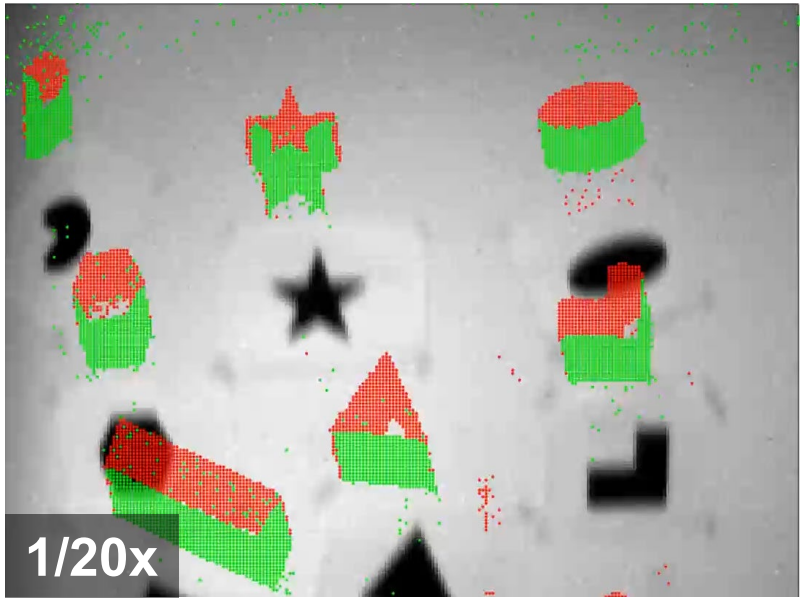
- Sensor: **Fast** Perception, **HDR** capabilities, Low **Power**
- Output: **Asynchronous** and **Sparse**

*The data used in this presentation is from [Mueggler et al., IJRR'17] unless stated otherwise.

Asynchronous and Sparse Event Stream

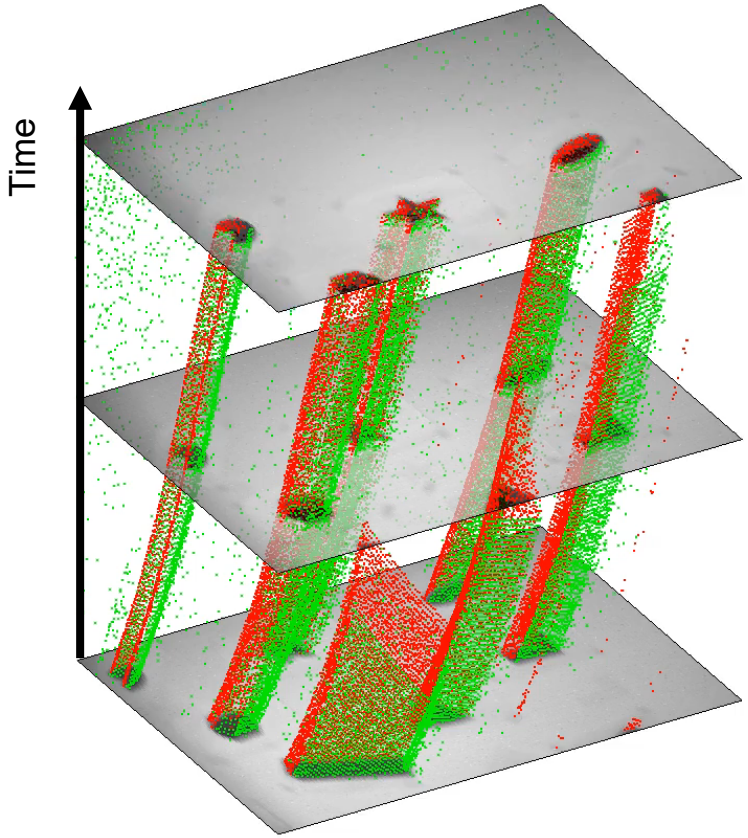
Events

Image plane



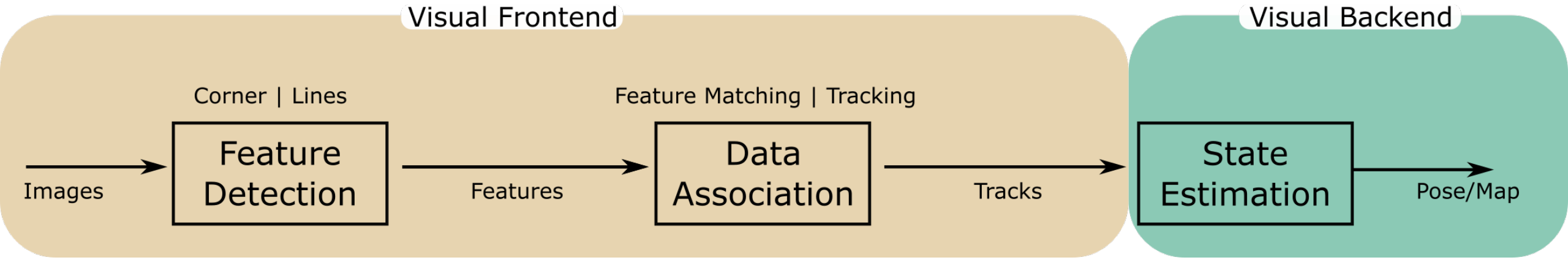
Event Stream

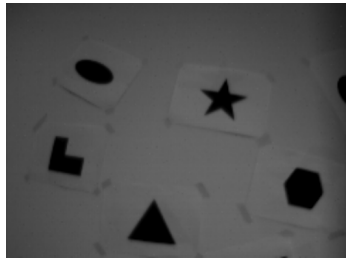
Spatio-temporal space

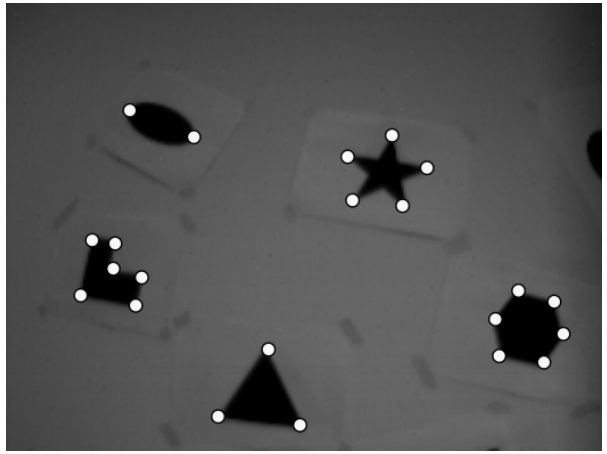


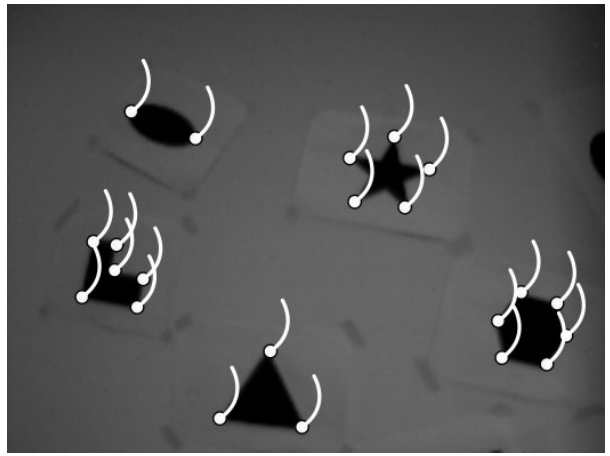
- **No** notion of **time-discretization**
- **Only** intensity **changes** are **captured**

Traditional Visual SLAM Pipeline

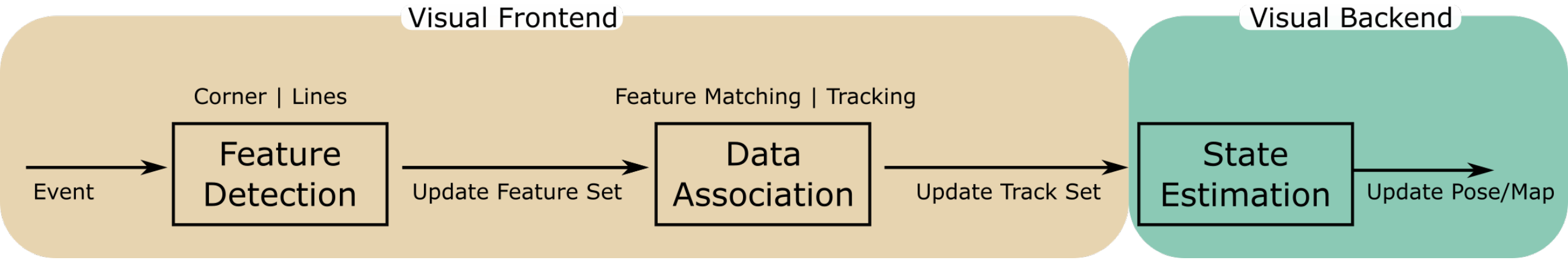


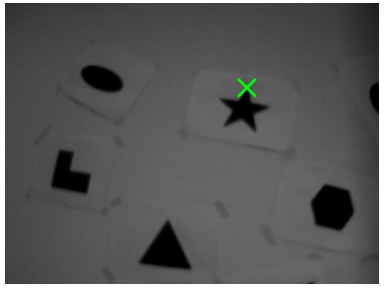


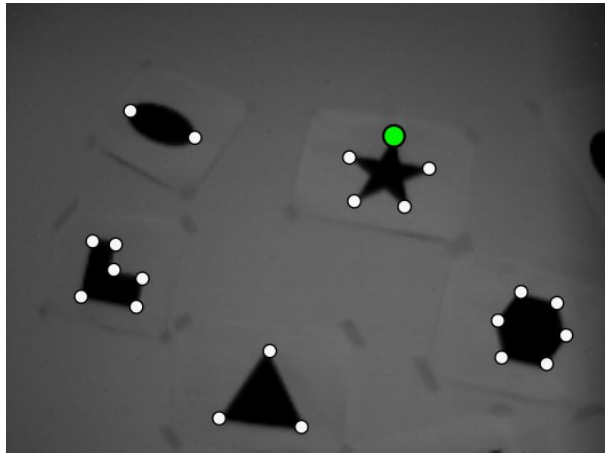


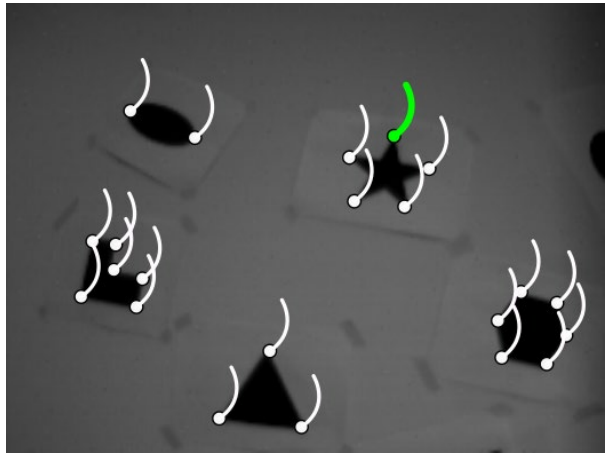


Asynchronous Event-Driven SLAM Pipeline



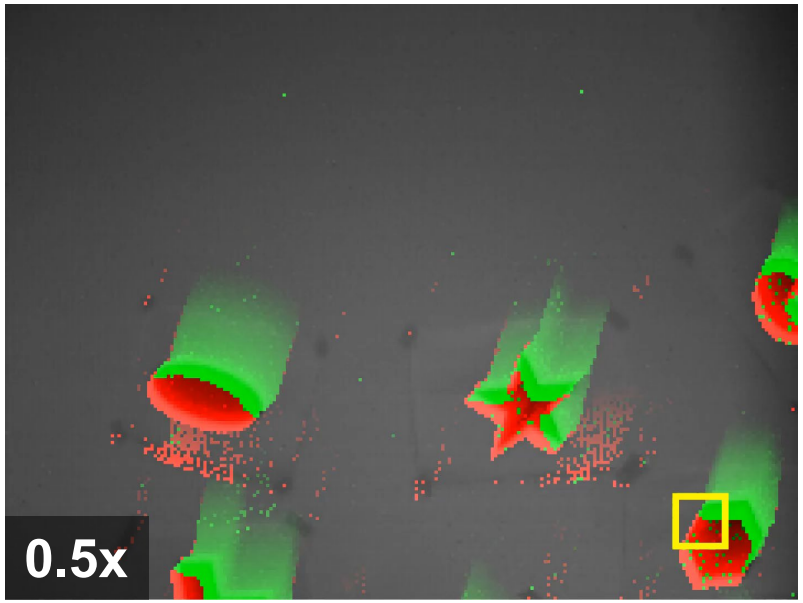




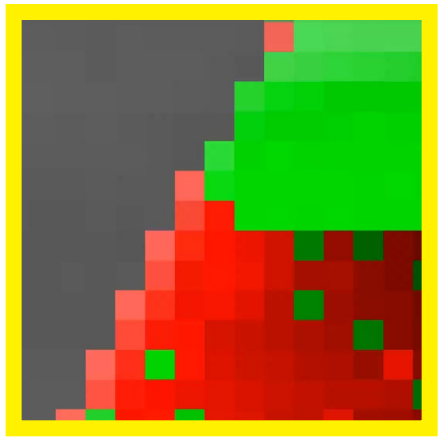


Asynchronous Corner Detection

Events

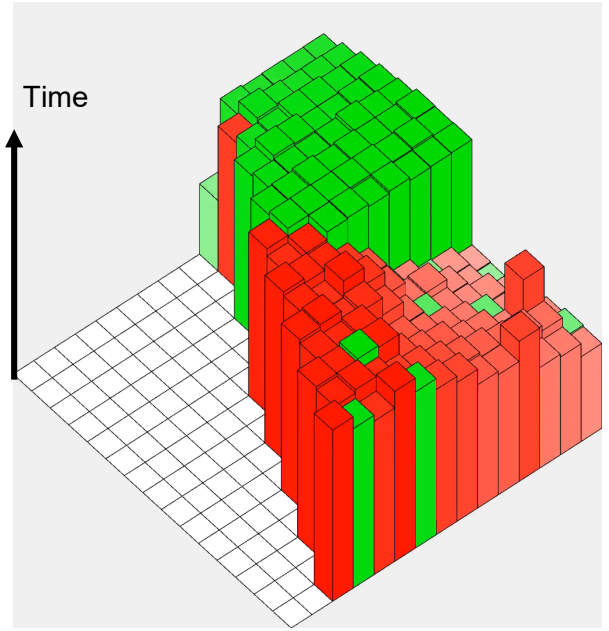


Corner Close-up



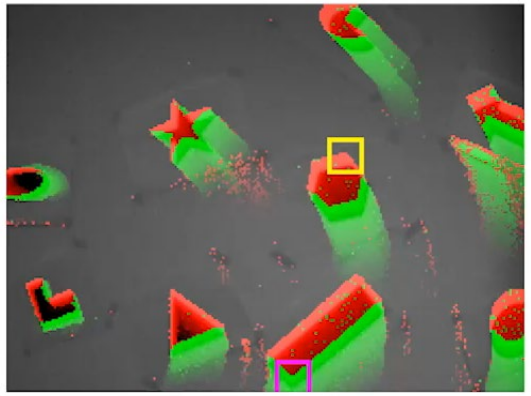
Surface of Active Events

(stores the timestamp of the last event in each location)

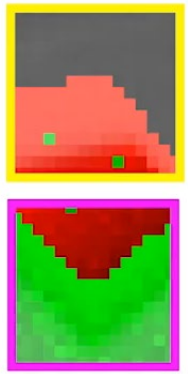


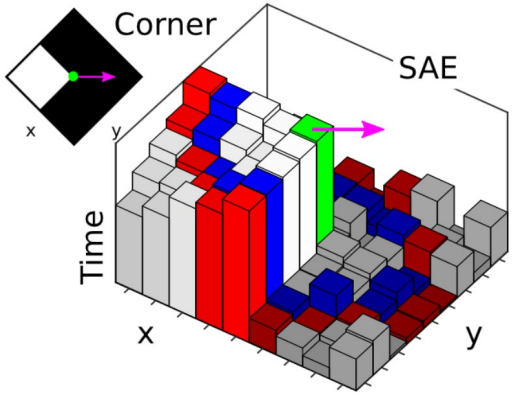
Asynchronous Corner Detection

Events



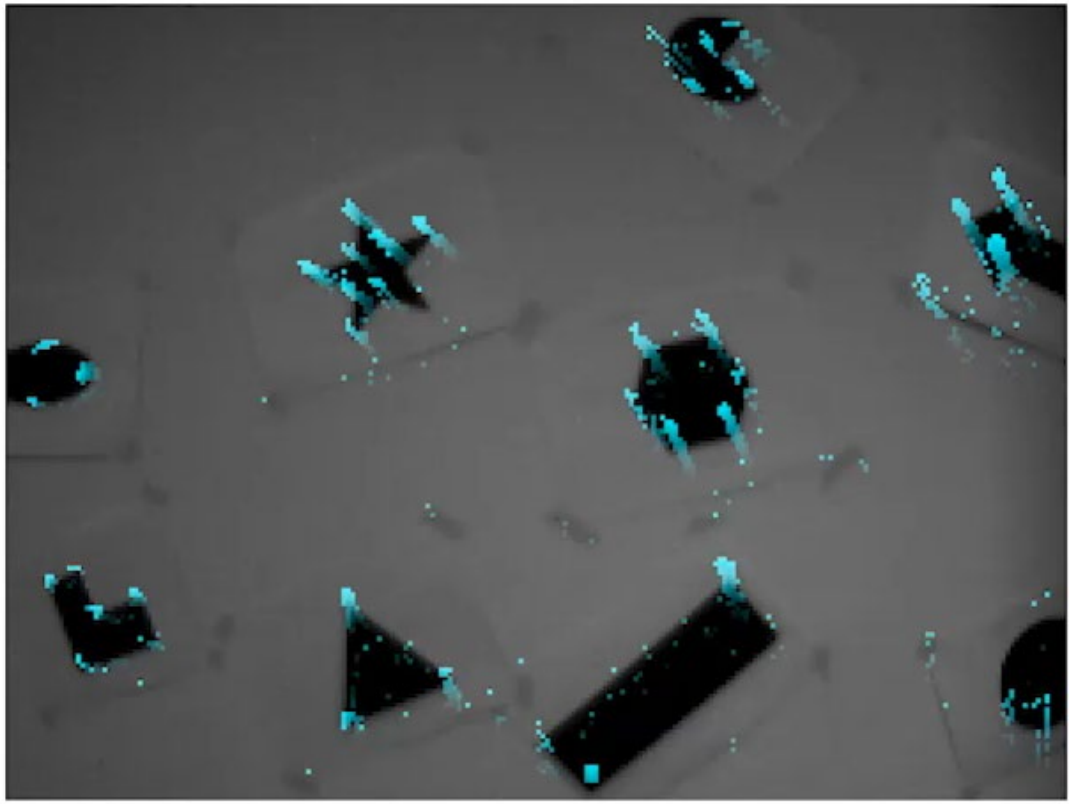
Close-up





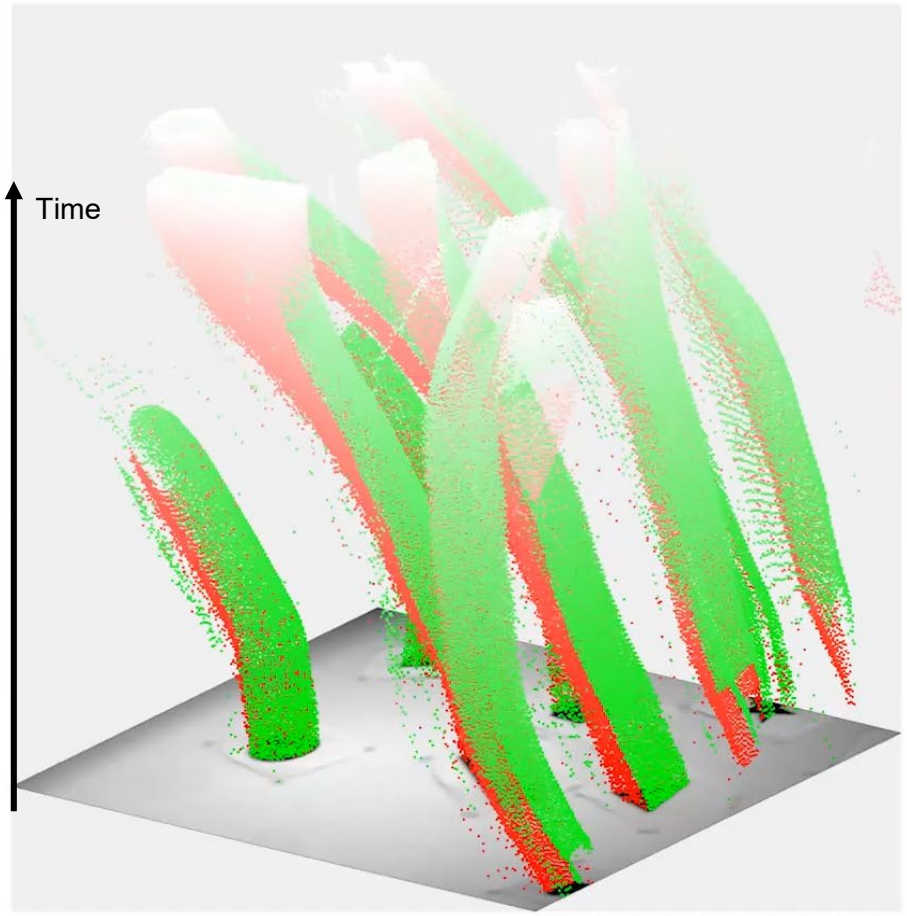
Local Surface of Events
(centered at the newest event)

Corner Events

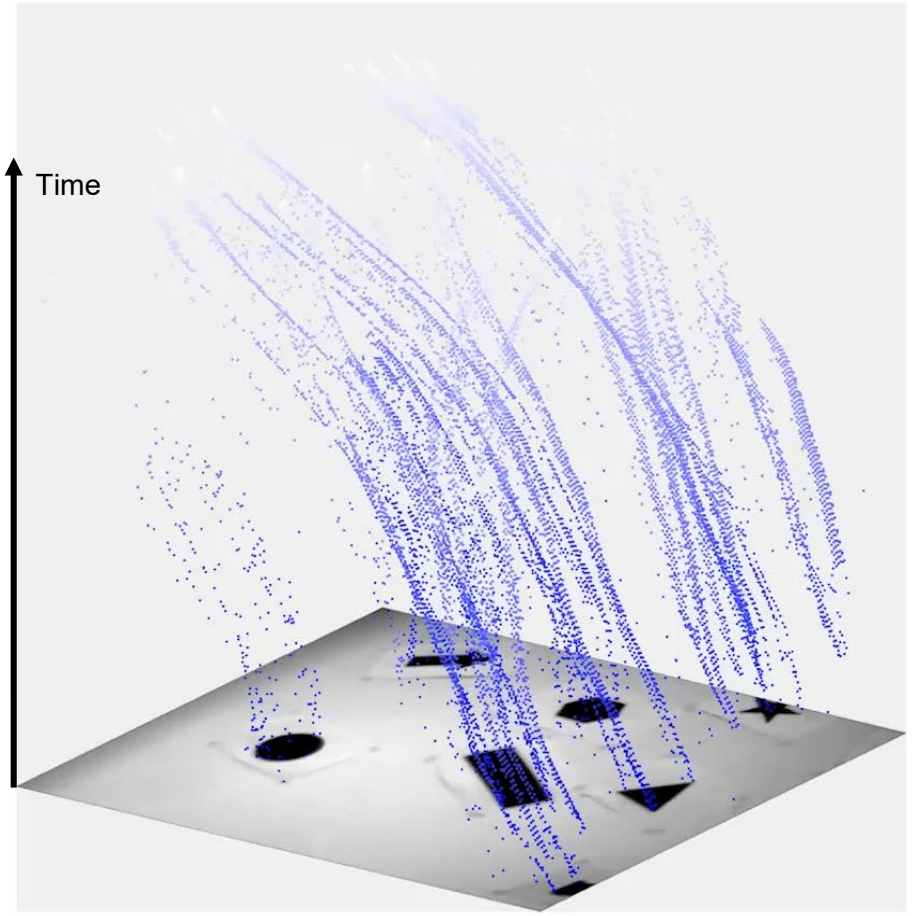


Asynchronous Corner Detection

Stream of Events



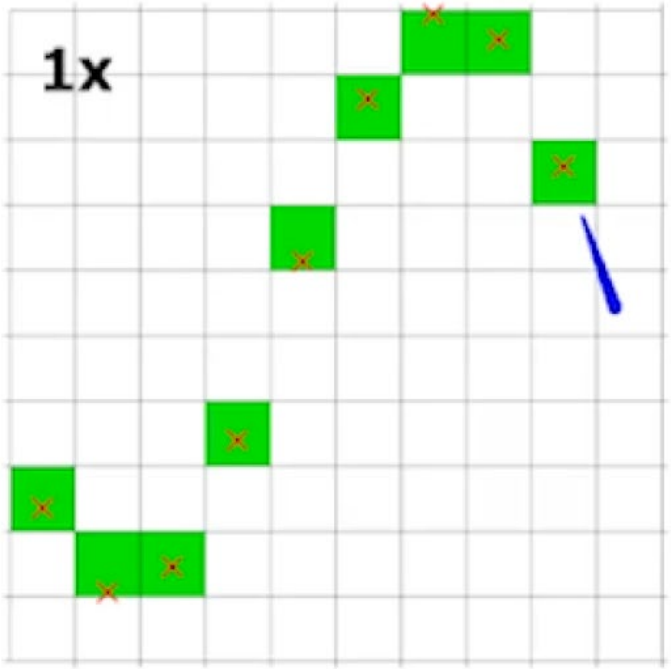
Stream of Corner Events



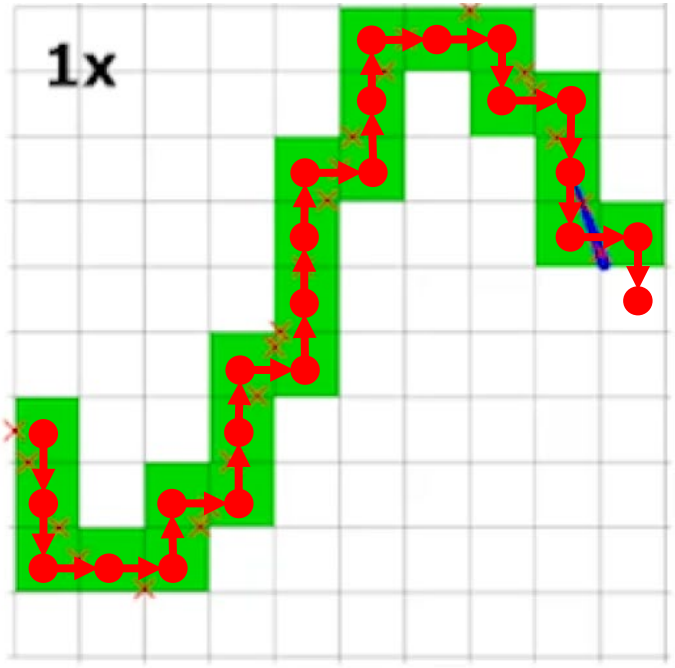
Asynchronous Corner Detection and Tracking for Event Cameras in Real-Time [Alzugaray & Chli, RAL'18]

Asynchronous Corner Detection

Frame-based detection



Event-driven detection

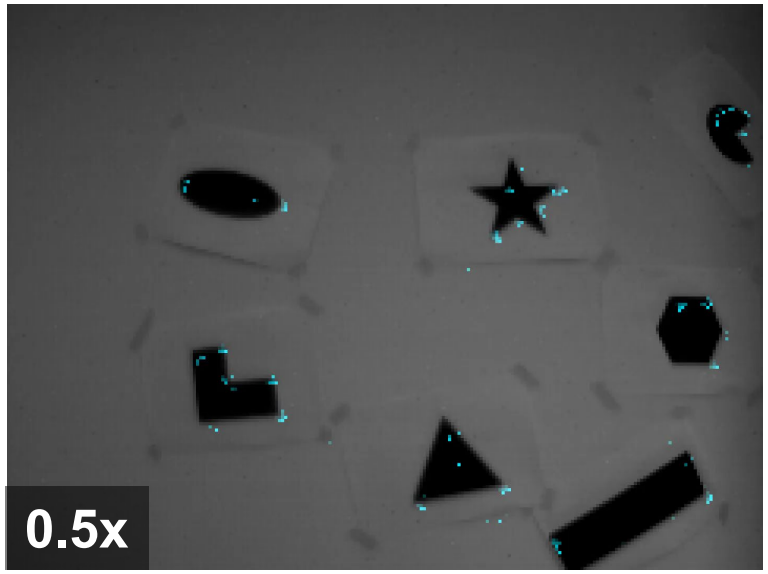


Feature projection Feature detection Feature pixel-detection

Naïve Asynchronous Corner Tracking

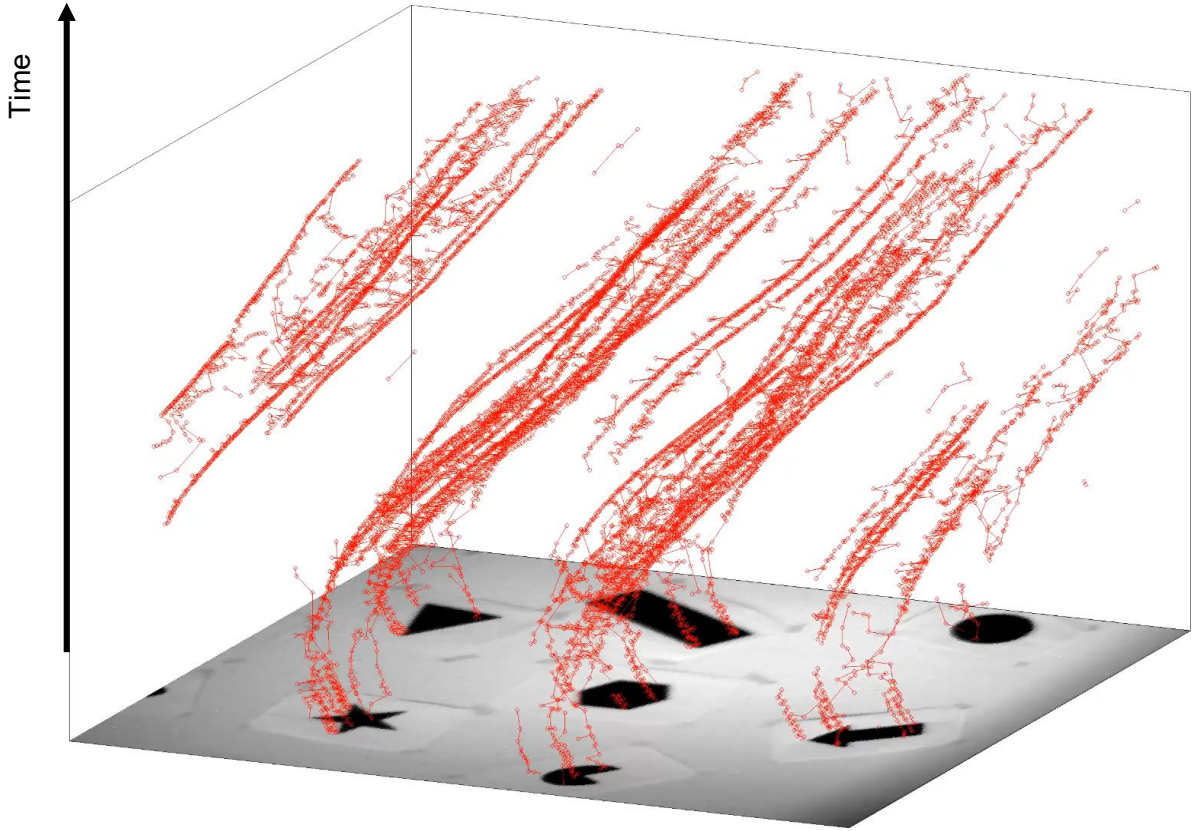
Corner Events

Image plane



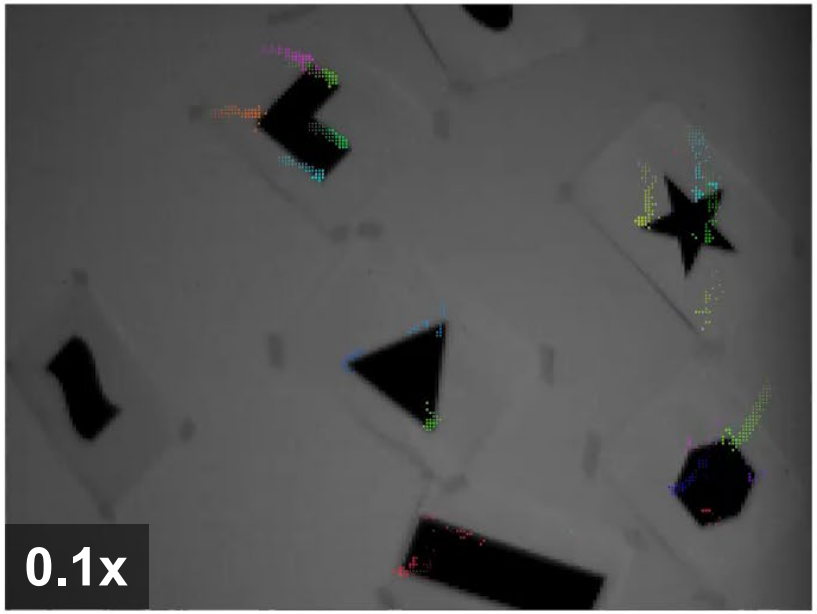
Tracking Graphs

Spatio-temporal space

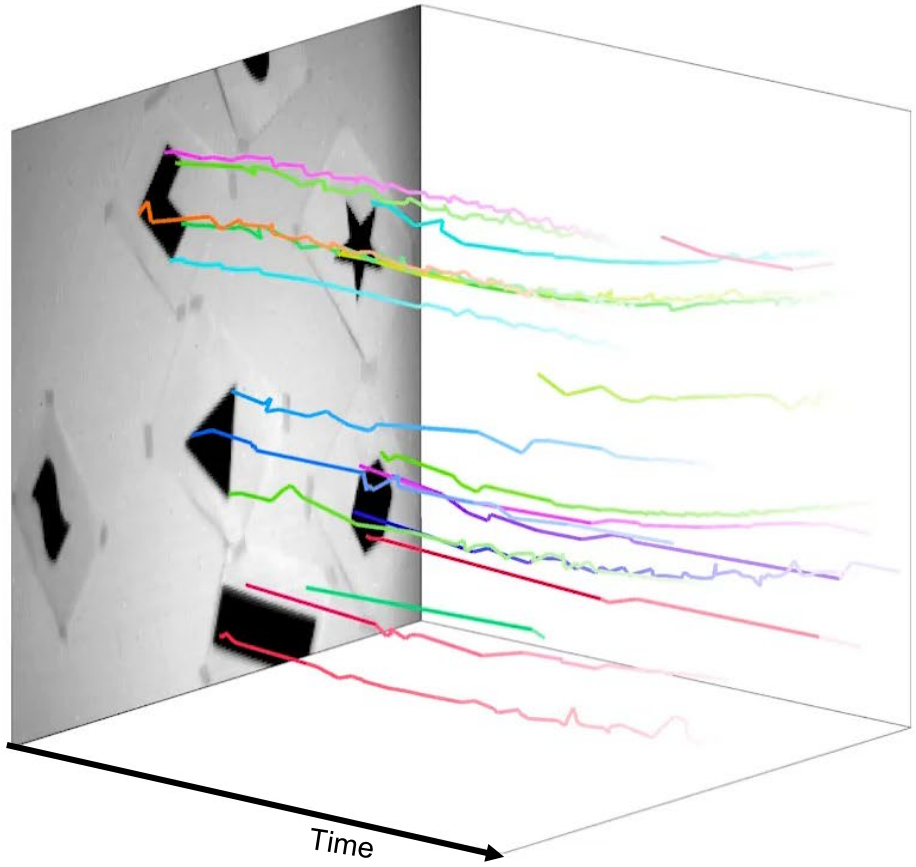


Naïve Asynchronous Corner Tracking

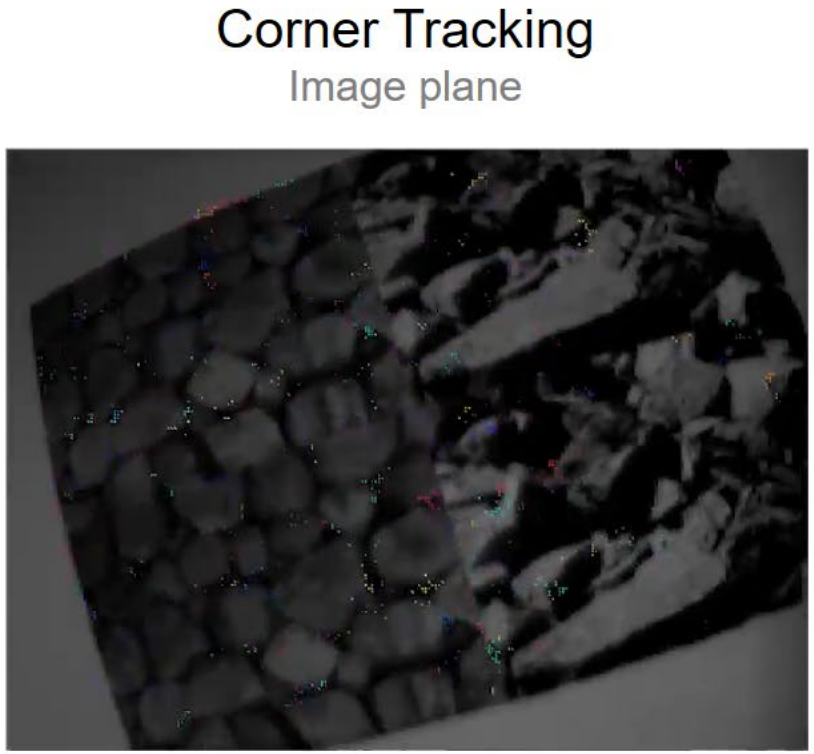
Corner Tracking
Image plane

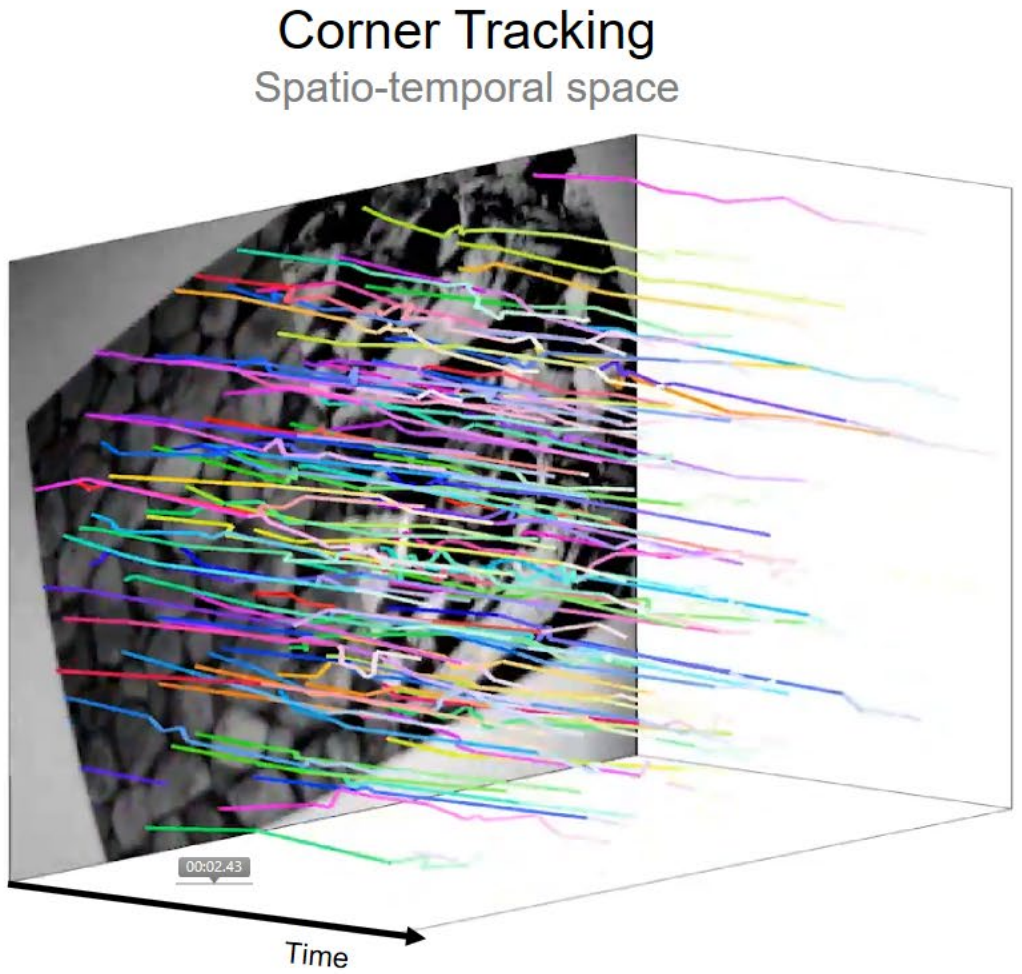


Corner Tracking
Spatio-temporal space

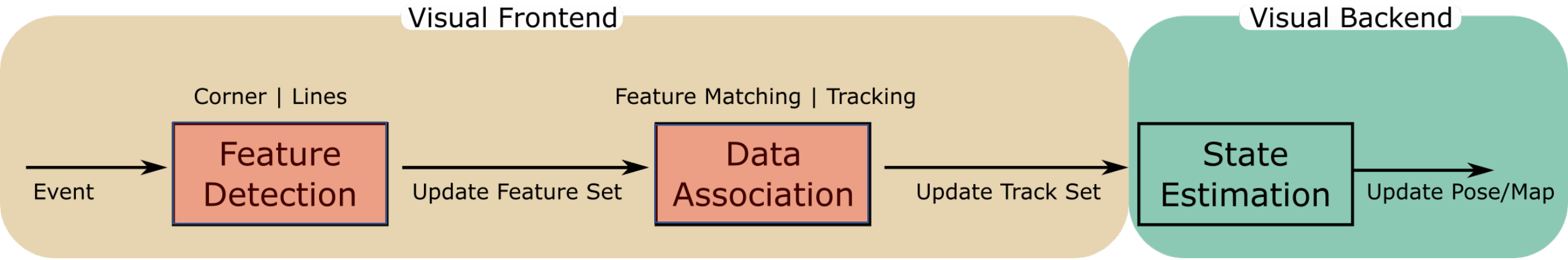


Naïve Asynchronous Corner Tracking





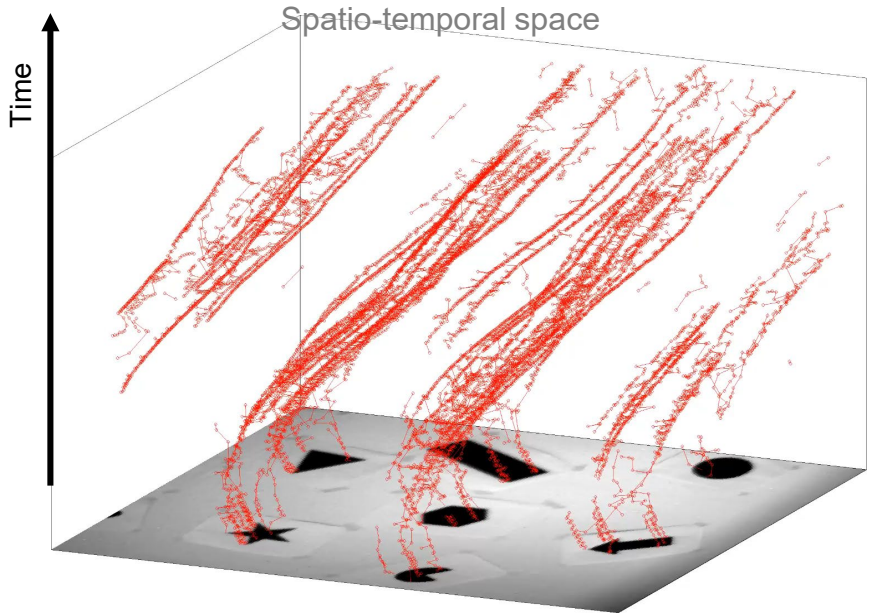
Asynchronous Event-Driven SLAM Pipeline



- Event Corner Detection
- Naïve Event Corner Association
- Offline Corner Tracks Retrieval

Asynchronous Corner Detection and Tracking for Event Cameras in Real-Time
[Alzugaray & Chli, RAL'18]

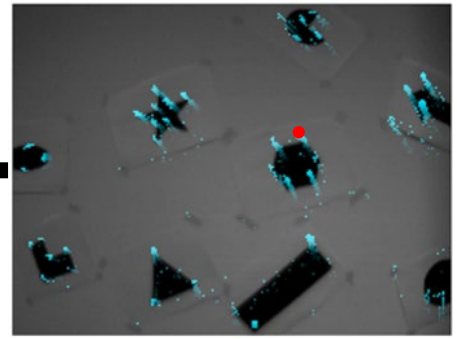
Tracking Graphs



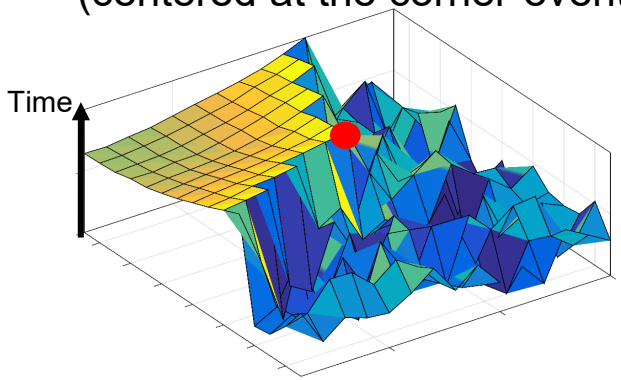
Unreliable Data Association

Asynchronous Multi-hypothesis Corner Tracking

Corner Event Detected

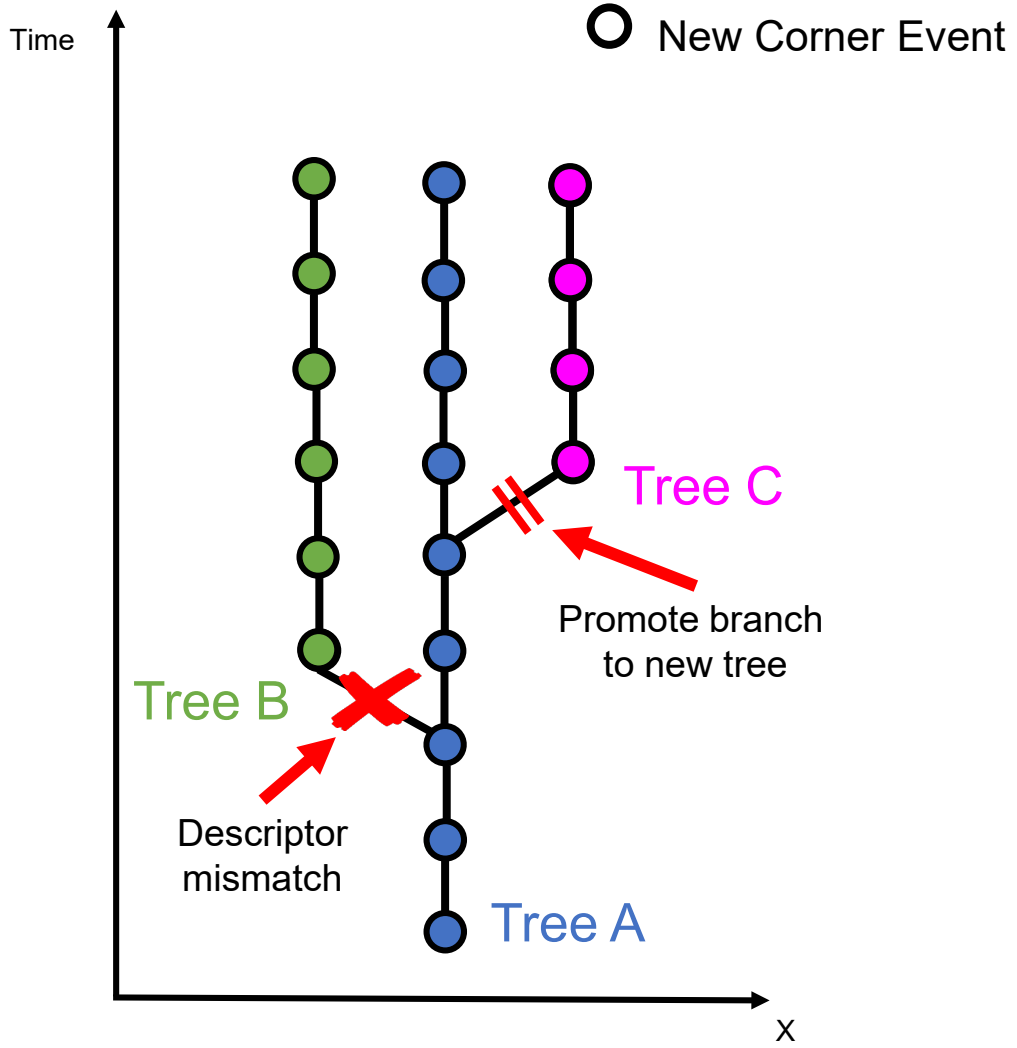


Local Surface Active of Events
(centered at the corner-event)



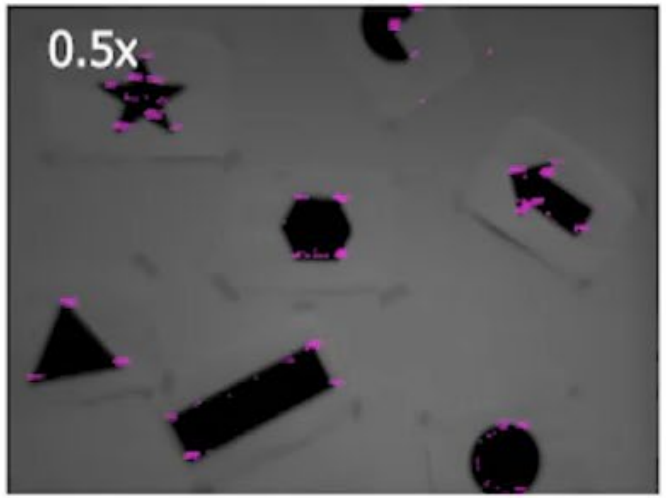
Light-weight Descriptor

$\mathcal{D}$ $\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix}$



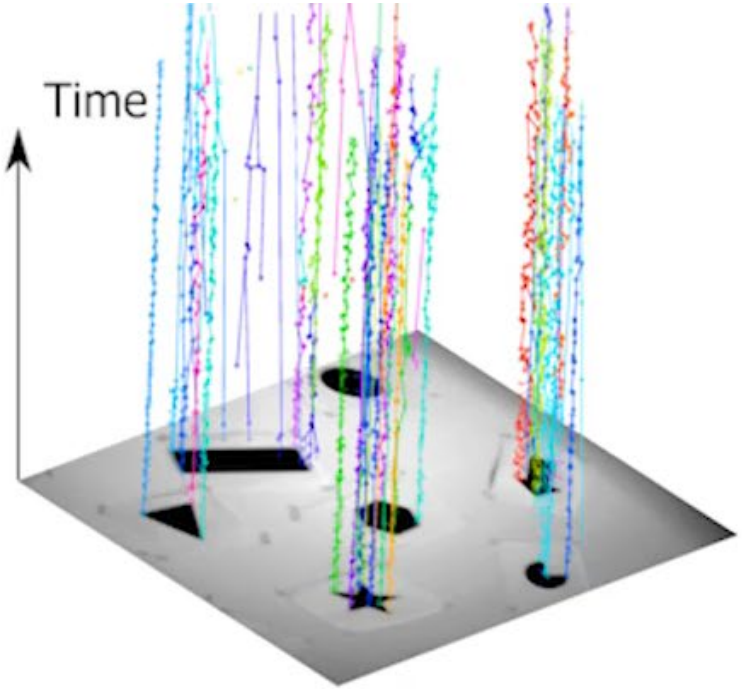
Asynchronous Multi-hypothesis Corner Tracking

Corner Events



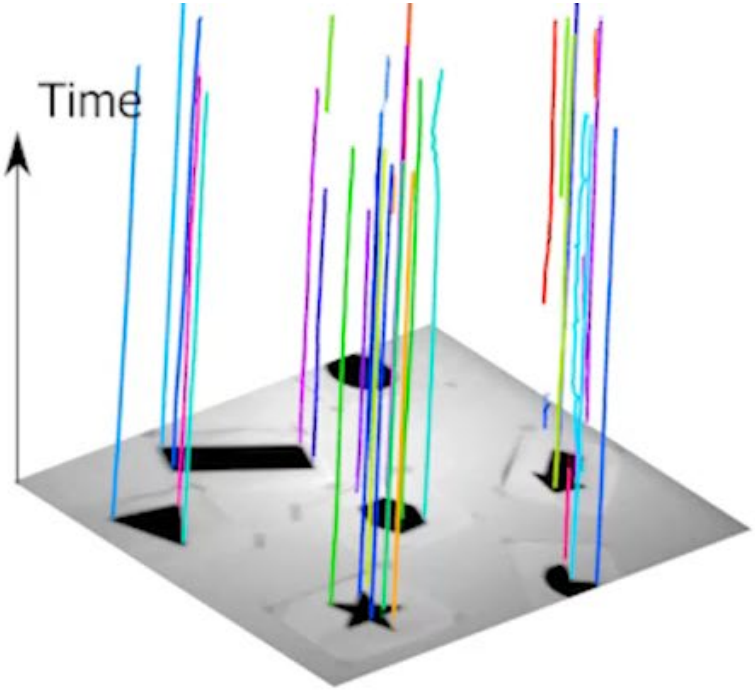
Tracking Graph

Multi-hypothesis features



Feature Tracks

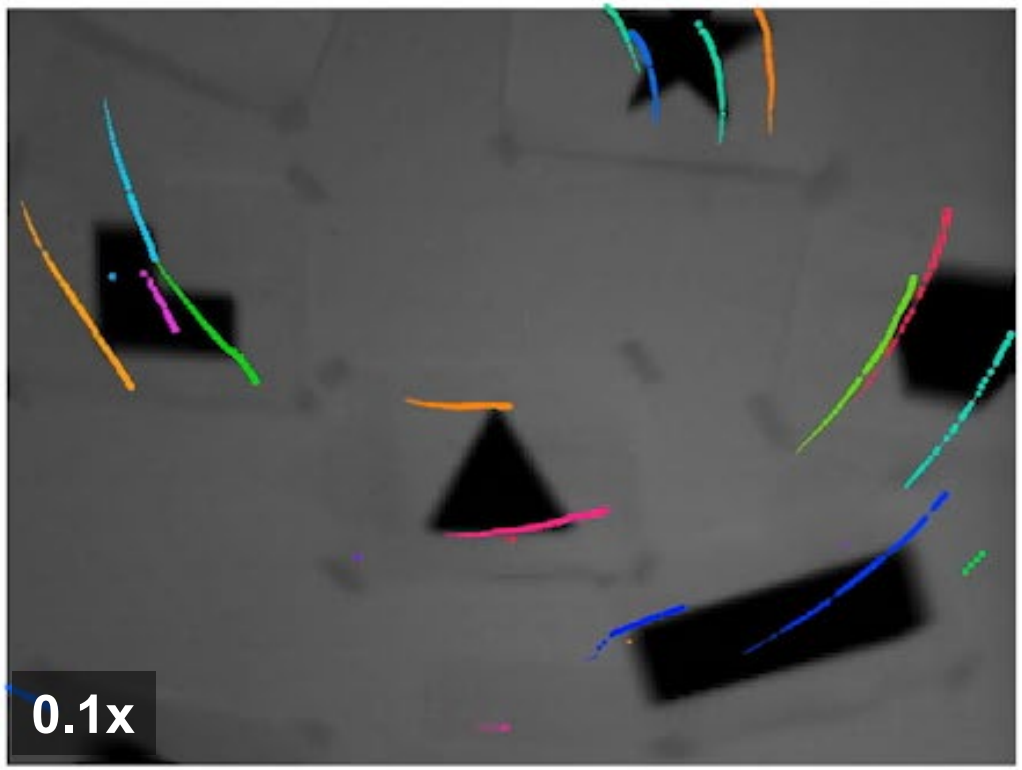
Hypothesis selection



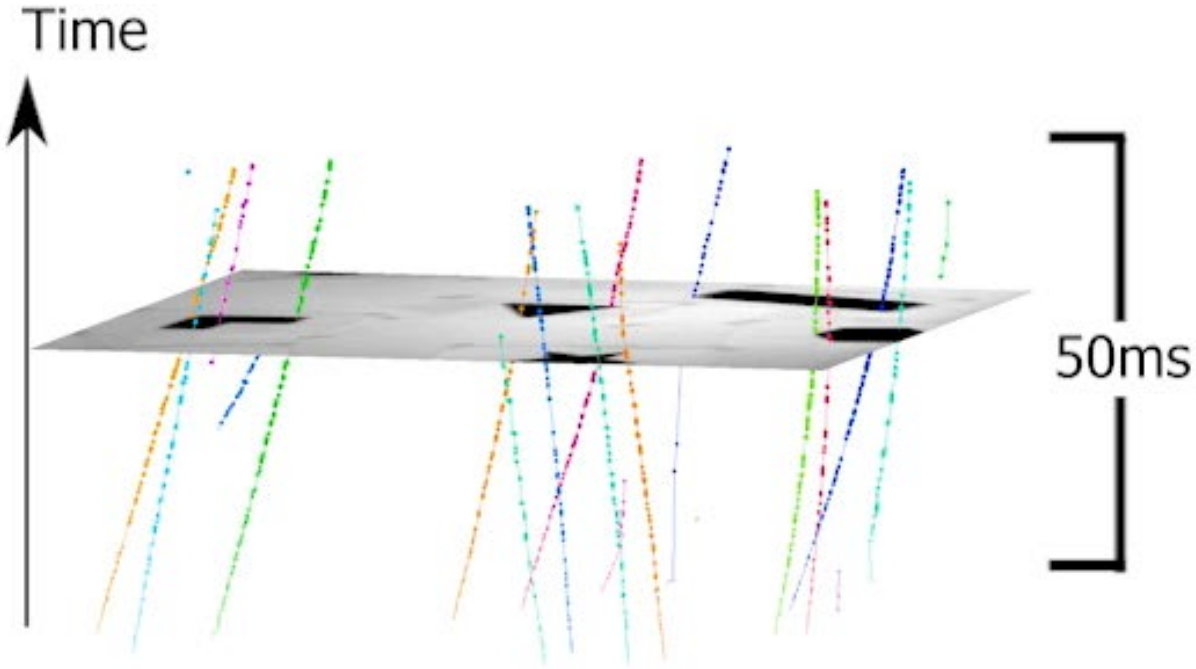
ACE: An Efficient Asynchronous Corner Tracker for Event Cameras [Alzugaray & Chli, 3DV'18]

Asynchronous Multi-hypothesis Corner Tracking

Corner Tracking
Image plane



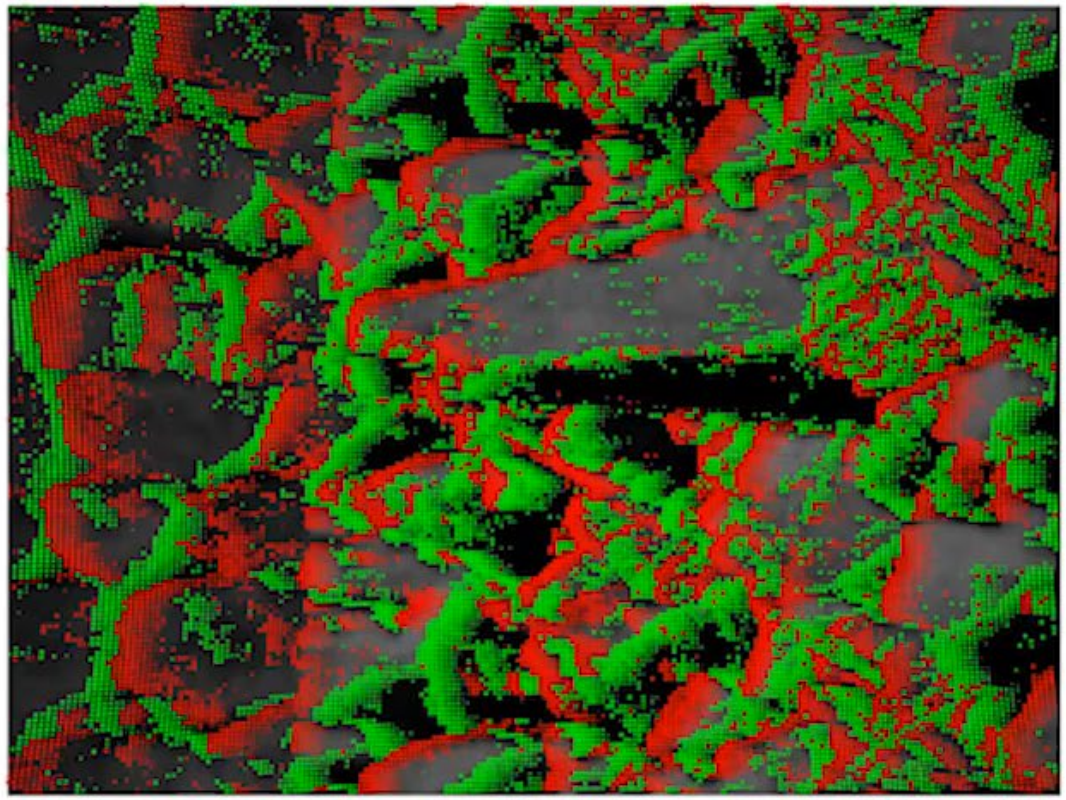
Corner Tracking
Spatio-temporal space



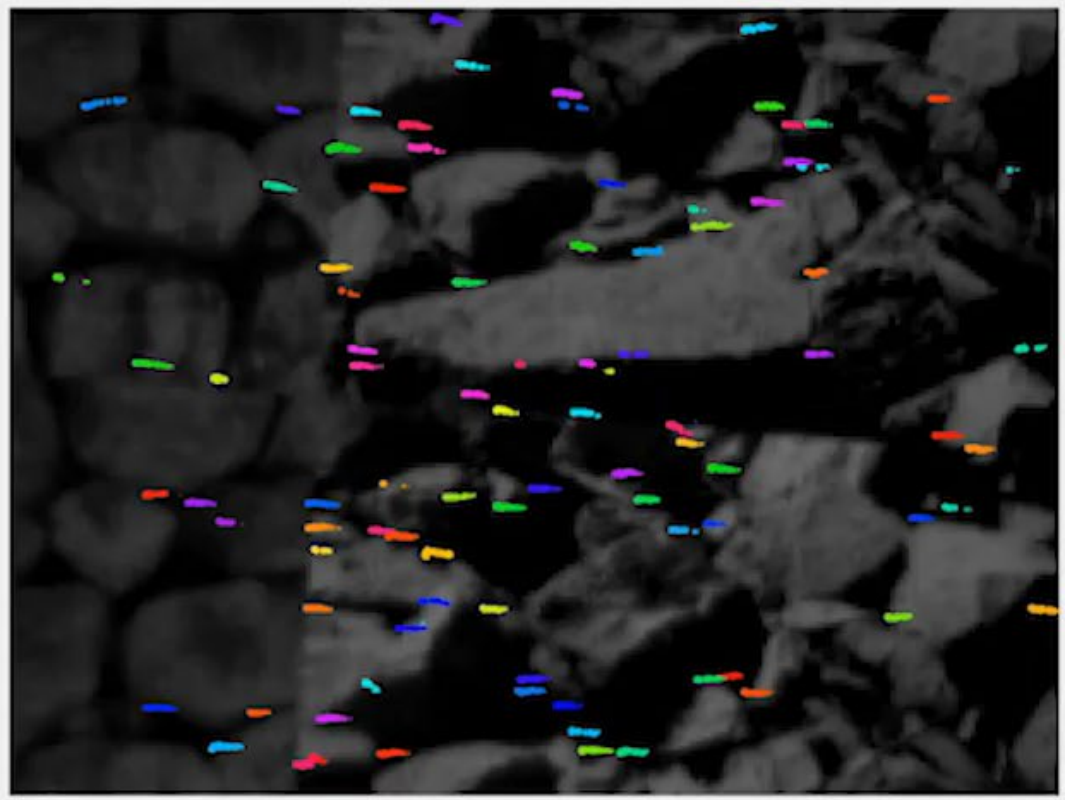
ACE: An Efficient Asynchronous Corner Tracker for Event Cameras [Alzugaray & Chli, 3DV'18]

Asynchronous Multi-hypothesis Corner Tracking

Events



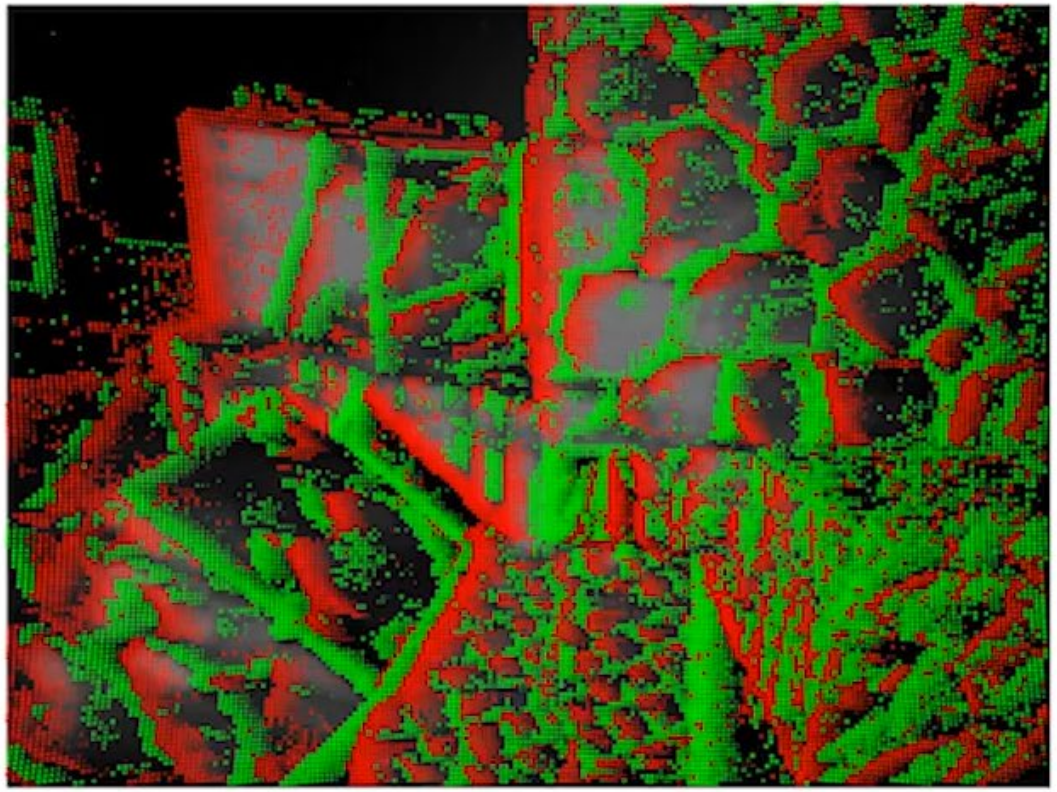
Corner Tracking



ACE: An Efficient Asynchronous Corner Tracker for Event Cameras [Alzugaray & Chli, 3DV'18]

Asynchronous Multi-hypothesis Corner Tracking

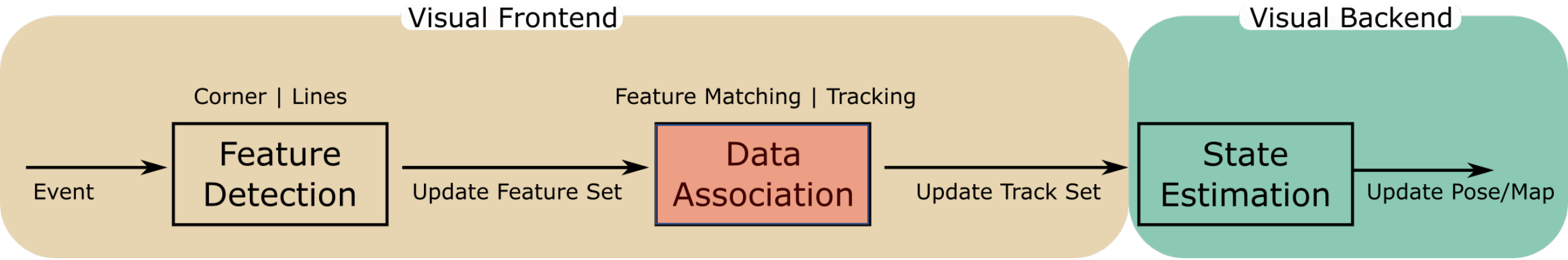
Events



Corner Tracking

ACE: An Efficient Asynchronous Corner Tracker for Event Cameras [Alzugaray & Chli, 3DV'18]

Asynchronous Event-Driven SLAM Pipeline

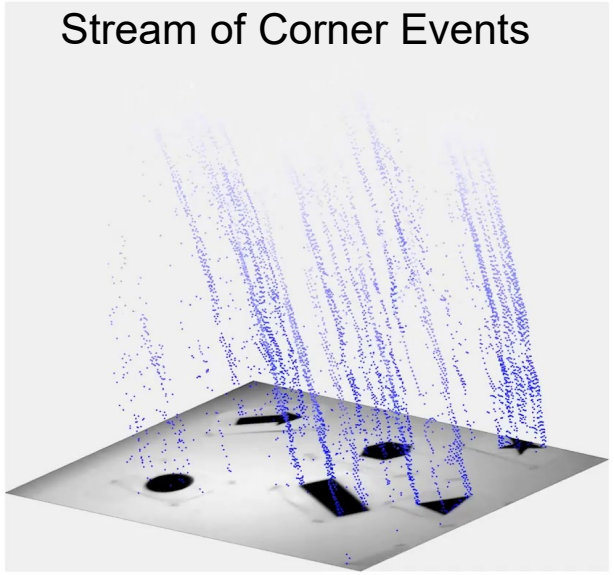


- Event Corner Detection
- Naïve Event Corner Association
- Offline Corner Tracks Retrieval

Asynchronous Corner Detection and Tracking for Event Cameras in Real-Time
[Alzugaray & Chli, RAL'18]

- Local Event Descriptor
- Multi-hypothesis Data Association
- Online Corner Track Retrieval

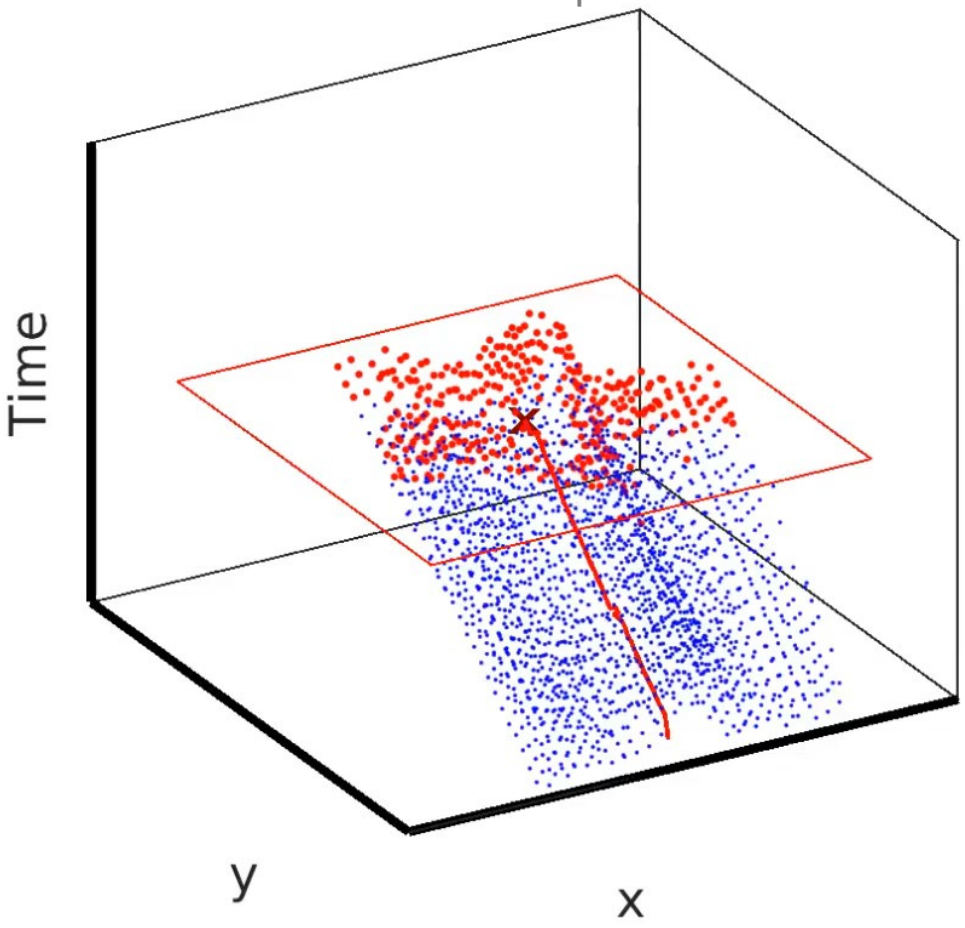
ACE: An Efficient Asynchronous Corner Tracker for Event Cameras
[Alzugaray & Chli, 3DV'18]



Asynchronous Tracking of Events

Feature Track in the Event Stream

Close-up view



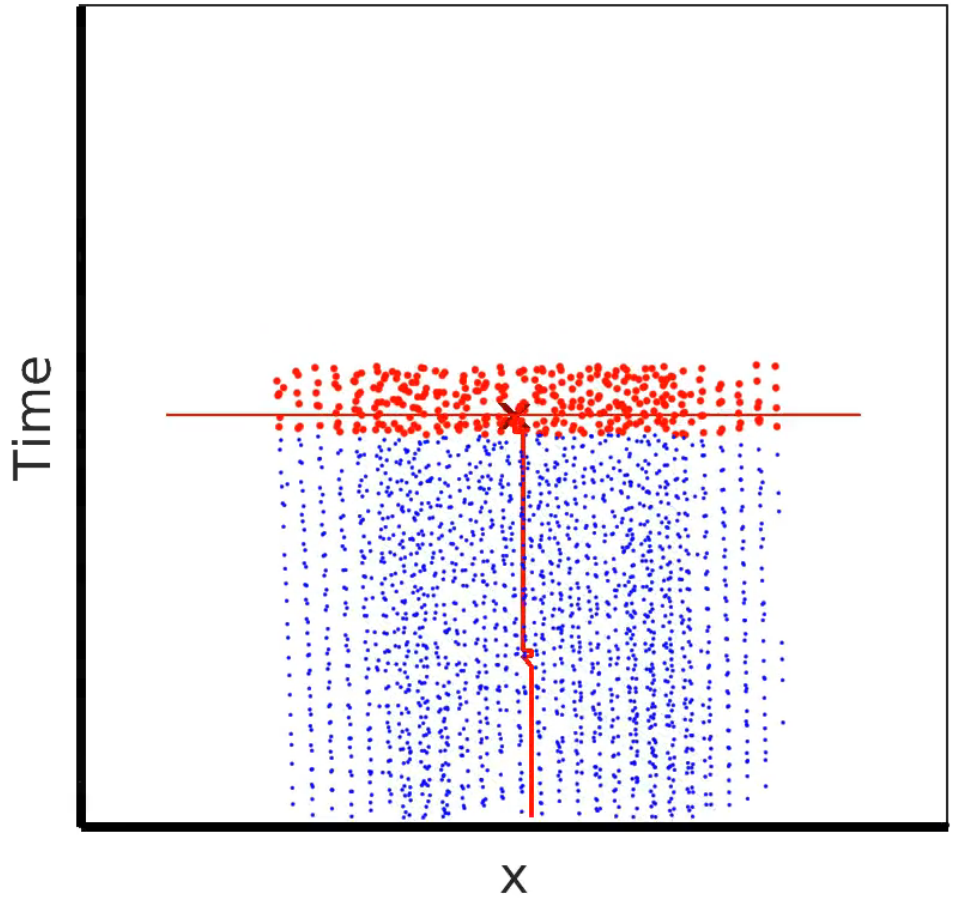
Feature $\mathcal{F}$

- State $\mathbf{x} = \{x, y, \theta\}$
  - xy-pixel coordinates
  - in-plane orientation
- Window of Latest Events $\mathcal{E}$
  - Fixed number of events

Asynchronous Tracking of Events

Feature Track in the Event Stream

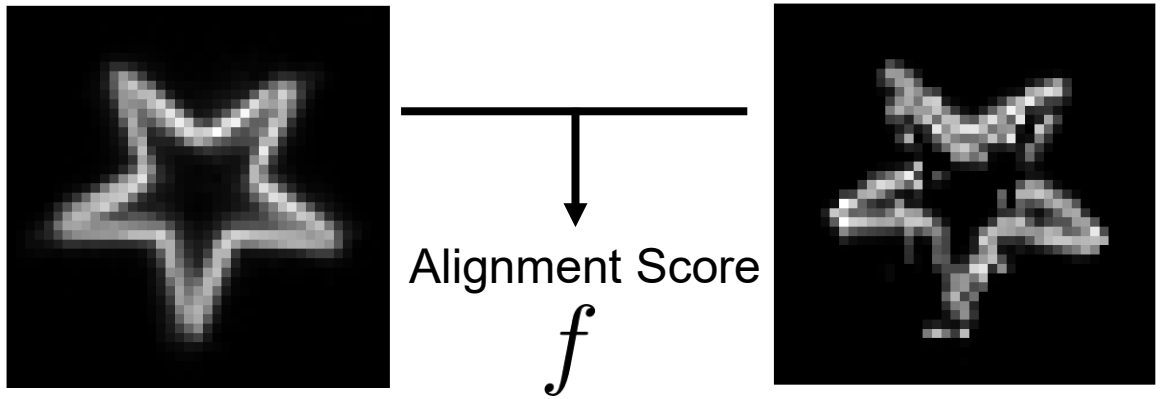
Close-up view



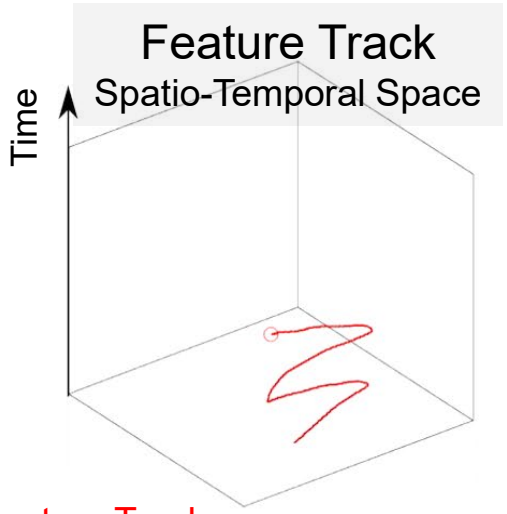
Feature $\mathcal{F}$

- State $\mathbf{x} = \{x, y, \theta\}$
- Window of Latest Events $\mathcal{E}$
  - Fixed number of events
- Template $\mathcal{T}$

Model $\mathcal{M}(\mathbf{x}, \mathcal{E})$

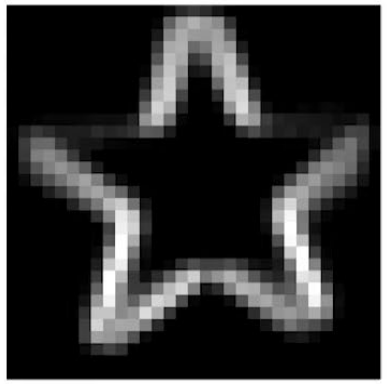


Feature Tracking as Optimization Problem

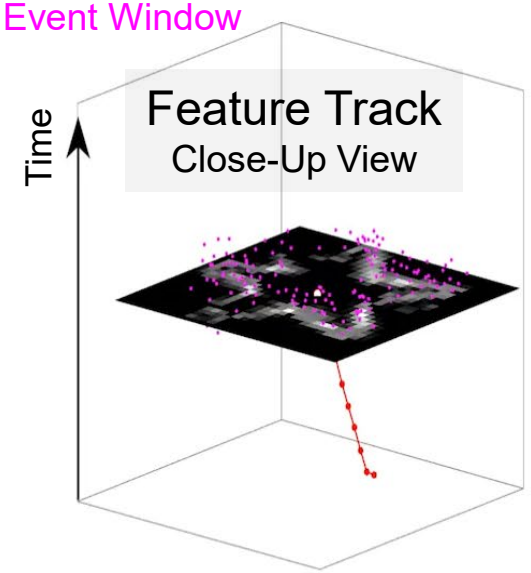


Model $\mathcal{M}(\mathbf{x}, \mathcal{E})$

Template $\mathcal{T}$



- Feature Track
- Event Window



Alignment Score Function

$$\mathbf{x}^* = \arg\max_{\mathbf{x} \in \mathcal{X}} f(\mathbf{x}, \mathcal{E}, \mathcal{T})$$

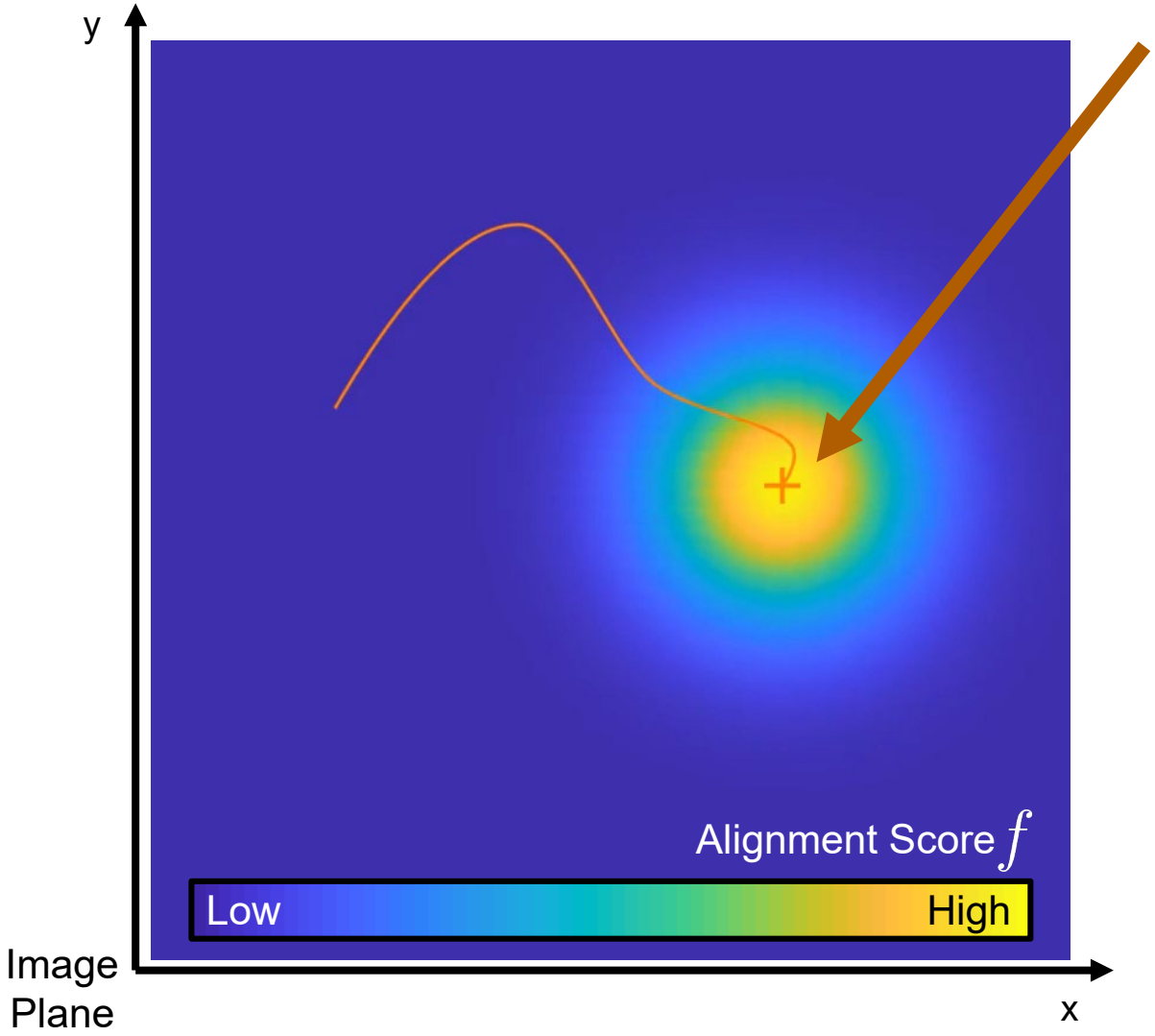
Optimal Feature State

Window of latest events

Template

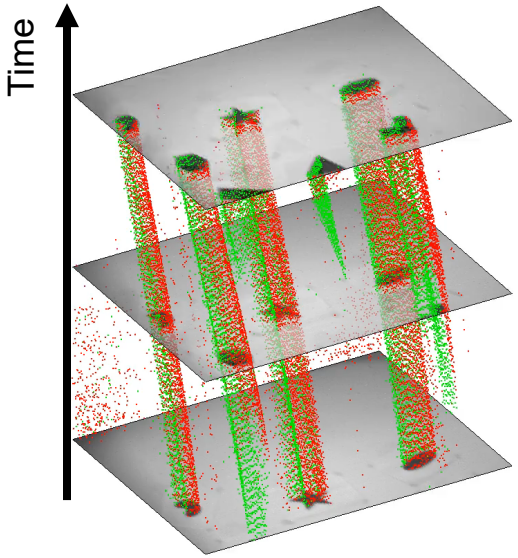
Up to Millions of Events per second!

Feature Tracking with Asynchronous Hypotheses Evaluation



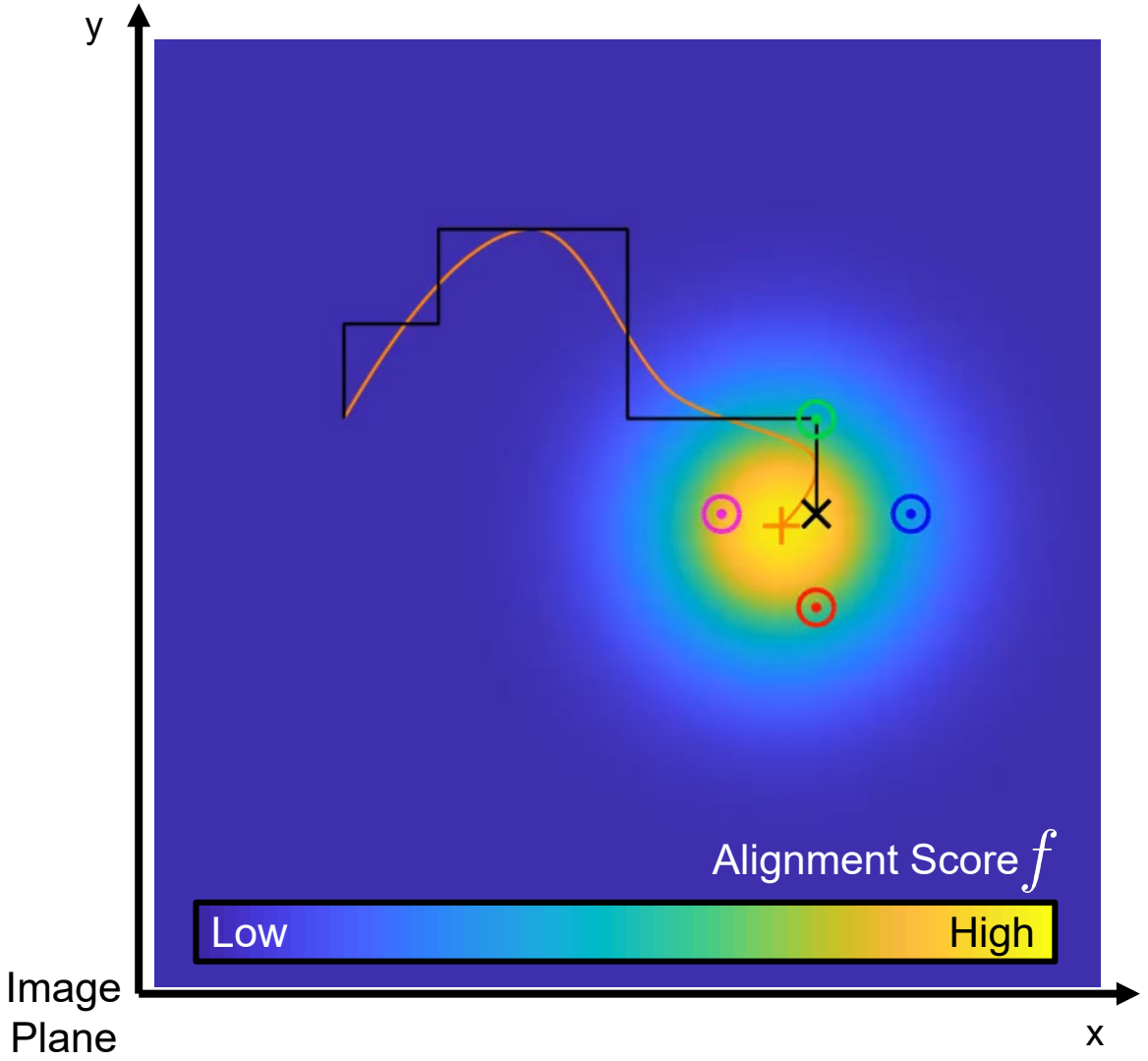
+ Optimal State (Continuous)

$$\mathbf{x}^{(k+1)} = \arg\max_{\mathbf{x}\in\mathcal{X}} f(\mathbf{x}, \mathcal{E}^{(k+1)}, \mathcal{T}^{(k+1)})$$



Continuous stream of information

Feature Tracking with Asynchronous Hypotheses Evaluation



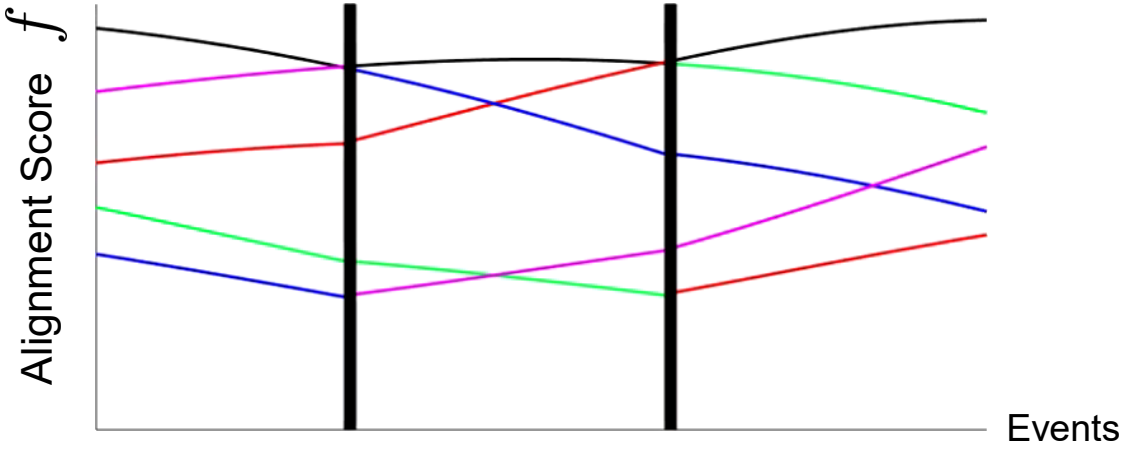
+ Optimal State (Continuous)

$$\mathbf{x}^{(k+1)} = \arg\max_{\mathbf{x}\in\mathcal{X}} f(\mathbf{x}, \mathcal{E}^{(k+1)}, \mathcal{T}^{(k+1)})$$

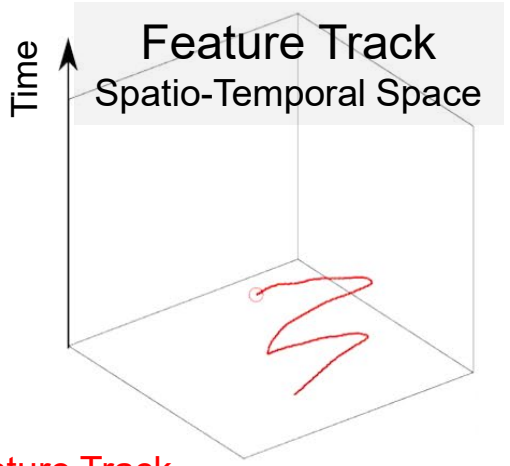
x Current Optimal State (Discrete)

$$\mathbf{x}^{(k+1)} = \arg\max_{\mathbf{x}\in\mathcal{H}(\mathbf{x}^{(k)})\subset\mathcal{X}} f(\mathbf{x}, \mathcal{E}^{(k+1)}, \mathcal{T}^{(k+1)})$$

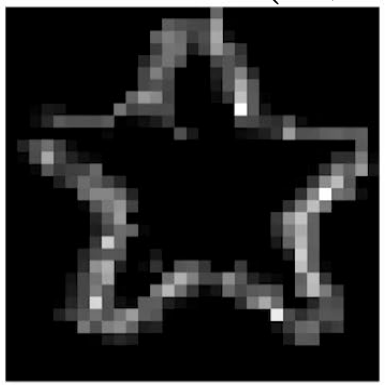
Set of hypothetical states: **{Null, North, East, South, West}**



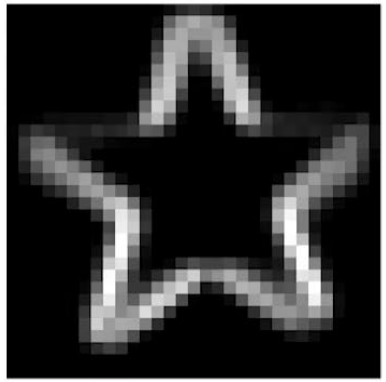
Feature Tracking with Asynchronous Hypotheses Evaluation



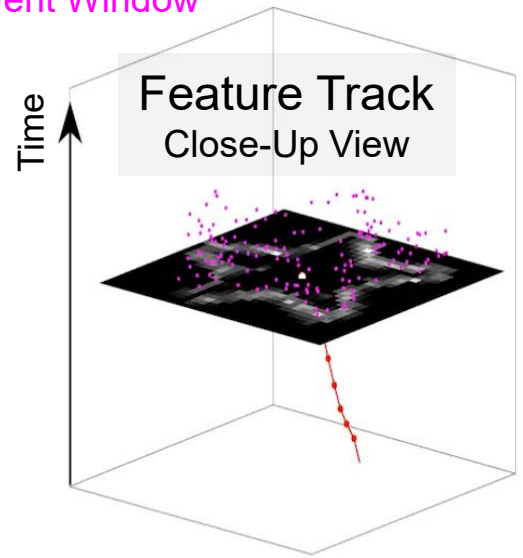
Model $\mathcal{M}(\mathbf{x}, \mathcal{E})$



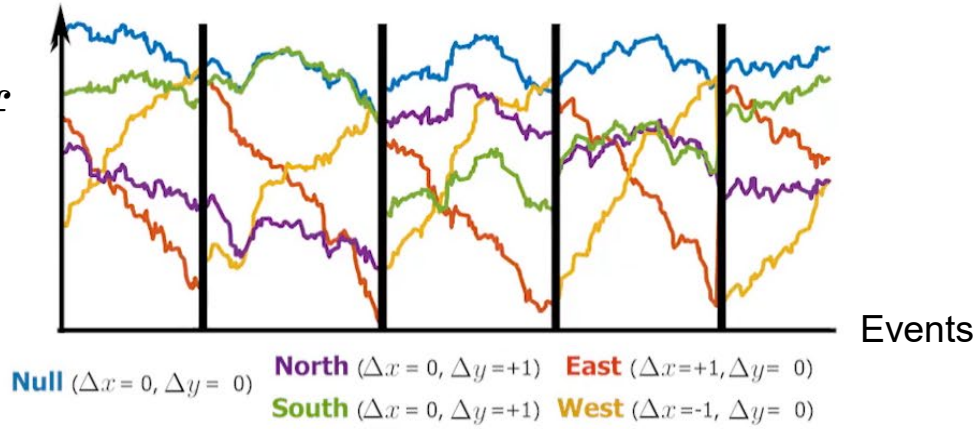
Template $\mathcal{T}$



- Feature Track
- Event Window



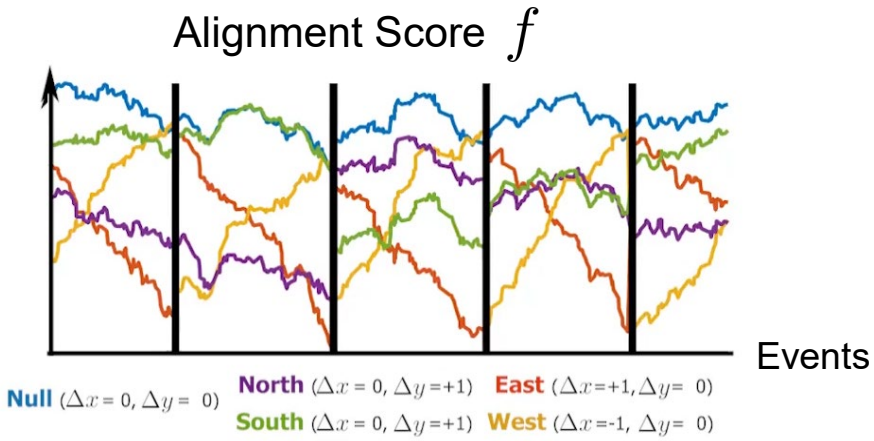
Alignment Score f
per hypothesis



Feature Tracking with Incremental Alignment Score

For **hypothesis** $\mathbf{x}_h$

with **alignment score** $f^{(k)} = f(\mathbf{x}_h, \mathcal{E}^{(k)}, \mathcal{T}^{(k)})$



New event is generated $\mathbf{e}_{k+1}$

Update Event Window $\mathcal{E}^{(k)} \rightarrow \mathcal{E}^{(k+1)}$

Template $\mathcal{T}^{(k)} \rightarrow \mathcal{T}^{(k+1)}$

→ **alignment score** must be **revaluated** $f^{(k+1)}$

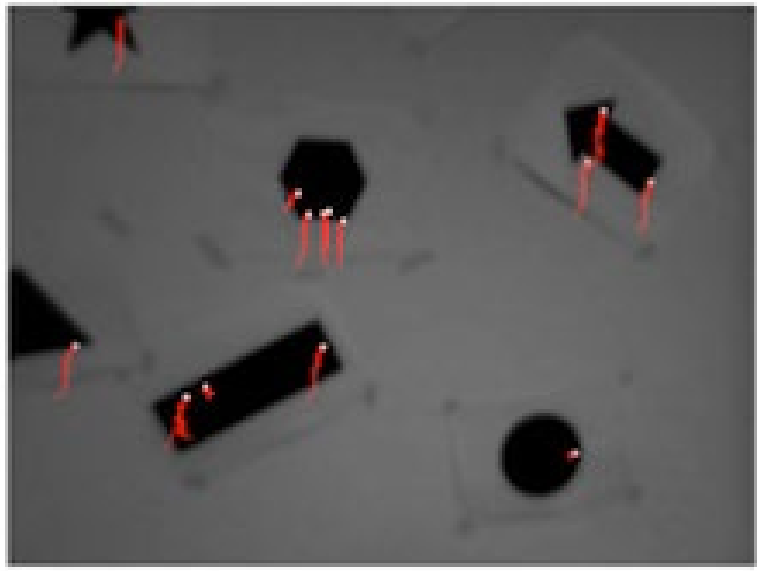
in [Alzugaray & Chli, 3DV'19]

Incremental Alignment Score update:

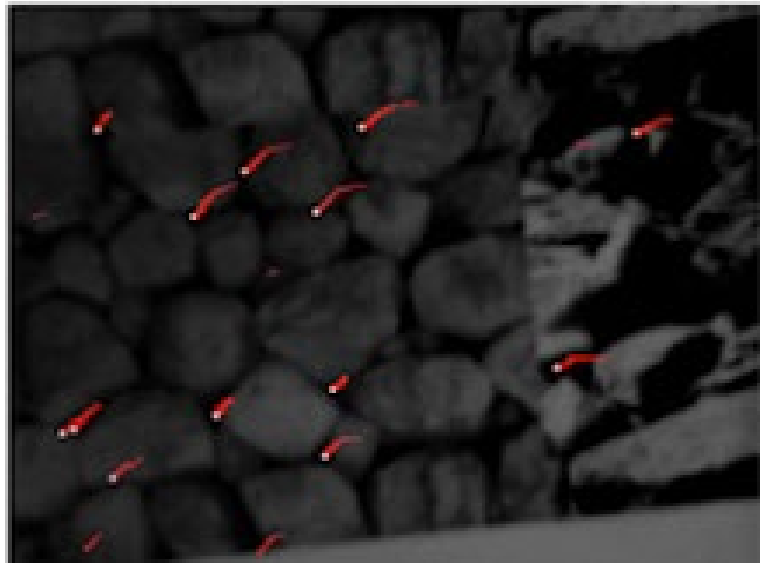
$$f^{(k+1)} = g(f^{(k)}, \mathbf{e}_{k+1})$$

Asynchronous Multi-Hypothesis Tracking of Events

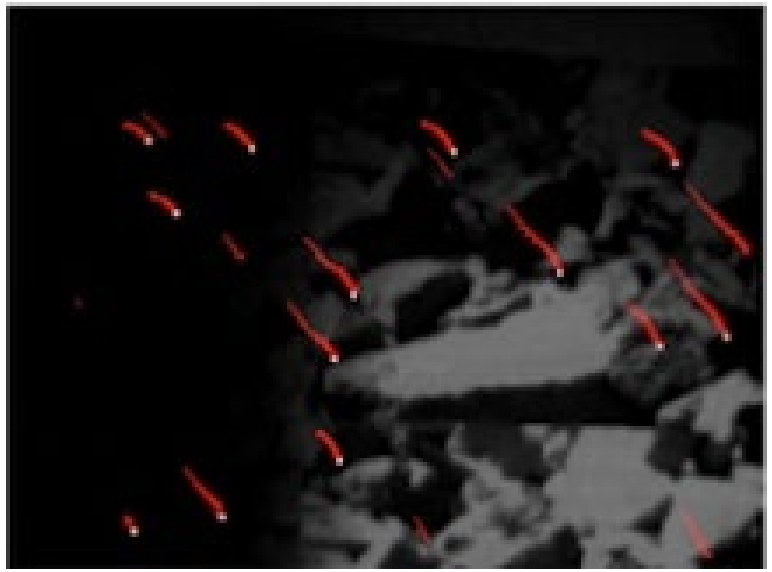
Simple Scene



High-Textured Scene

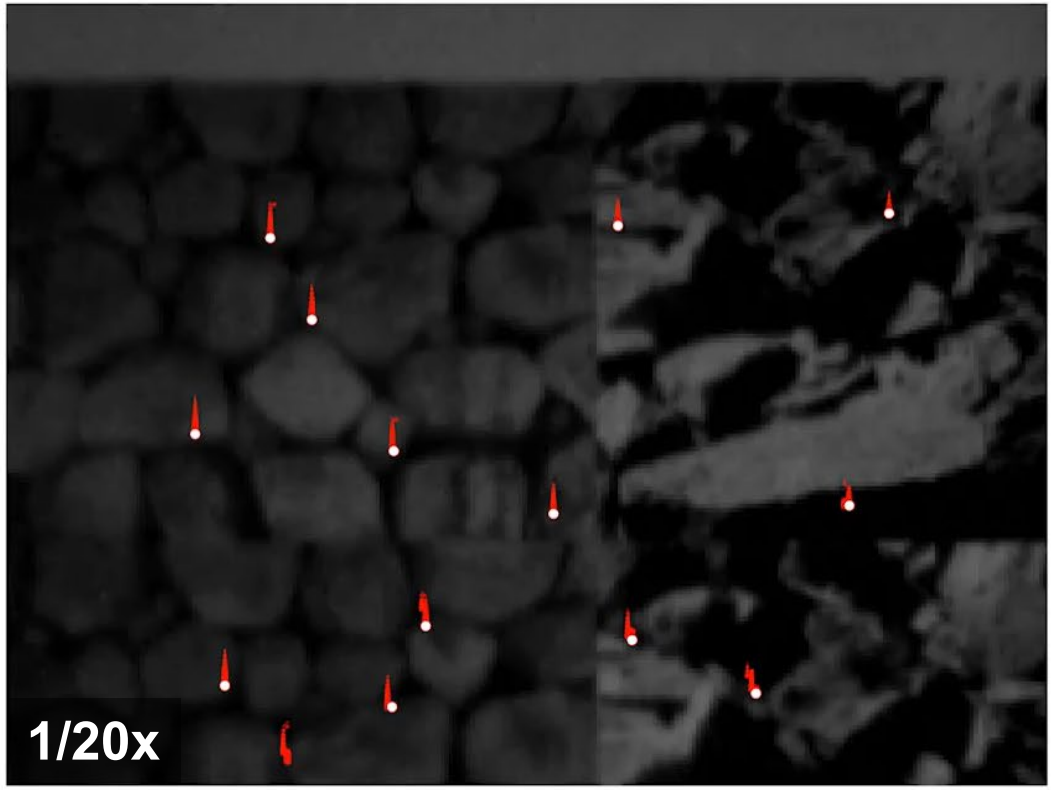


HDR Illumination

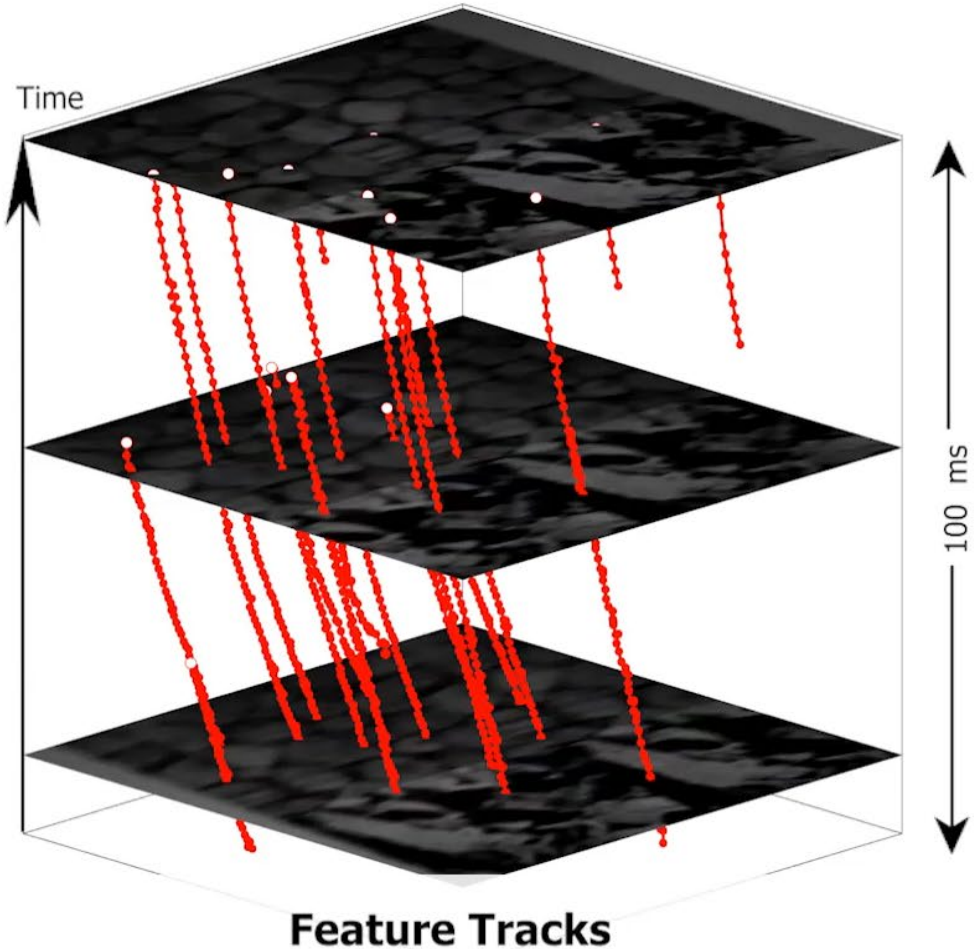


Asynchronous Multi-Hypothesis Tracking of Events

Tracking under high-speed camera motion

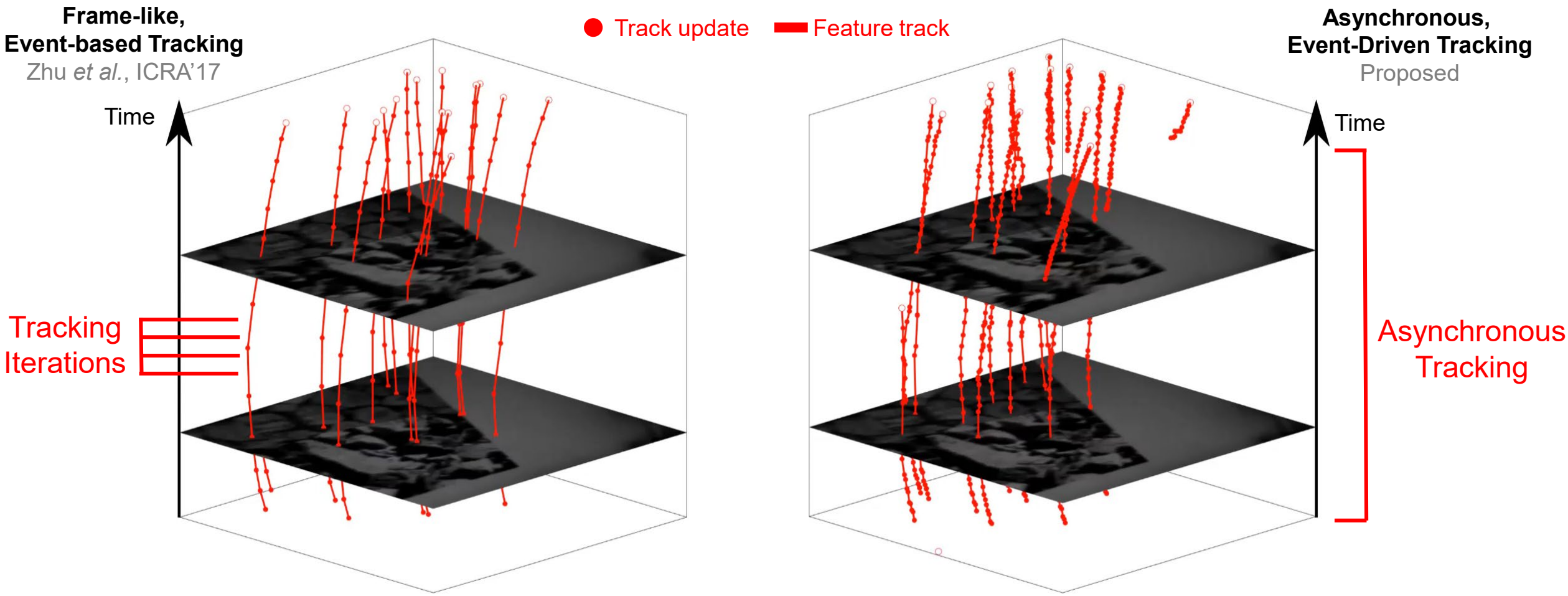


Feature Tracks
in image space

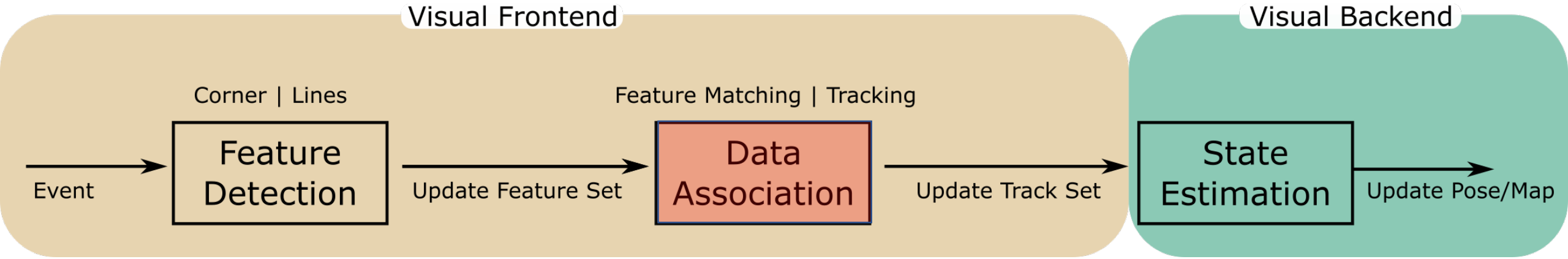


Feature Tracks
in spatio-temporal space

Asynchronous Event-Driven Feature Tracking



Asynchronous Event-Driven SLAM Pipeline



- Event Corner Detection
- Naïve Event Corner Association
- Offline Corner Tracks Retrieval

Asynchronous Corner Detection and Tracking for Event Cameras in Real-Time
[Alzugaray & Chli, RAL'18]

- Local Event Descriptor
- Multi-hypothesis Data Association
- Online Corner Track Retrieval

ACE: An Efficient Asynchronous Corner Tracker for Event Cameras
[Alzugaray & Chli, 3DV'18]

- Hypothesis-based Optimization Framework
- Tracking directly on Raw Events
- Not Real-Time

Asynchronous Multi-Hypothesis Tracking of Features with Event Cameras
[Alzugaray & Chli, 3DV'19]

- Incremental Hypothesis-based Optimization
- Real-time capabilities.

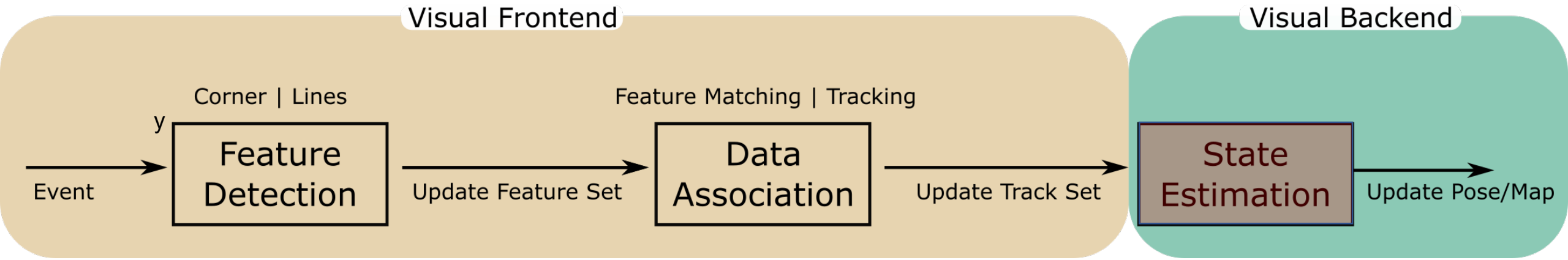
HASTE: multi-Hypothesis Asynchronous Speeded-up Tracking of Events
[Alzugaray & Chli, BMVC'20]

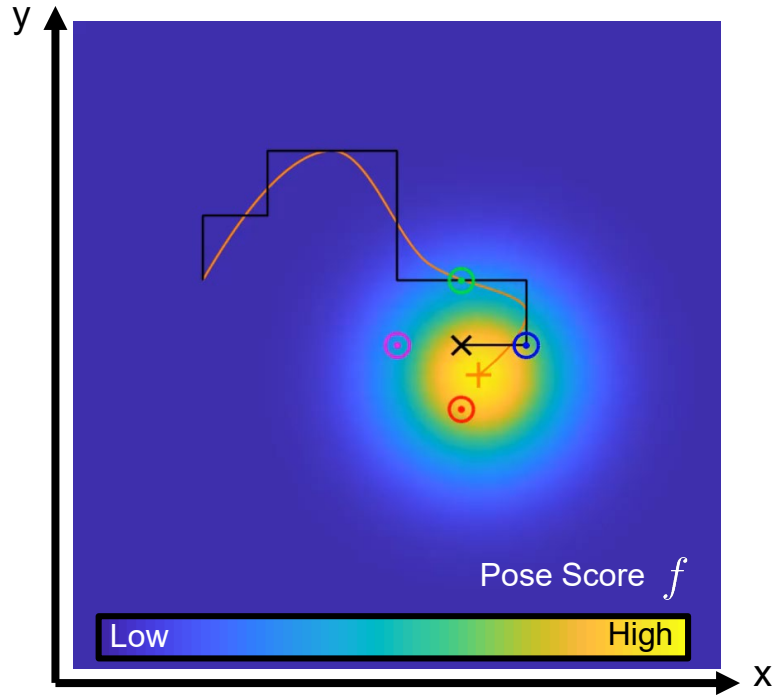
Publicly available:

github.com/ialzugaray/arc_star_ros

github.com/ialzugaray/haste

Asynchronous Event-Driven SLAM Pipeline





- Hypothesis-based Optimization Framework
- Tracking directly on Raw Events
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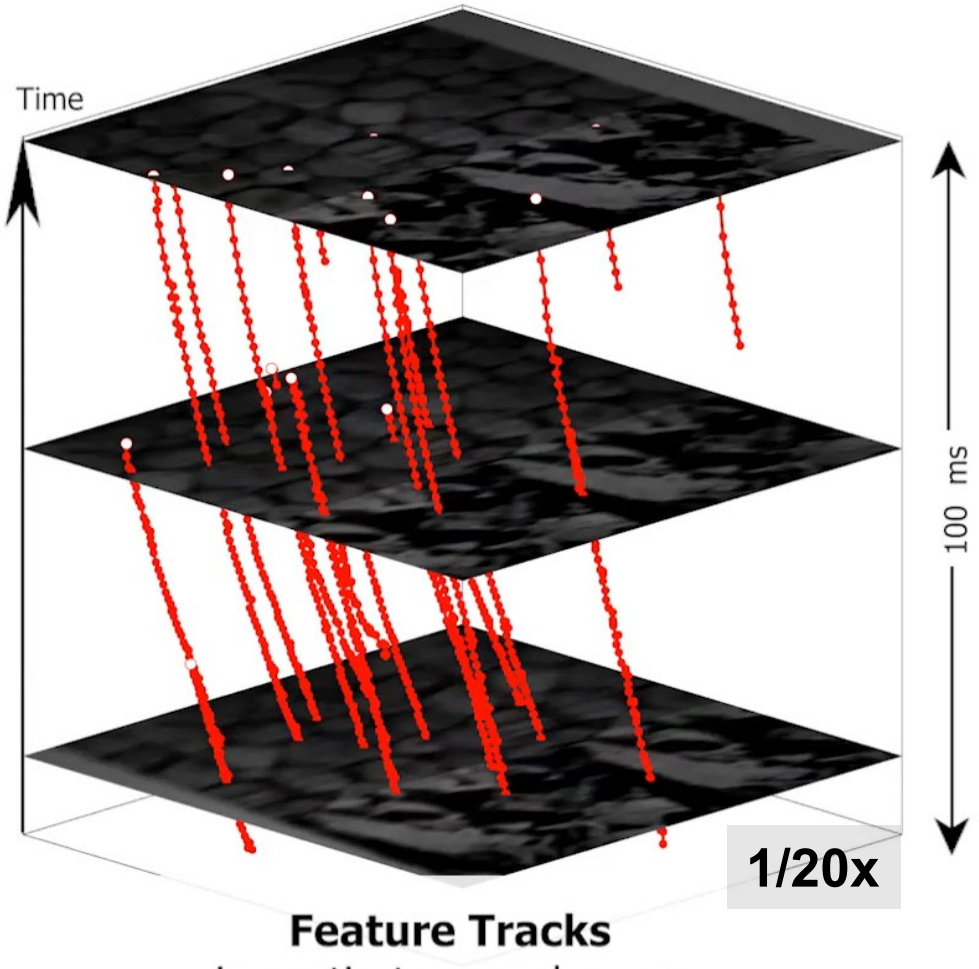
Asynchronous Multi-Hypothesis Tracking of Features with Event Cameras
[Alzugaray & Chli, 3DV'19]

- Incremental Hypothesis-based Optimization
- Real-time capabilities.

HASTE: multi-Hypothesis Asynchronous Speeded-up Tracking of Events
[Alzugaray & Chli, BMVC'20]

On Event-Driven Perception

- Natural to event cameras
  - Exploit Sparsity & Asynchronicity
- Reduce the number of assumptions
  - Motion-speed tuning / Event-window tuning
- Algorithms require careful design
  - Efficiency / Robustness / Scalability



Feature Tracks
in spatio-temporal space