

Seeing through Space and Time:

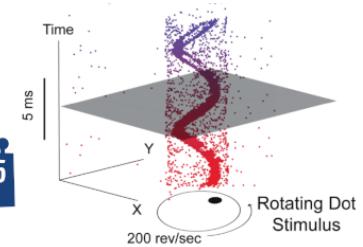
Asynchronous Event Blob Tracking, Detection and Optical Communication

Presenter: Ziwei Wang

System Theory and Robotics Group (STR), CIICADA, Australian National University



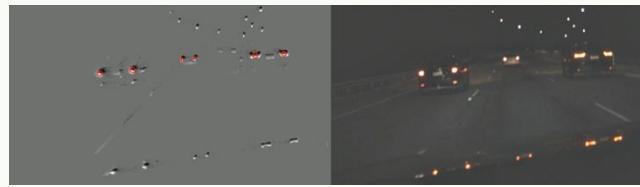
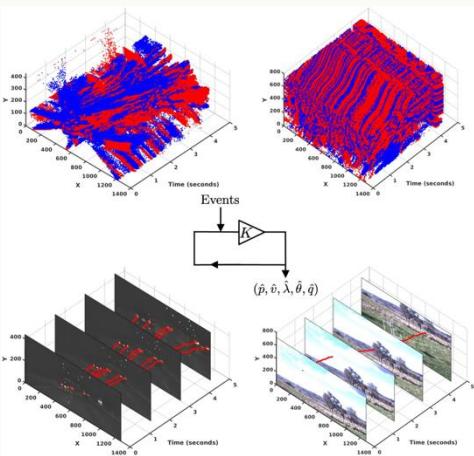
Australian
National
University



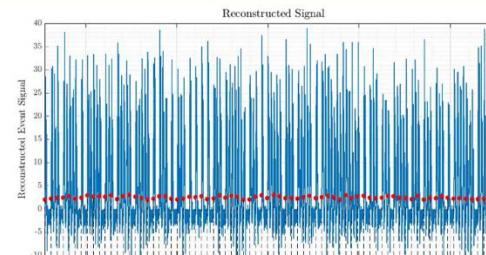
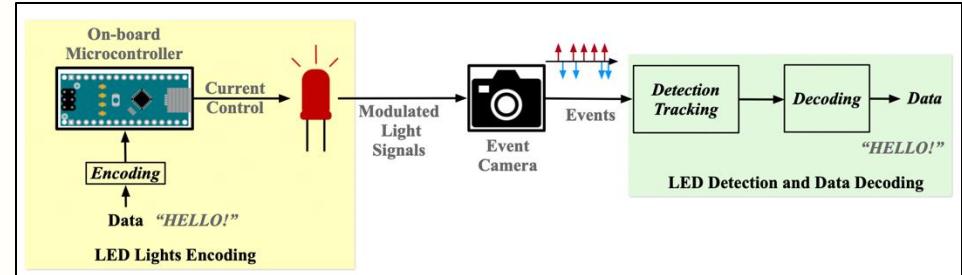
**Systems Theory and
Robotics group**

Asynchronous Event Processing for Robots

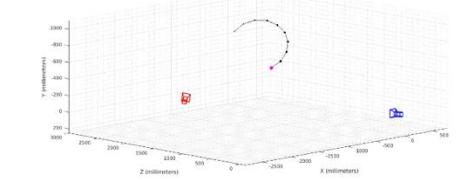
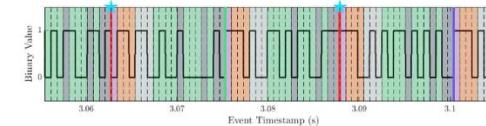
Asynchronous High Speed Blob Tracking (AEB Tracker)



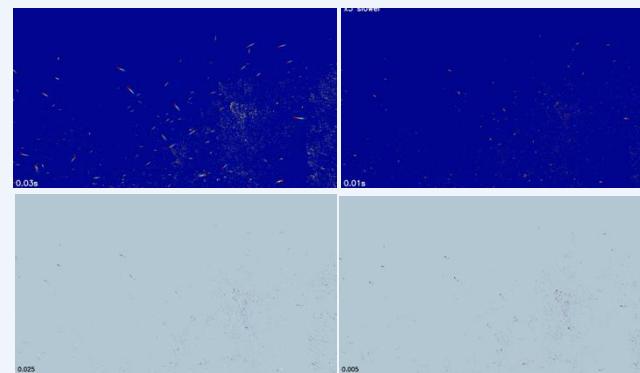
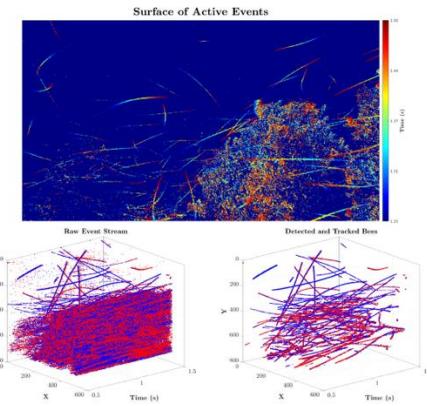
Asynchronous Optical Communication using Smart Beacons



3D Reconstruction

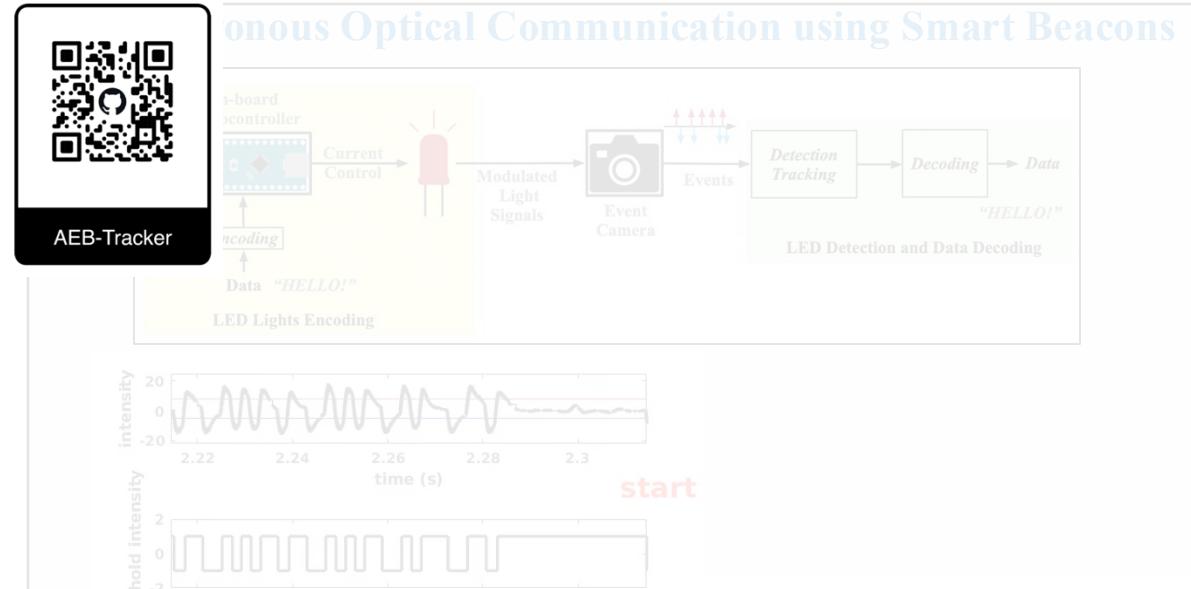
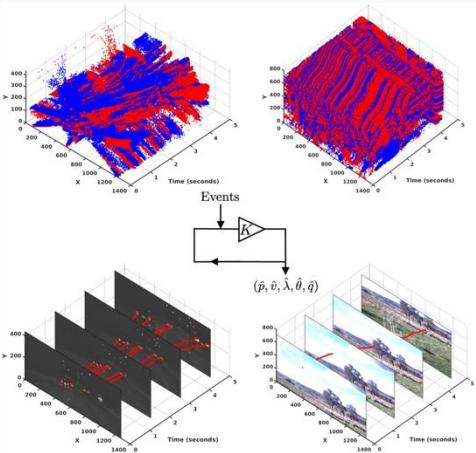


Asynchronous Blob Detection and Track Management

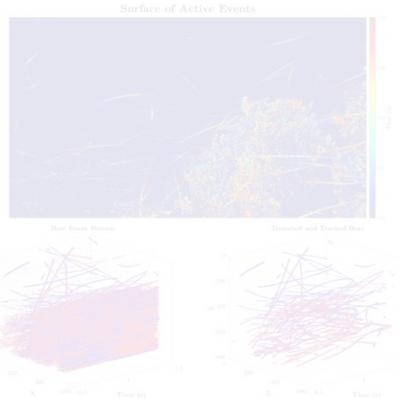


Asynchronous Event Processing for Robots

Asynchronous High Speed Blob Tracking (AEB Tracker)



Asynchronous Blob Detection and Track Management



Asynchronous Blob Tracker for Event Cameras

IEEE Transactions on Robotics (TRO), 2024



Ziwei Wang

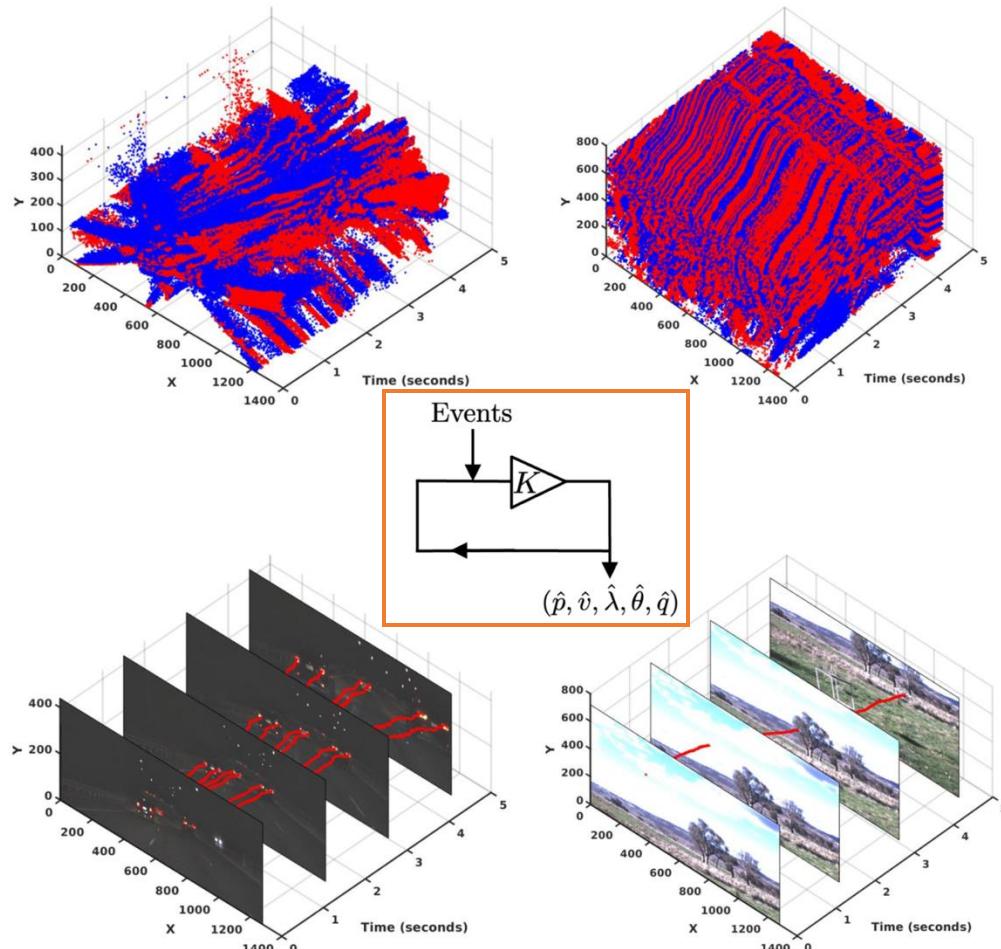
Timothy Molloy

Left Event Camera

Pieter Van Goor

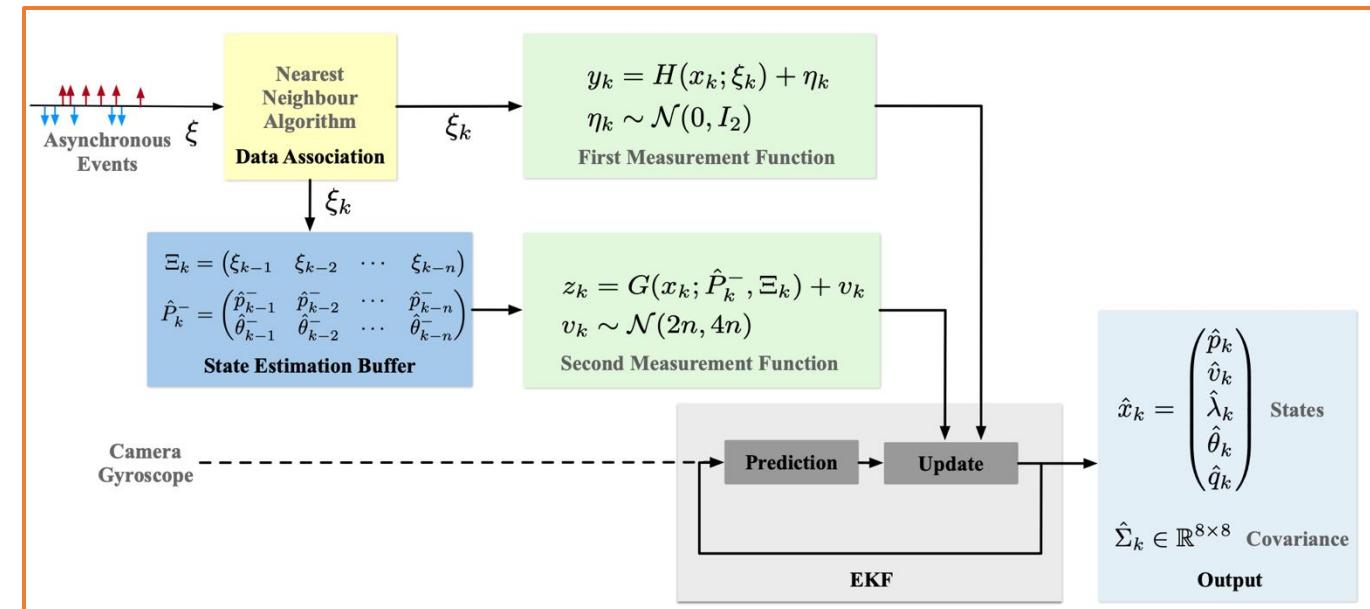
Right Event Camera

Asynchronous Blob Tracker Pipeline



Asynchronous Blob Tracker for Event Cameras
IEEE Transactions on Robotics (TRO), 2024

Input Events



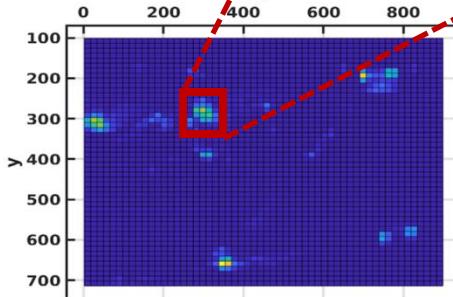
Output Tracks

Output State:
Position, Velocity, Size, Rotation, Angular Velocity

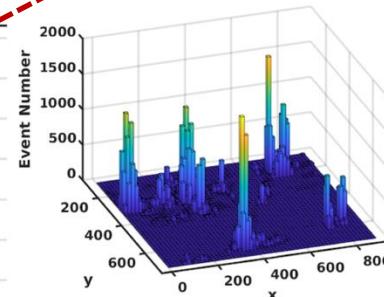
Event Blob



(a)



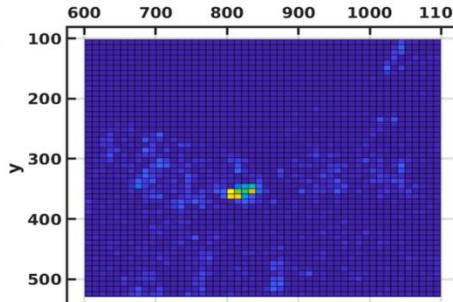
(b)



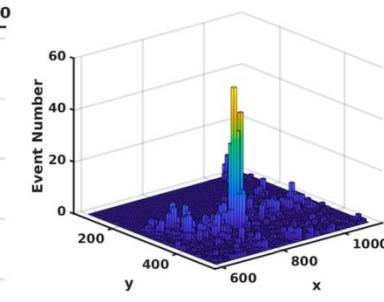
(c)



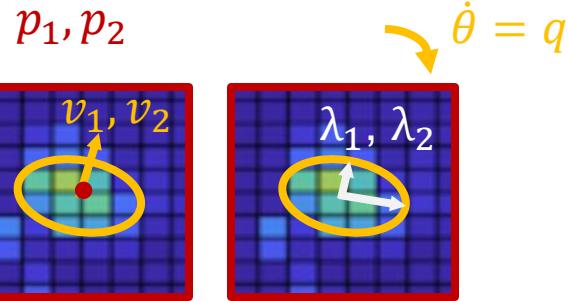
(d)



(e)



(f)



A sequence of events $\{e_k\}$:

$$e_k = (\xi_k, t_k, \rho_k)$$

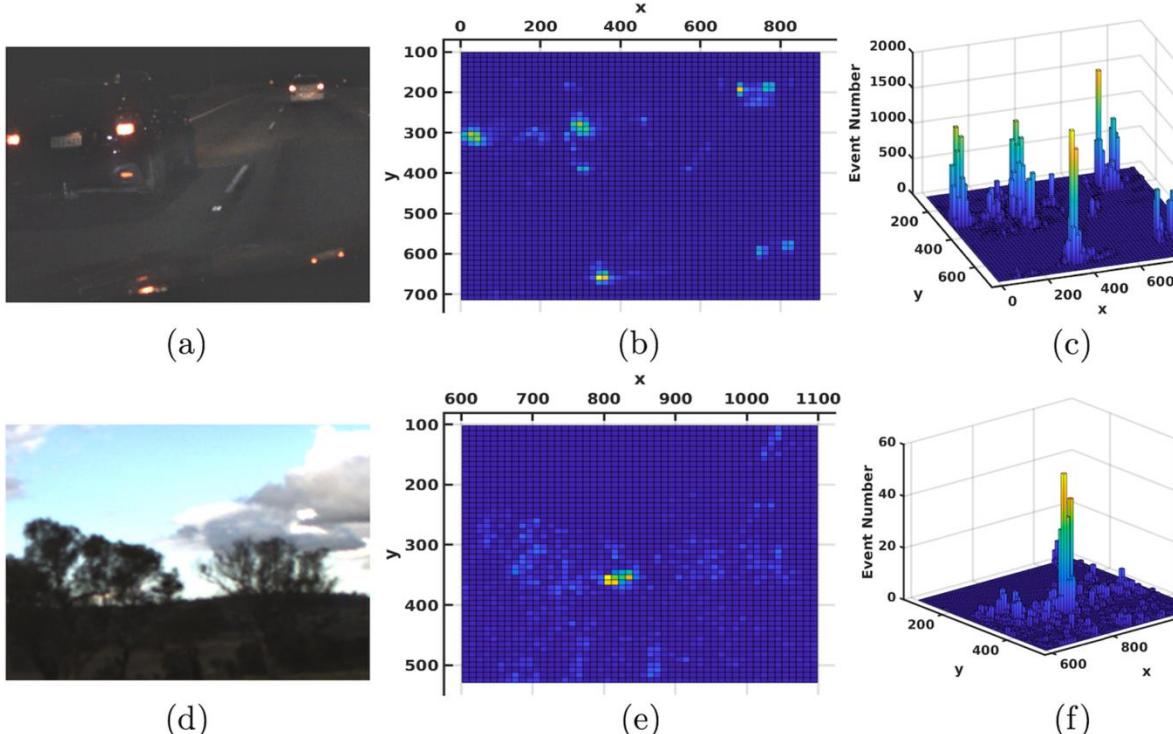
States:

$$x(t_k) = \begin{pmatrix} p(t_k) \\ v(t_k) \\ \lambda(t_k) \\ \theta(t_k) \\ q(t_k) \end{pmatrix} = \begin{pmatrix} p_k \\ v_k \\ \lambda_k \\ \theta_k \\ q_k \end{pmatrix}$$

Position
Velocity
Size
Rotation
Angular Velocity

Event Blob

Spatio-Temporal Gaussian Likelihood Model



A sequence of events $\{e_k\}$:

$$e_k = (\xi_k, t_k, \rho_k)$$

States:

$$x(t_k) = \begin{pmatrix} p(t_k) \\ v(t_k) \\ \lambda(t_k) \\ \theta(t_k) \\ q(t_k) \end{pmatrix} = \begin{pmatrix} p_k \\ v_k \\ \lambda_k \\ \theta_k \\ q_k \end{pmatrix}$$

Position
Velocity
Size
Rotation
Angular Velocity

A generative noise model for the event location:

$$\xi_k = p_k + \eta_k, \quad \eta_k \sim \mathcal{N}(0, \Lambda_k^2)$$

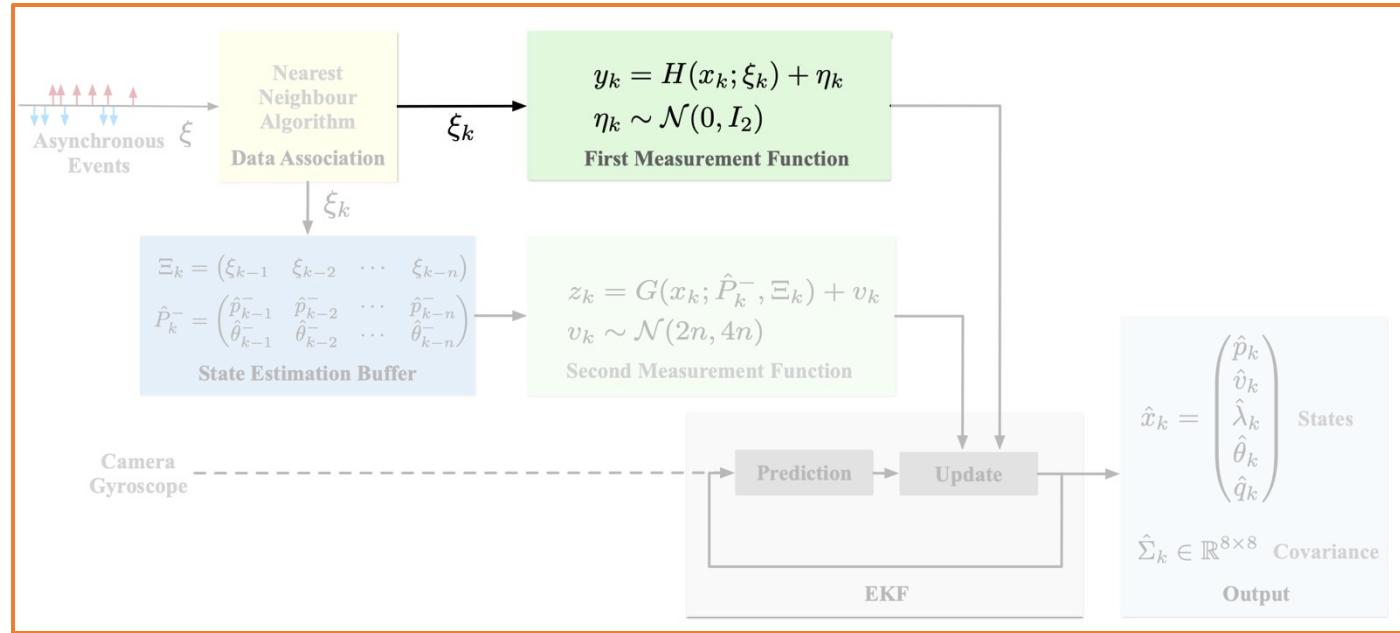
$$\Lambda_k := R(\theta_k) \begin{pmatrix} \lambda_k^1 & 0 \\ 0 & \lambda_k^2 \end{pmatrix} R^\top(\theta_k)$$

Move Λ_k :

$$\xi_k = p_k + \Lambda_k \eta_k, \quad \eta_k \sim \mathcal{N}(0, I_2)$$

Two-Stage Measurement Construction

First Measurement y_k



Recall:

$$\xi_k = p_k + \Lambda_k \eta_k, \quad \eta_k \sim \mathcal{N}(0, I_2)$$

Define a measurement function:

$$H(x_k; \xi_k) := \Lambda_k^{-1}(\xi_k - p_k)$$

Define a new measurement model:

$$y_k = H(x_k; \xi_k) + \eta_k, \quad \eta_k \sim \mathcal{N}(0, I_2)$$

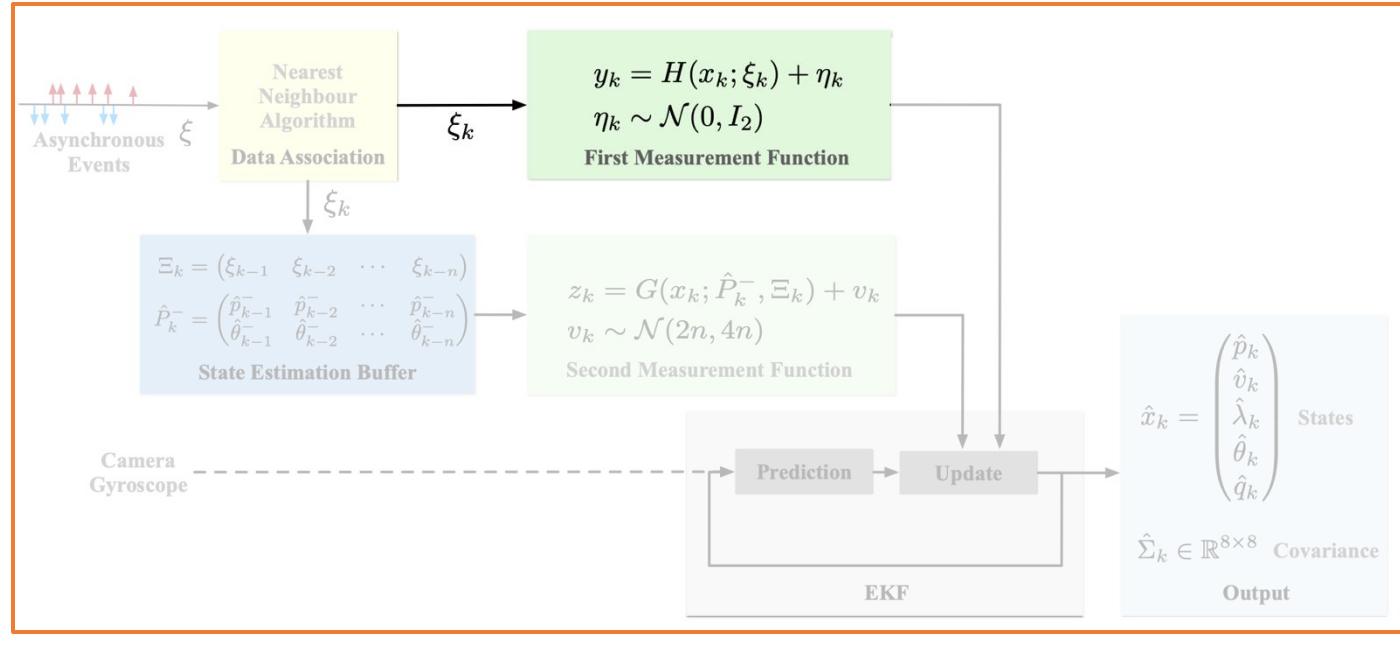
Use pseudo measurements:

$$y_k = 0$$

Julier, S.J. and LaViola, J.J., 2007. On Kalman filtering with nonlinear equality constraints. *IEEE transactions on signal processing*, 55(6), pp.2774-2784.

Two-Stage Measurement Construction

First Measurement y_k



Recall:

$$\xi_k = p_k + \Lambda_k \eta_k, \quad \eta_k \sim \mathcal{N}(0, I_2)$$

Define a measurement function:

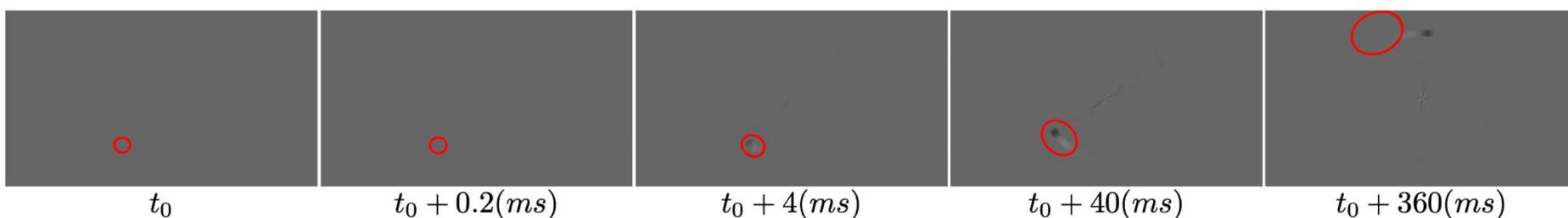
$$H(x_k; \xi_k) := \Lambda_k^{-1}(\xi_k - p_k)$$

Define a new measurement model:

$$y_k = H(x_k; \xi_k) + \eta_k, \quad \eta_k \sim \mathcal{N}(0, I_2)$$

Measurement error:

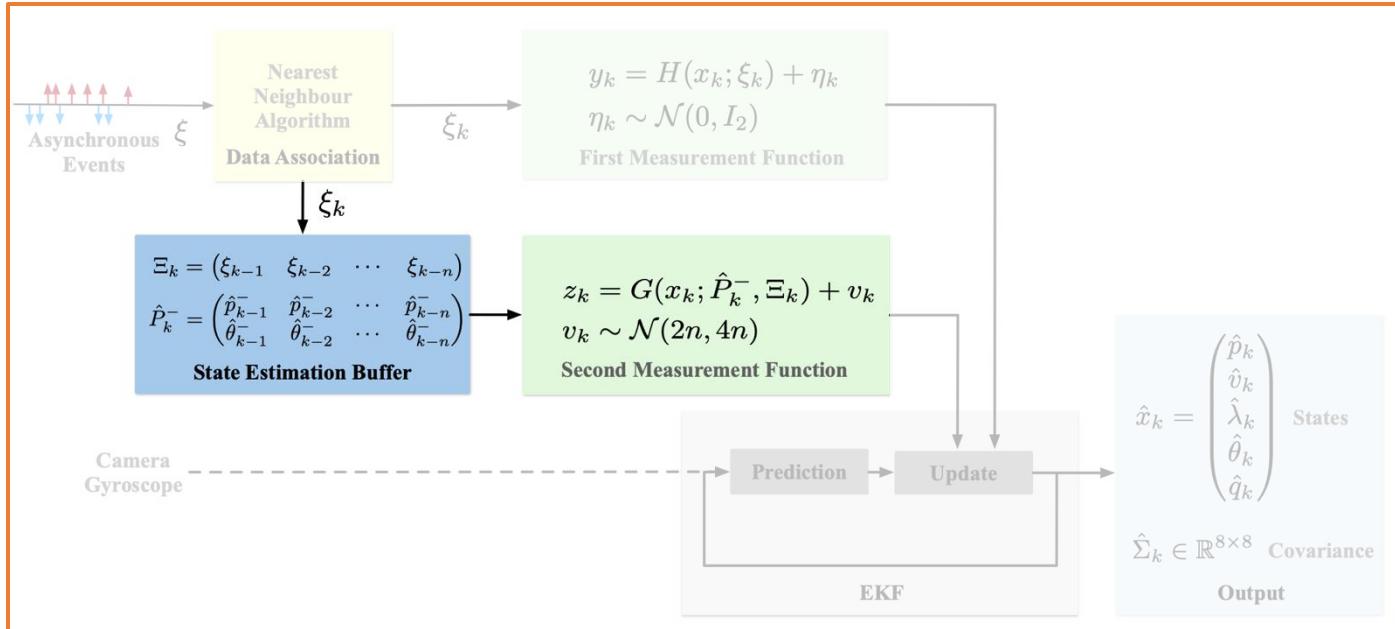
$$\|y_k - \Lambda_k^{-1}(\xi_k - p_k)\| = \|\Lambda_k^{-1}(\xi_k - p_k)\|$$



Unobservable Size!

Two-Stage Measurement Construction

Second Measurement z_k



Define a measurement function G :

$$G(x_k; \hat{P}_k^-, \Xi_k) := \sum_{j=1}^n \|\chi_{k-j}\|^2$$

$$\chi_{k-j} := \frac{1}{1+\beta} \hat{\Lambda}_{k-j}^{-1} (\xi_{k-j} - \hat{p}_{k-j}^-)$$

Define a new measurement model:

$$z_k := G(x_k; \hat{P}_k^-, \Xi_k) + v_k$$

$$v_k \sim \mathcal{N}(0, 4n)$$

Use pseudo measurements:

$$z_k = 2n$$

Julier, S.J. and LaViola, J.J., 2007. On Kalman filtering with nonlinear equality constraints. *IEEE transactions on signal processing*, 55(6), pp.2774-2784.

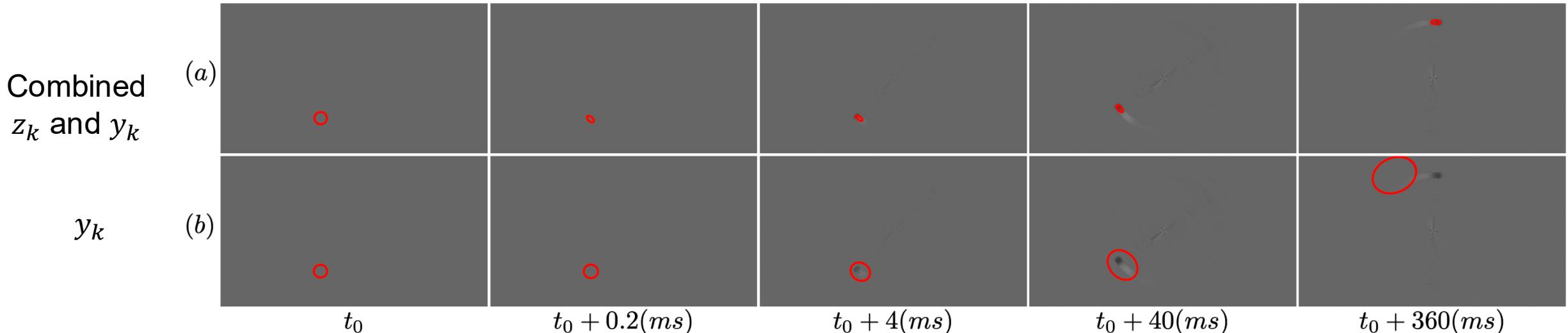
Two-Stage Measurement Construction

Combined Measurement y_k & z_k

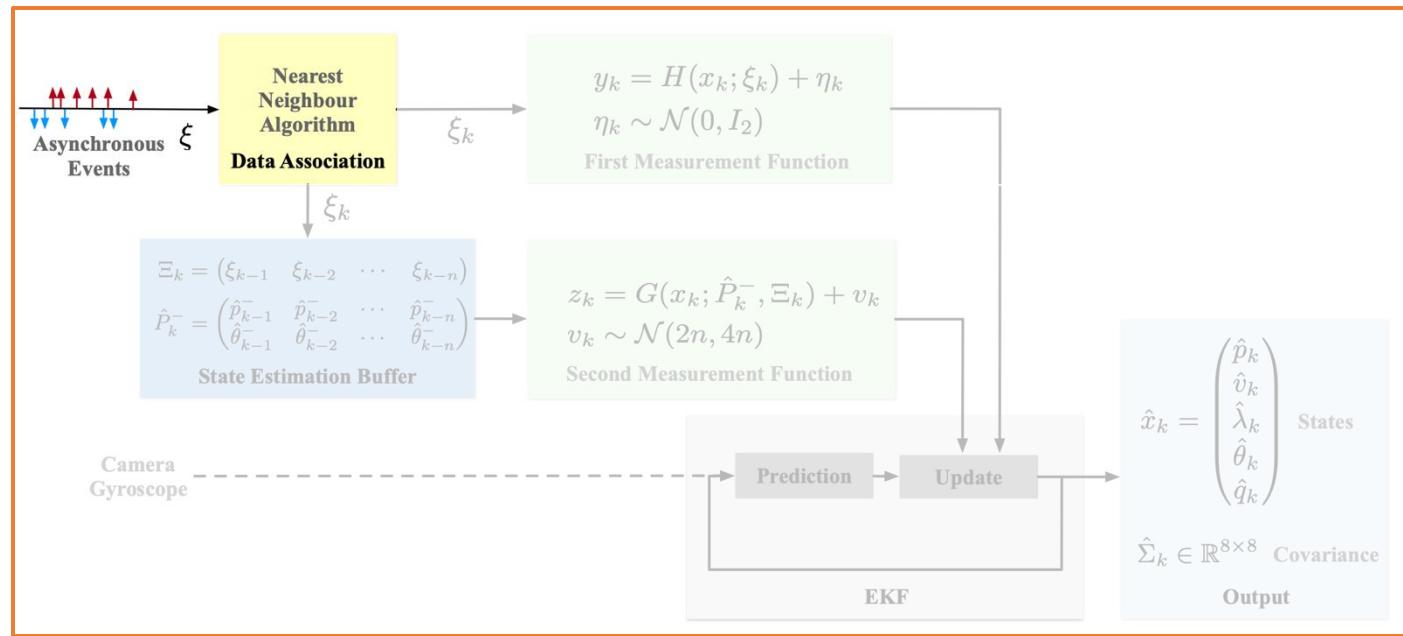
Two-stage measurement function:

$$m_k = \begin{pmatrix} H(x_k; \xi_k) \\ G(x_k; \hat{P}_k^-, \Xi_k) \end{pmatrix} + \nu_k, \quad \nu_k \sim \mathcal{N}(0, R)$$
$$R = \begin{pmatrix} I_2 & 0 \\ 0 & 4n \end{pmatrix},$$

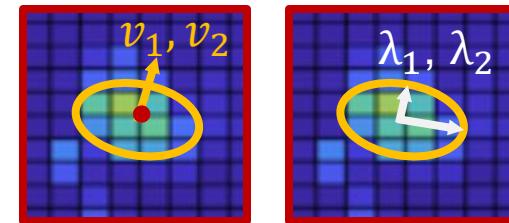
where $H(x_k; \xi_k)$ and $G(x_k; \hat{P}_k^-, \Xi_k)$ are independent.



Data Association



p_1, p_2



In continuous-time, the data association threshold ODE:

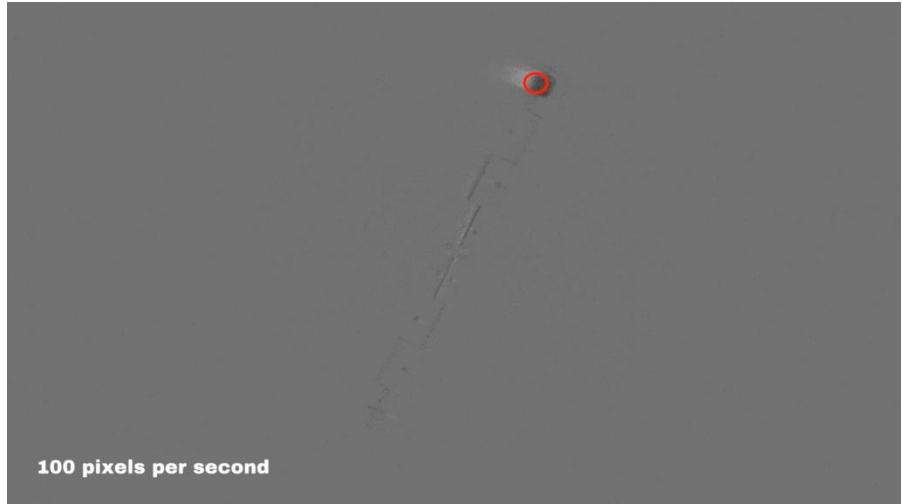
$$\dot{\sigma}(t) = -\alpha\sigma(t) + b\alpha \max(\hat{\lambda}_k^1, \hat{\lambda}_k^2)$$

At each event timestamp:

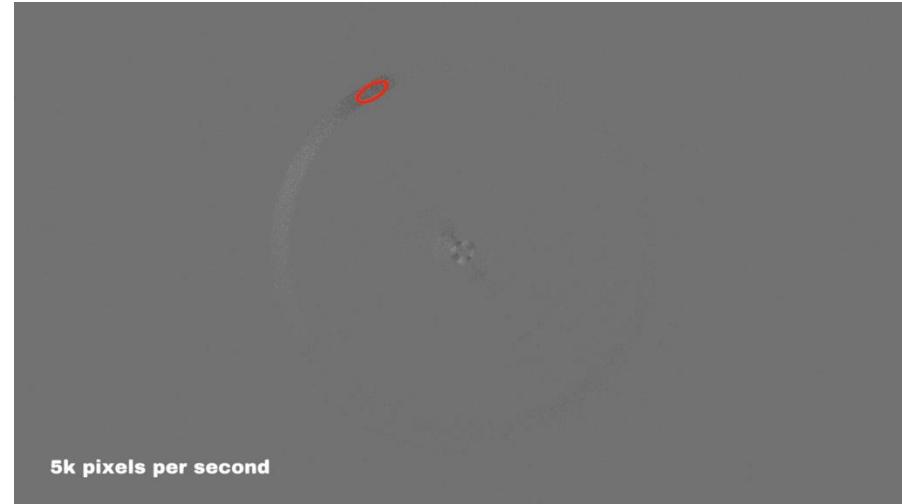
$$\sigma_k = \beta_k \sigma_{k-1} + b(1 - \beta_k) \max(\hat{\lambda}_k^1, \hat{\lambda}_k^2)$$

$$\beta_k := \exp(-\alpha(t_k - t_{k-1}))$$

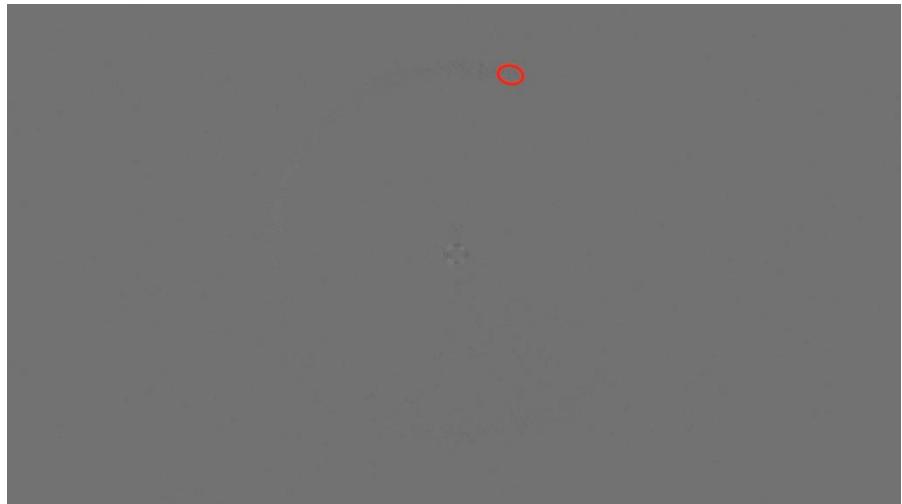
Fast Spinning Data



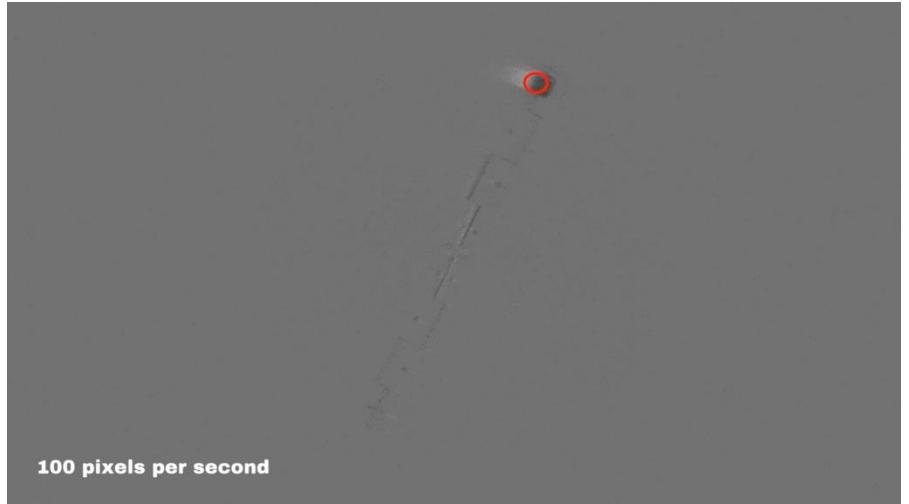
100-5,000 Pixels Per Second



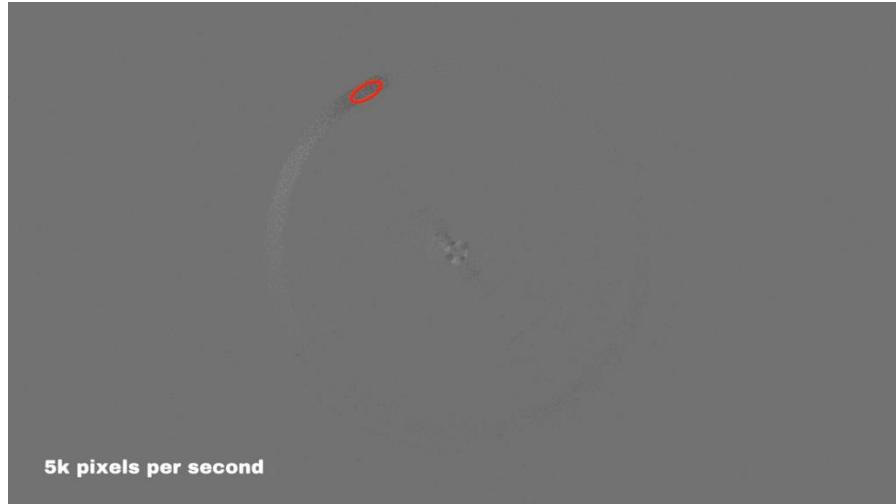
5,000-9,000 Pixels Per Second



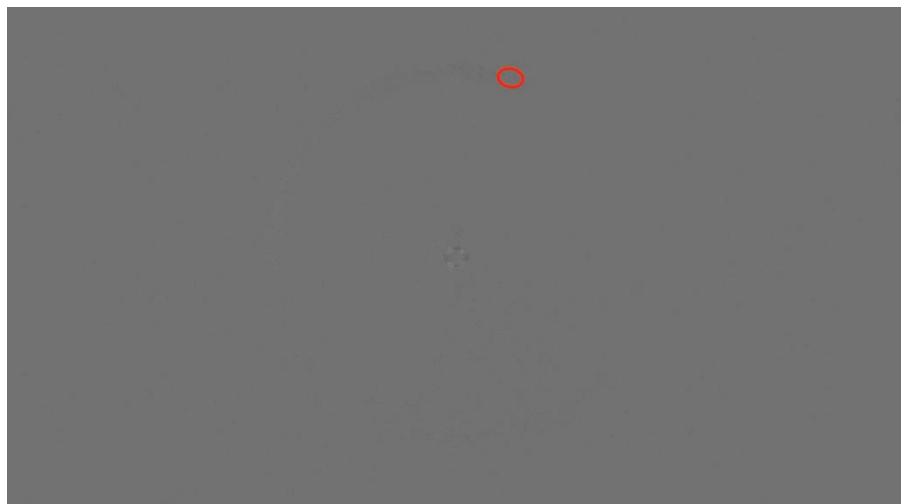
Fast Spinning Data



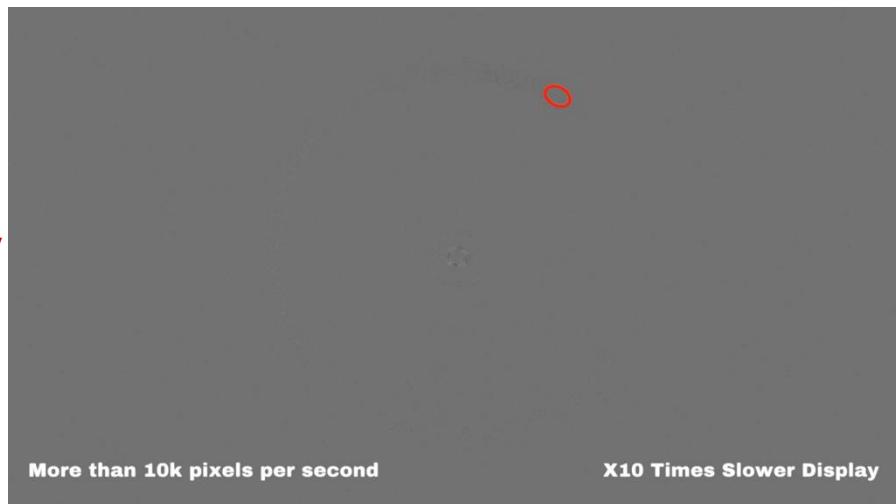
100-5,000 Pixels Per Second



5,000-9,000 Pixels Per Second



10,000-11,000 Pixels Per Second

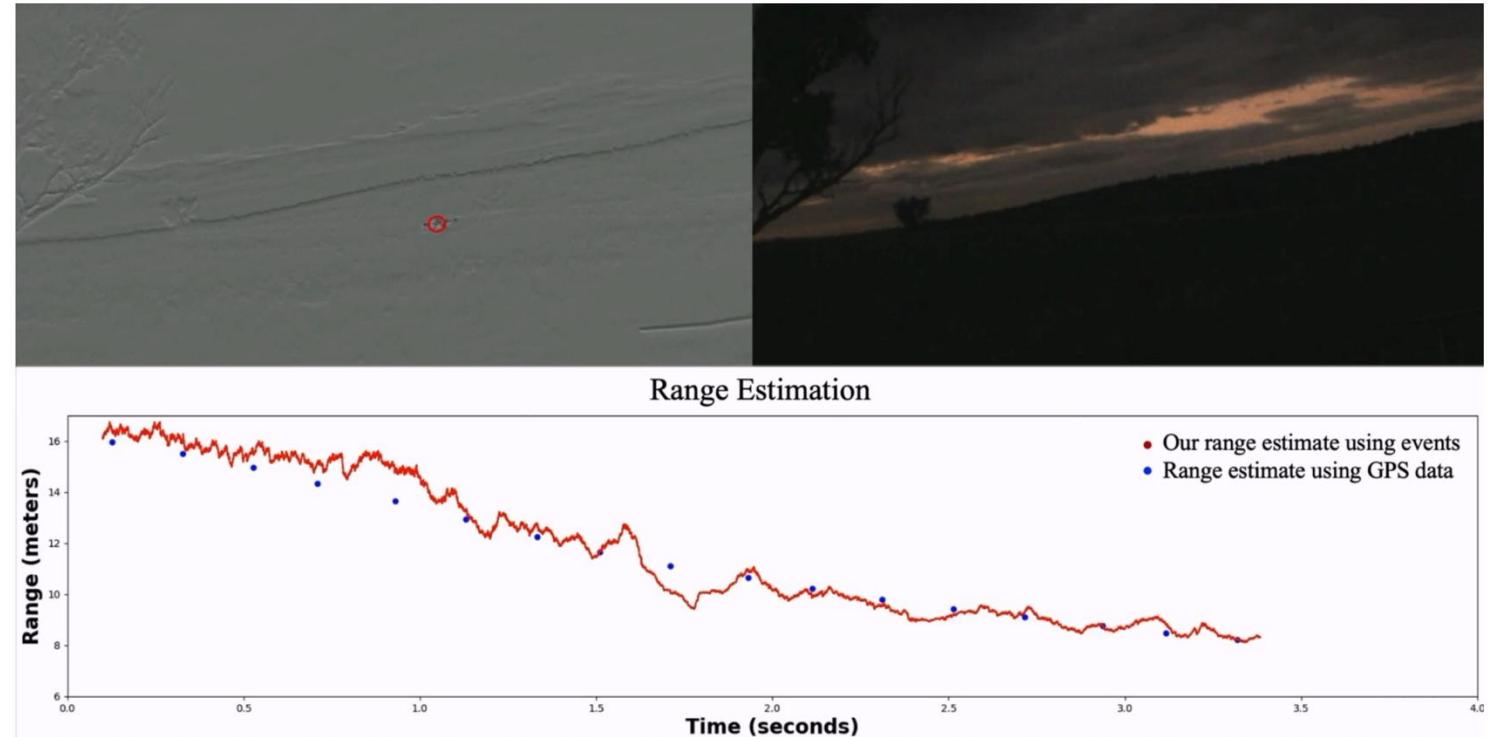


10,000-11,000 Pixels Per Second

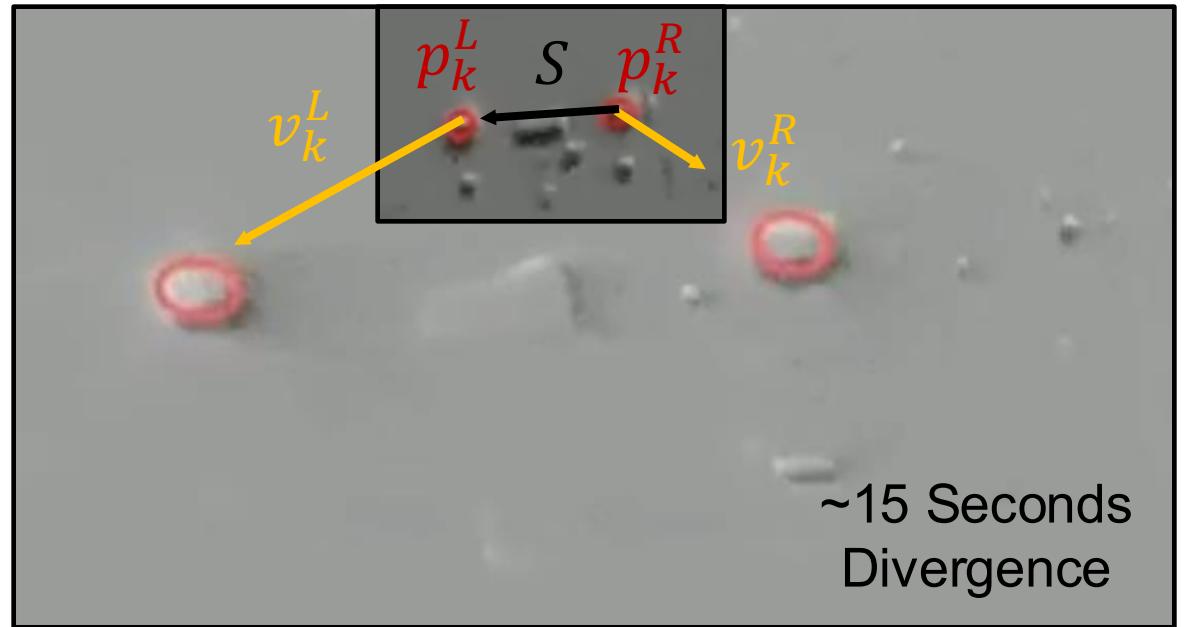
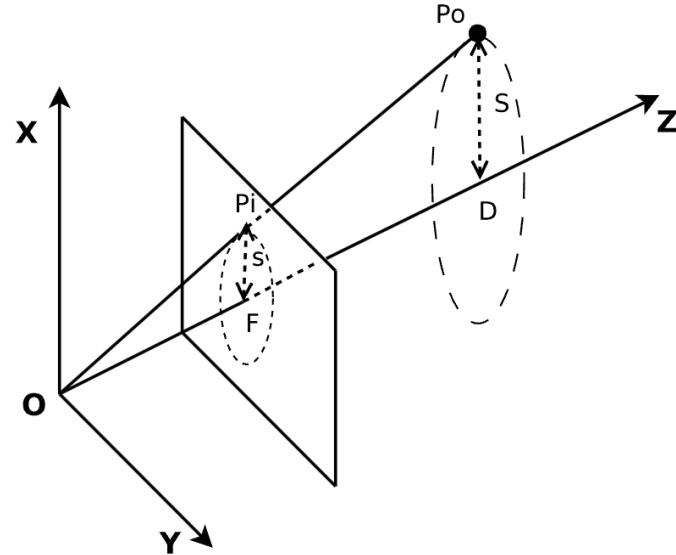
Flying Quadrotor Data



Quadrotor with an RTK-GPS and Our Stereo Event-Frame Camera



Time to Contact



$$s := \|\hat{p}_k^L - \hat{p}_k^R\|$$

TTC can be estimated with s and its derivatives [4]:

$$\tau = -\frac{Z}{\dot{Z}} = \frac{s}{\dot{s}}$$

$$v := (\hat{v}_k^L - \hat{v}_k^R)^\top \frac{\hat{p}_k^L - \hat{p}_k^R}{\|\hat{p}_k^L - \hat{p}_k^R\|}$$

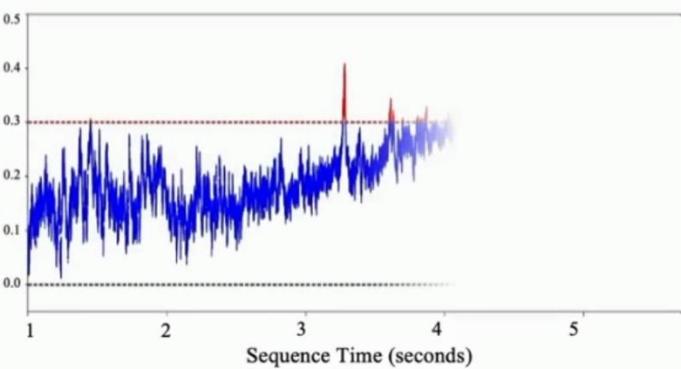
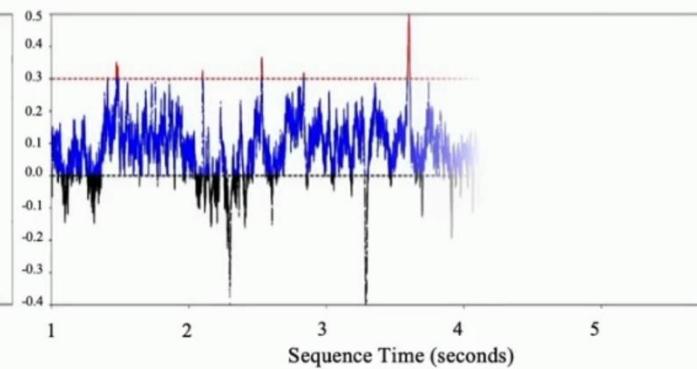
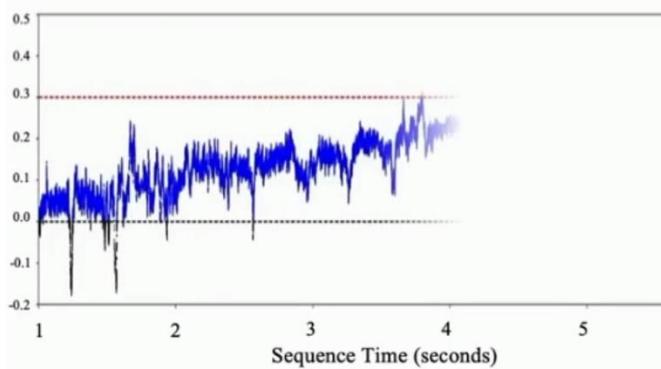
$$\frac{1}{\tau(t_k)} := \frac{(\hat{v}_k^L - \hat{v}_k^R)^\top (\hat{p}_k^L - \hat{p}_k^R)}{\|\hat{p}_k^L - \hat{p}_k^R\|^2}$$

[4] Negre, A., Braillon, C., Crowley, J. L., & Laugier, C. (2008, February). Real-time time-to-collision from variation of intrinsic scale. In Experimental Robotics: The 10th International Symposium on Experimental Robotics (pp. 75-84). Berlin, Heidelberg: Springer Berlin Heidelberg.

Night Driving Data



(Inverse) Time to Contact (TTC)



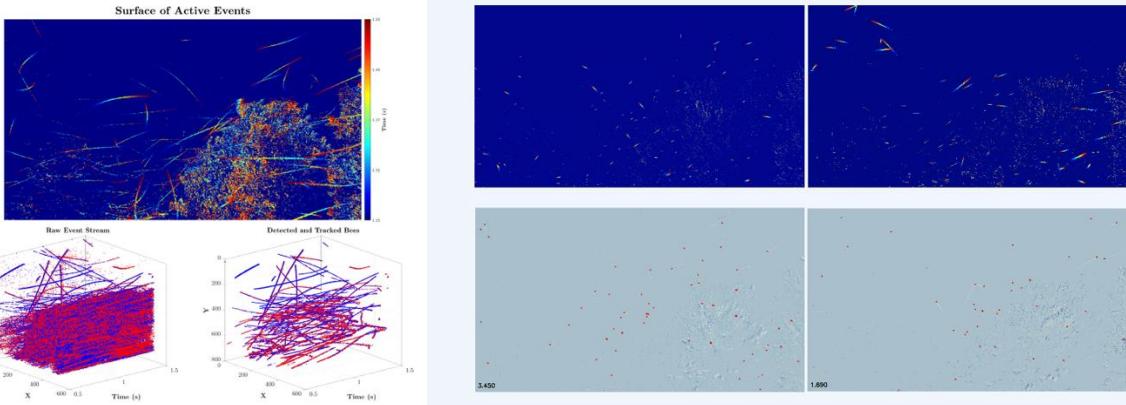
Asynchronous Event Processing for Robots

Asynchronous High Speed Blob Track | Asynchronous Multi-Object Tracking with an Event Camera | Asynchronous LED Detection and Data Decoding

IEEE International Conference on Robotics and Automation, 2025.

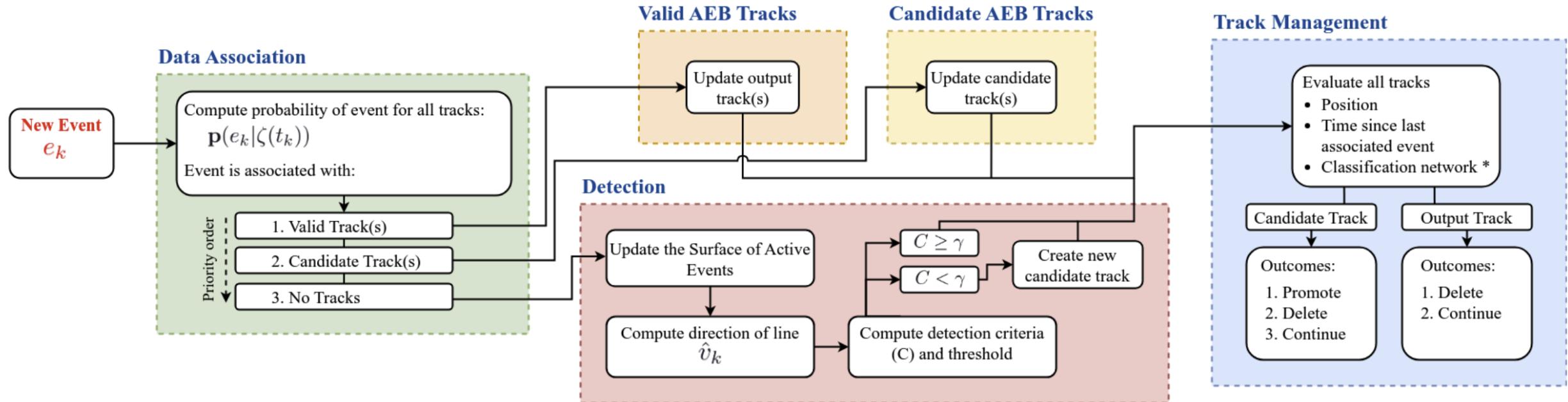
Angus Apps Ziwei Wang Timothy Molloy Robert Mahony Vladimir Perejogin

Asynchronous Blob Detection and Track Management

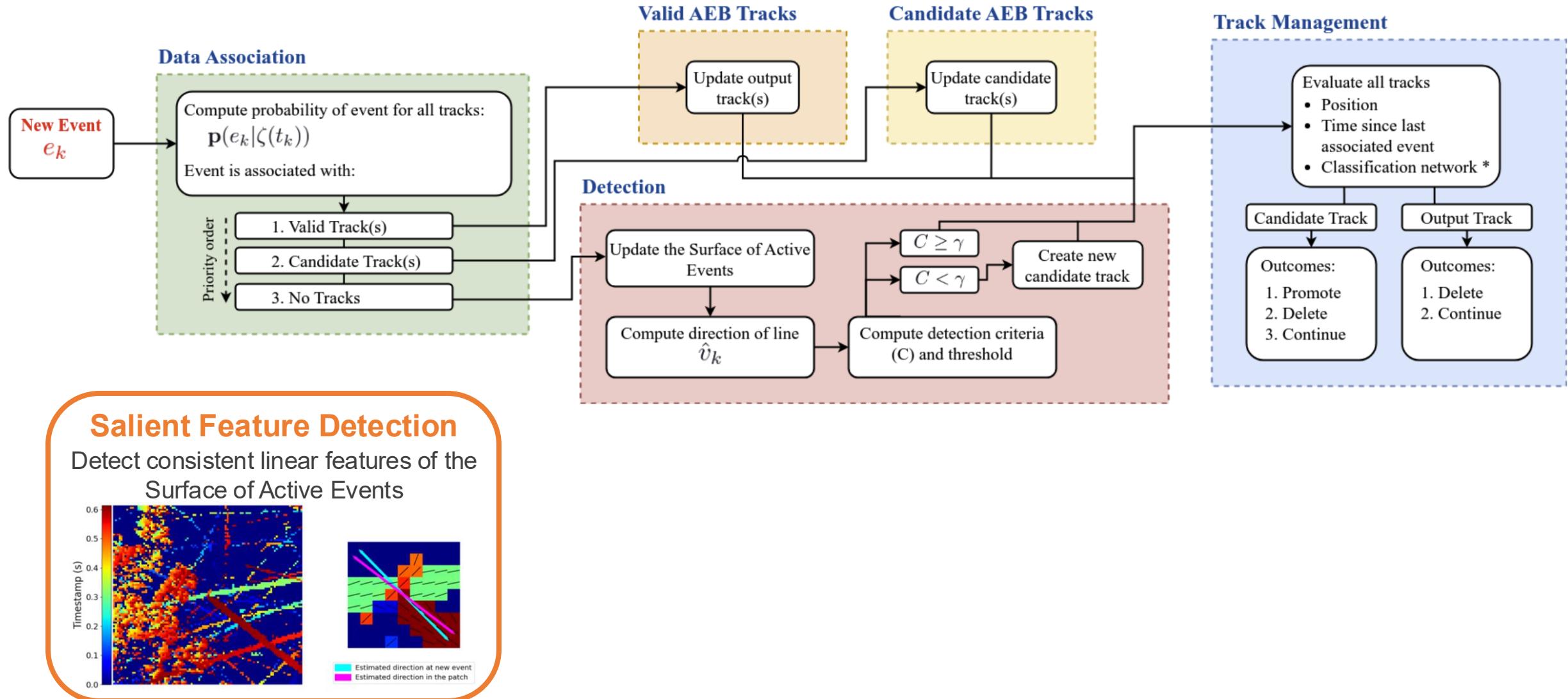


Asynchronous Event Blob Detection and Tracking

Asynchronous Event Blob Detection and Tracking

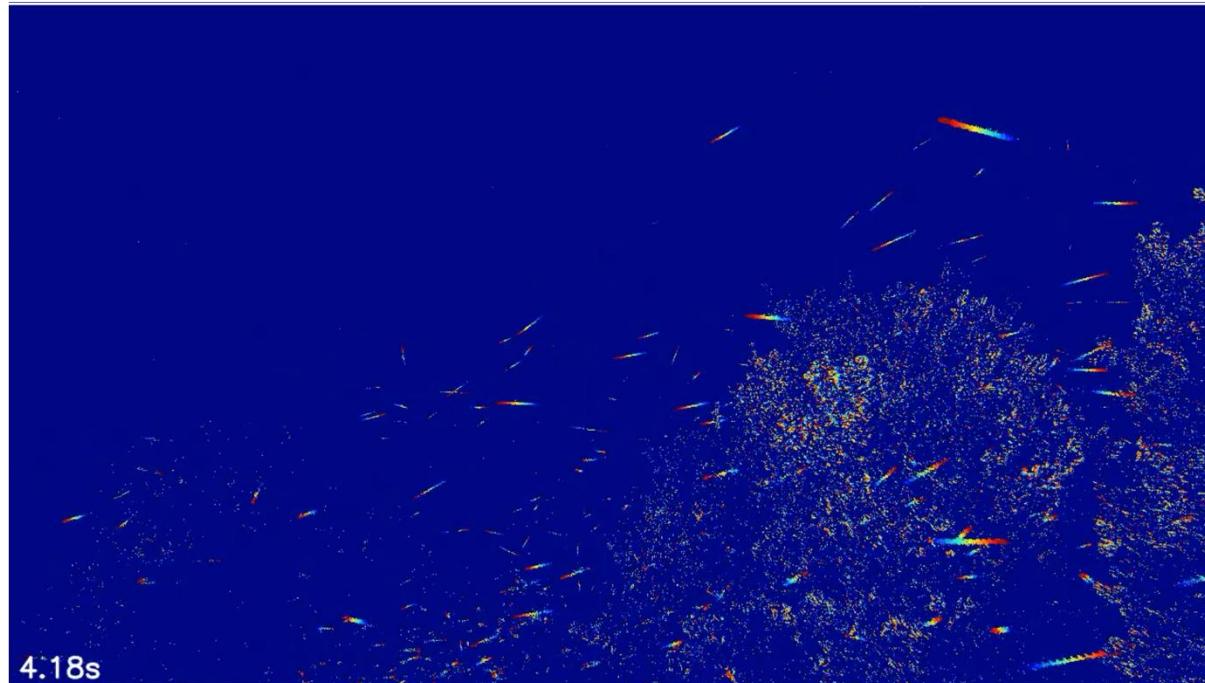


Asynchronous Event Blob Detection and Tracking

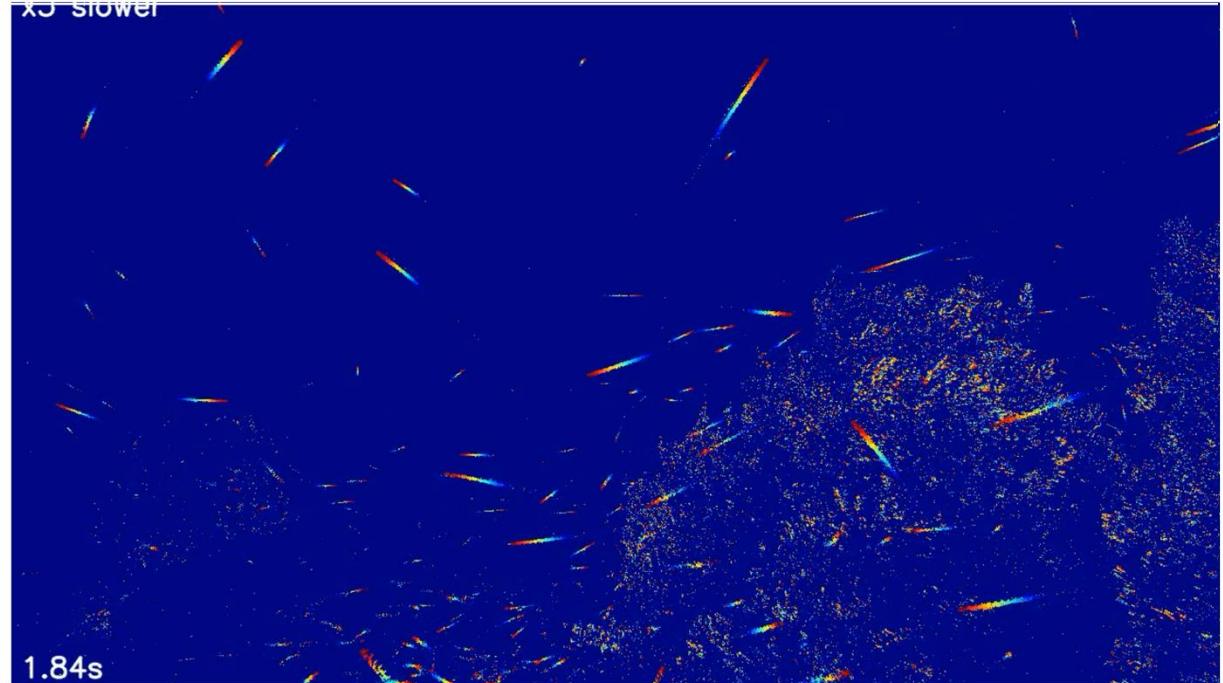


Asynchronous Event Blob Detection and Tracking

Surface of Active Events (SAE)



4.18s

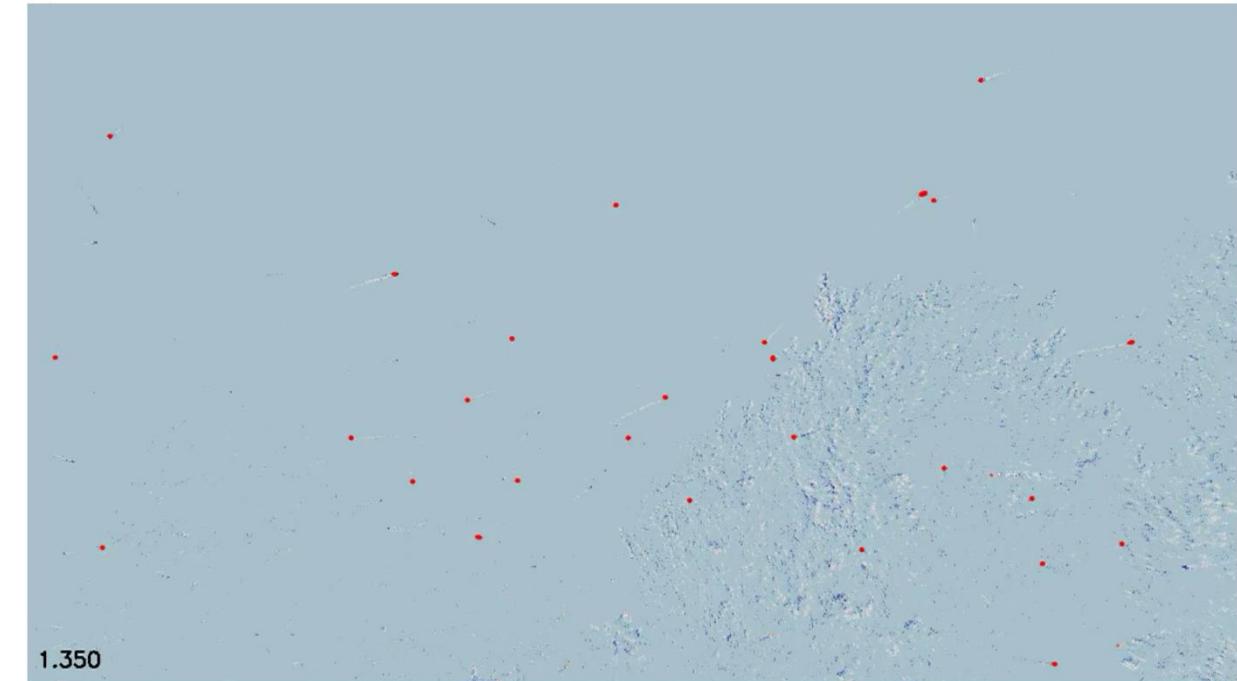
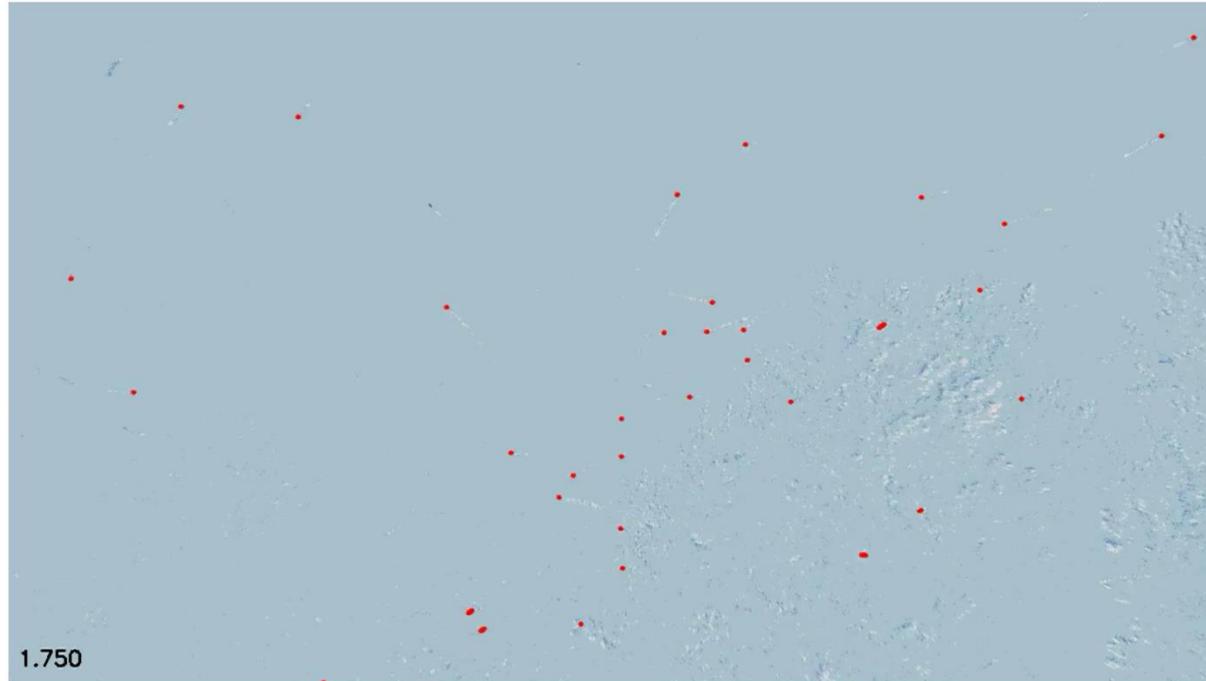


1.84s

X5 Times Slower Display

Asynchronous Event Blob Detection and Tracking

Detection and Tracking Demo



X5 Times Slower Display

Asynchronous Event Processing for Robots

Asynchronous High Speed Blob Tracking (AEB Tracker)

Smart Visual Beacons with Asynchronous Optical Communications using Event Cameras

International Conference on Intelligent Robots and Systems (IROS) 2022



Ziwei Wang



Yonhon Ng

Asynchronous Blob Detection and Track Management

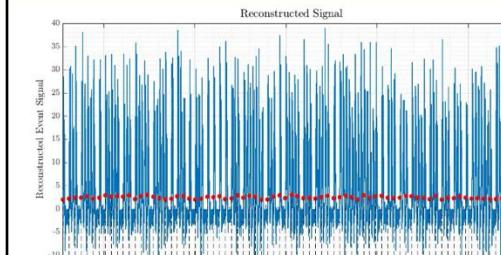
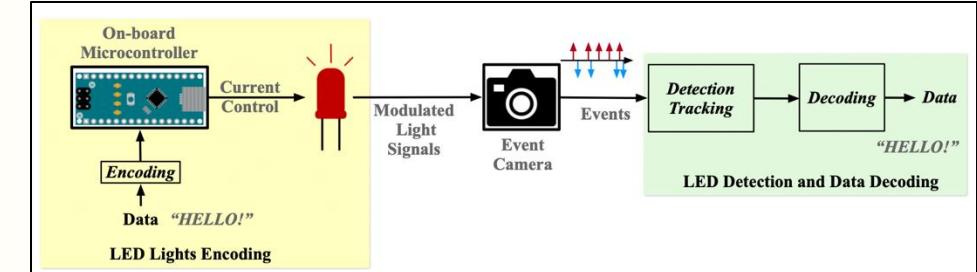


Jack Henderson

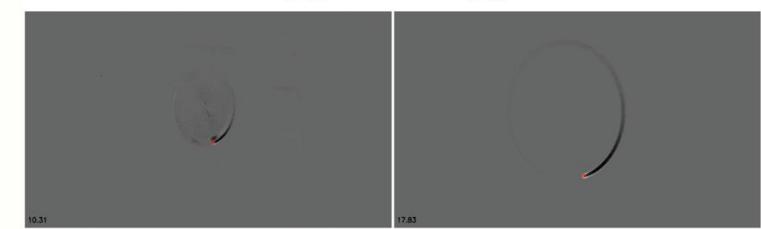
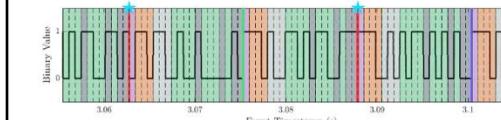


Robert Mahony

Asynchronous Optical Communication using Smart Beacons



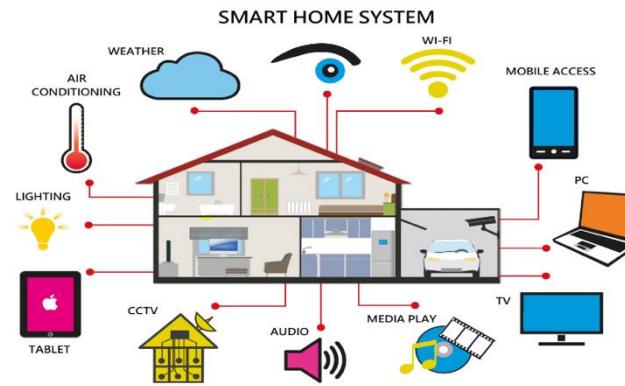
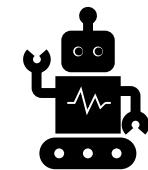
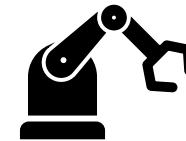
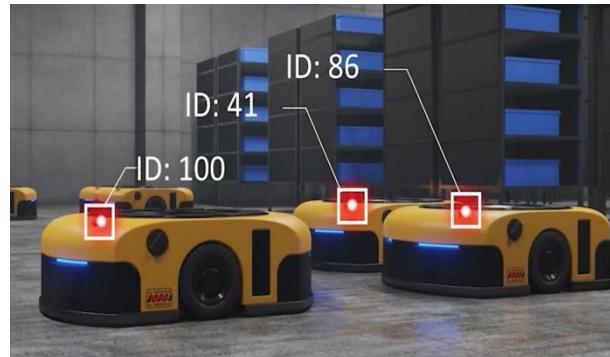
3D Reconstruction



Left Event Camera

Right Event Camera

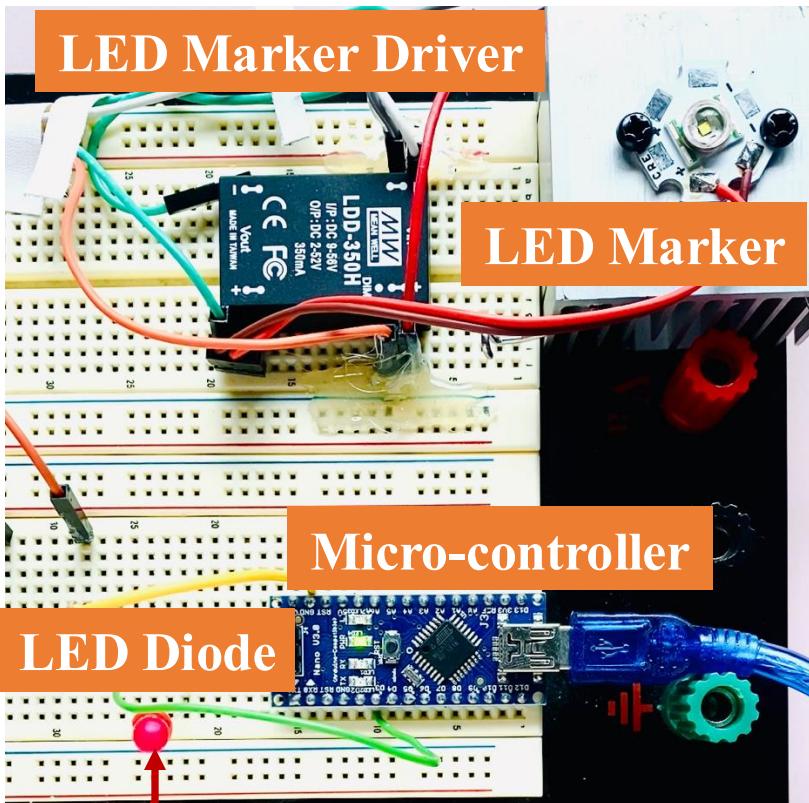
Smart Visual Beacon Communication



LED Lights

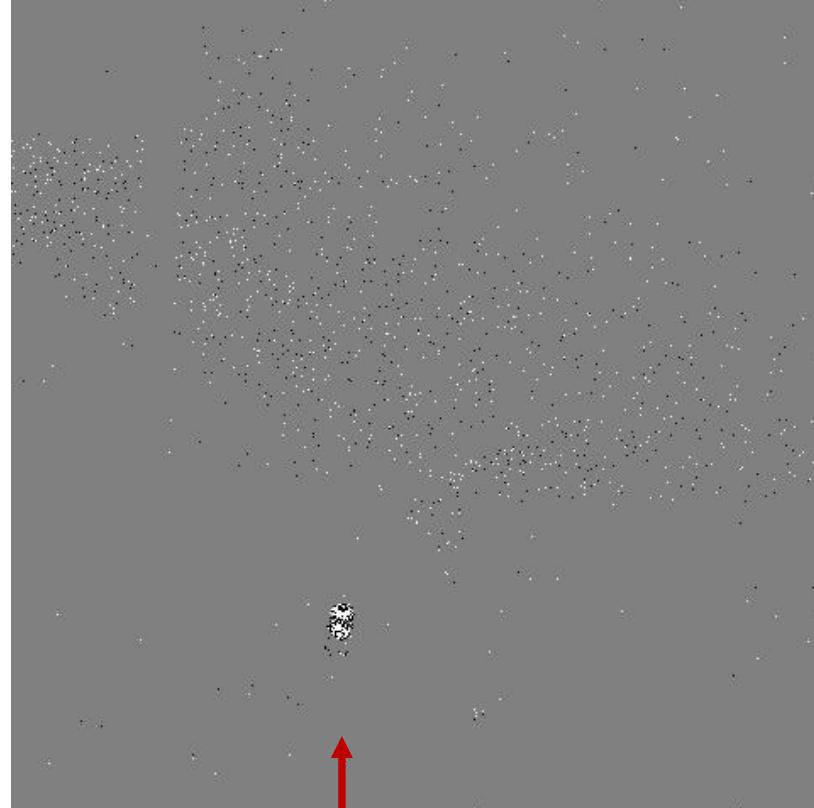
Smart Visual Beacon Communication

Transmitter



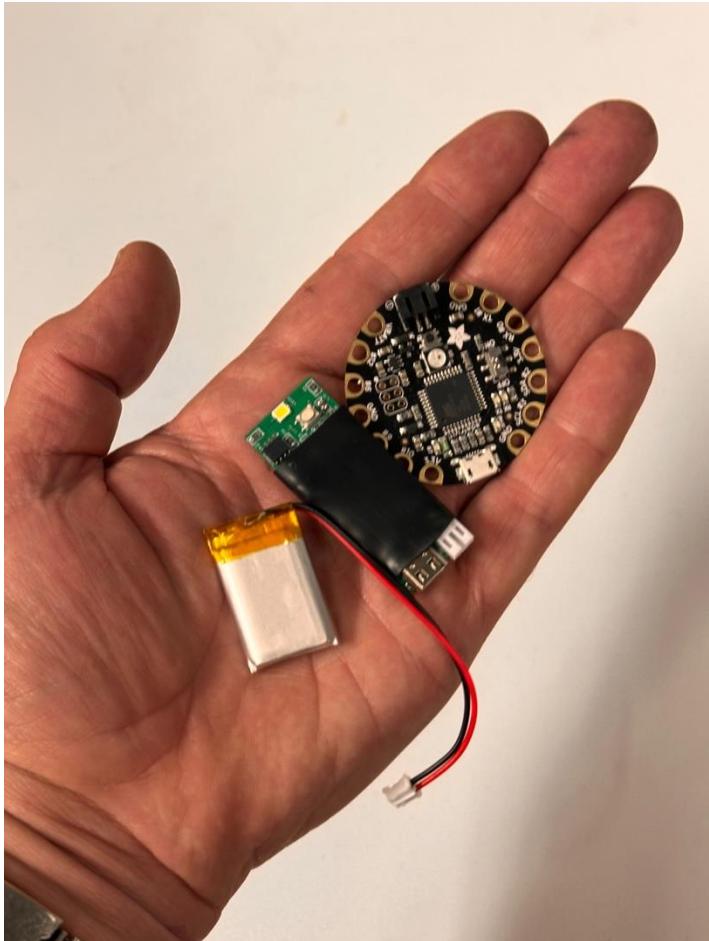
4000bps

Event Camera Receiver



Frame-based camera does not capture the
high-frequency blinking of LEDs
LED Beacon Communication

Smart Beacon Hardware



Adafruit - FLORA

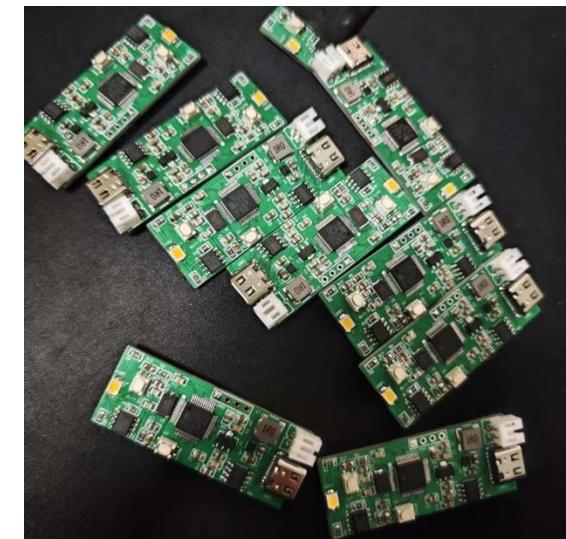
Off-the-shelf wearable electronic platform
14.9 USD
Atmega32u4

Ours Based Smart Beacon

~25 USD
STM32f103

Battery

300mAh
<10 USD



Motion Caption System: Vicon

- Wired infrared (IR) cameras
- Reflective markers
- Central computer
- Cabling & Network

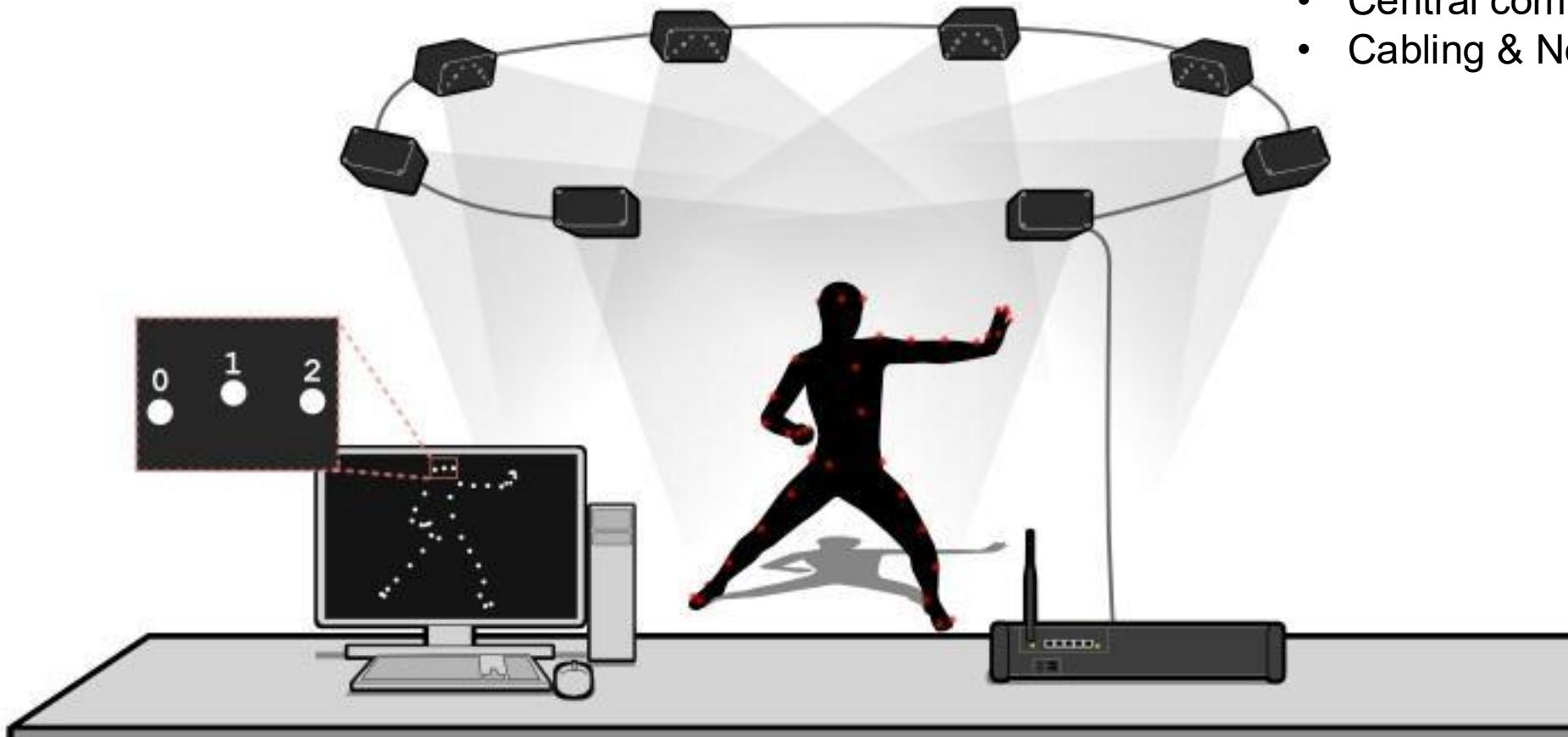
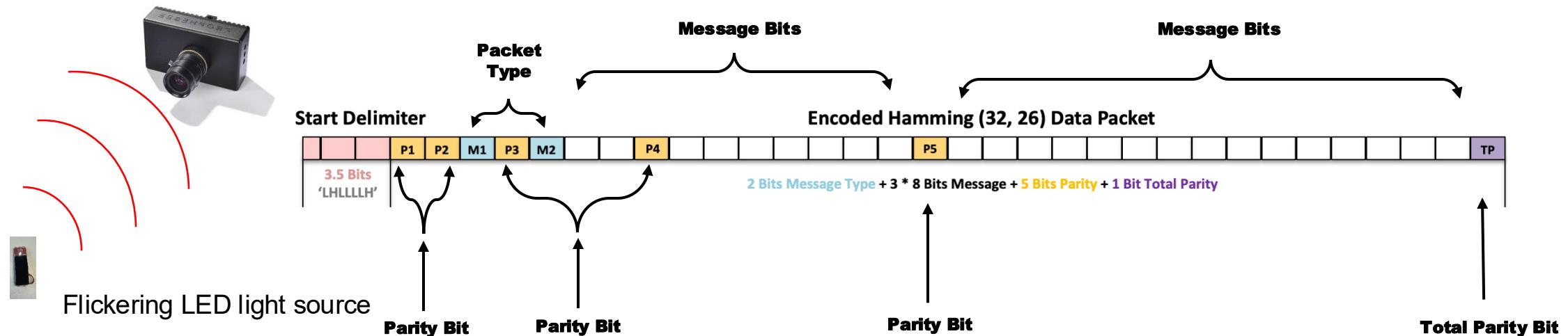
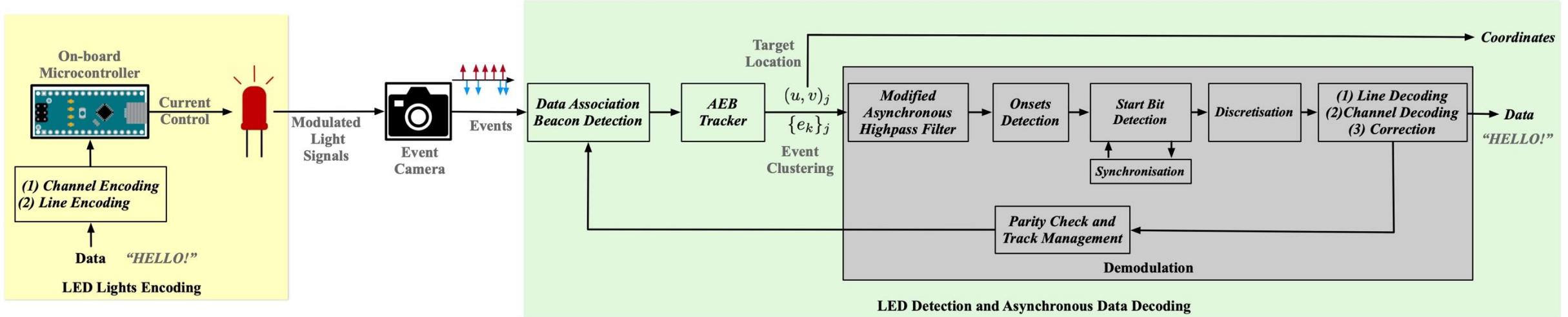


Image from: <https://www.openpr.com/news/3310762/motion-capture-system-market-is-gaining-momentum-with-vicon>

Optical Communication Pipeline



Spinning wheel experimental platform



Rotating at roughly 3 revolutions per second.
The optical flow was 3230 pixels per seconds.

We have achieved tracking and
communication at 7280 pixels per second.

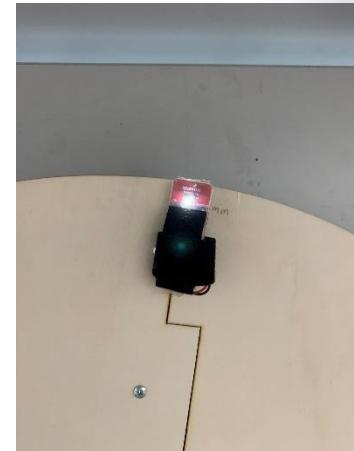
Experiments



Experimental test bed for event-based position and timing estimation



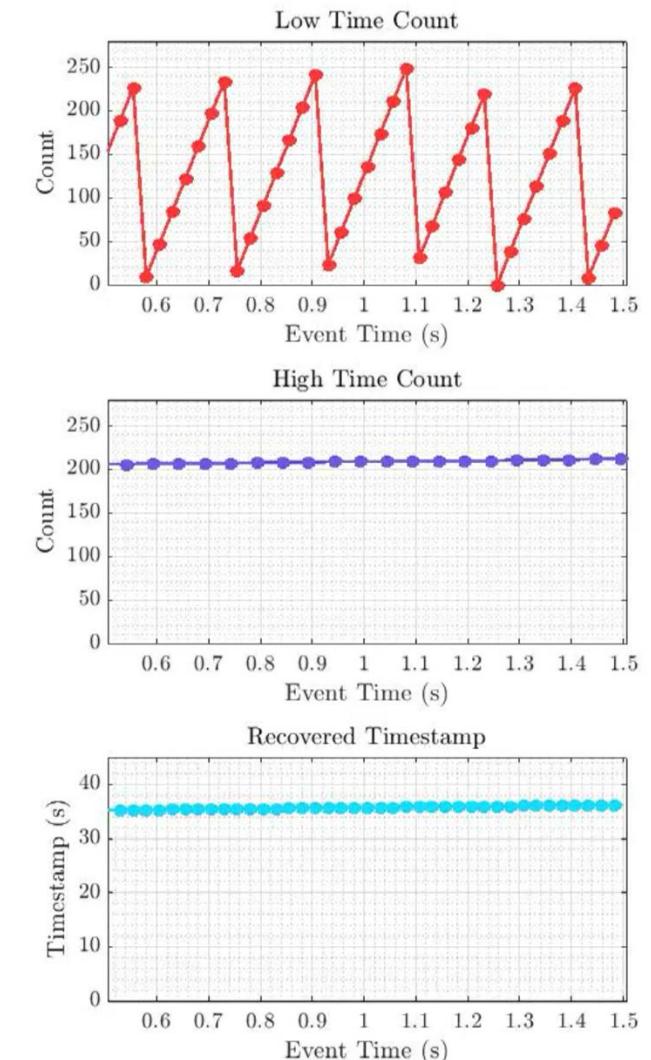
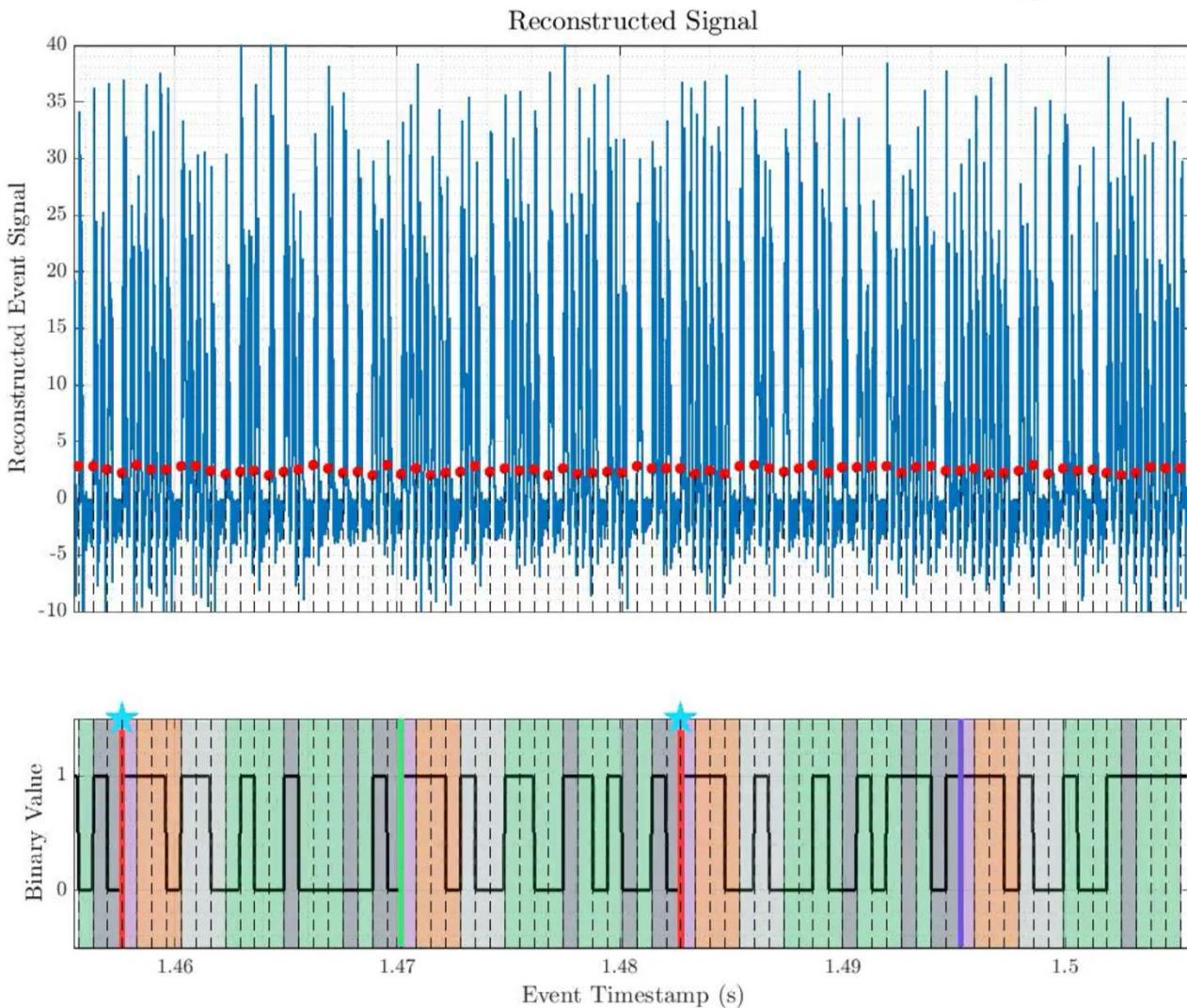
Holly Battisson



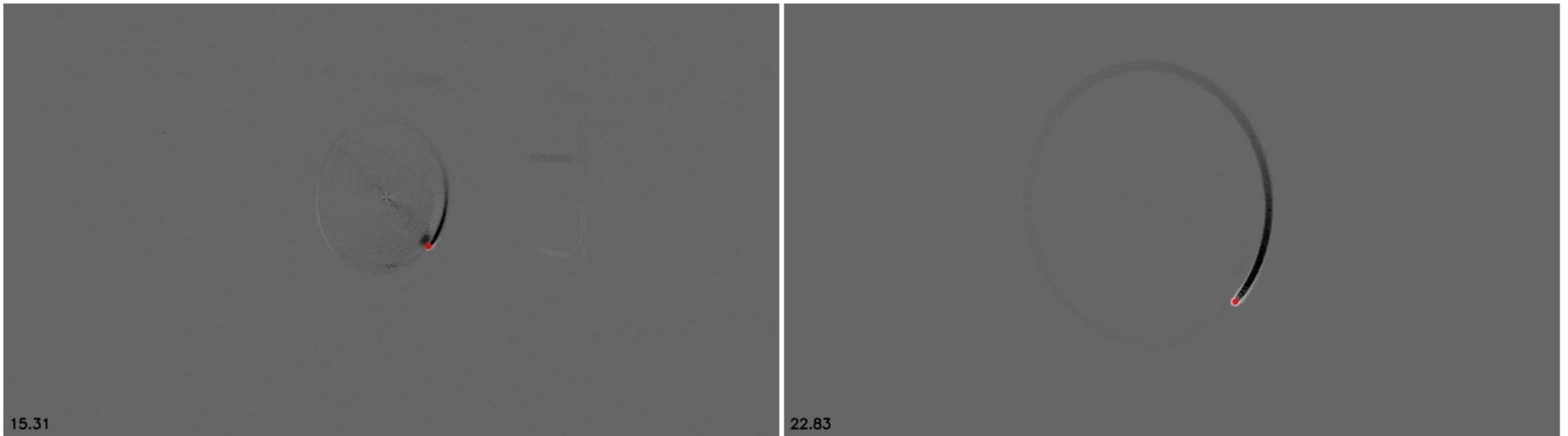
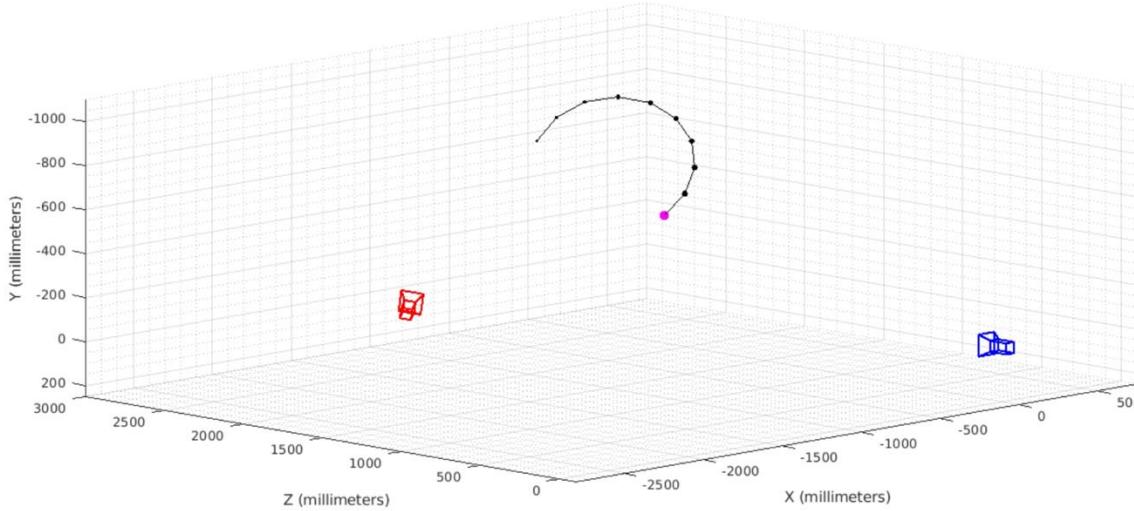
LED emits a flicking signal that encodes packets at 40Hz

Time stamp and ID

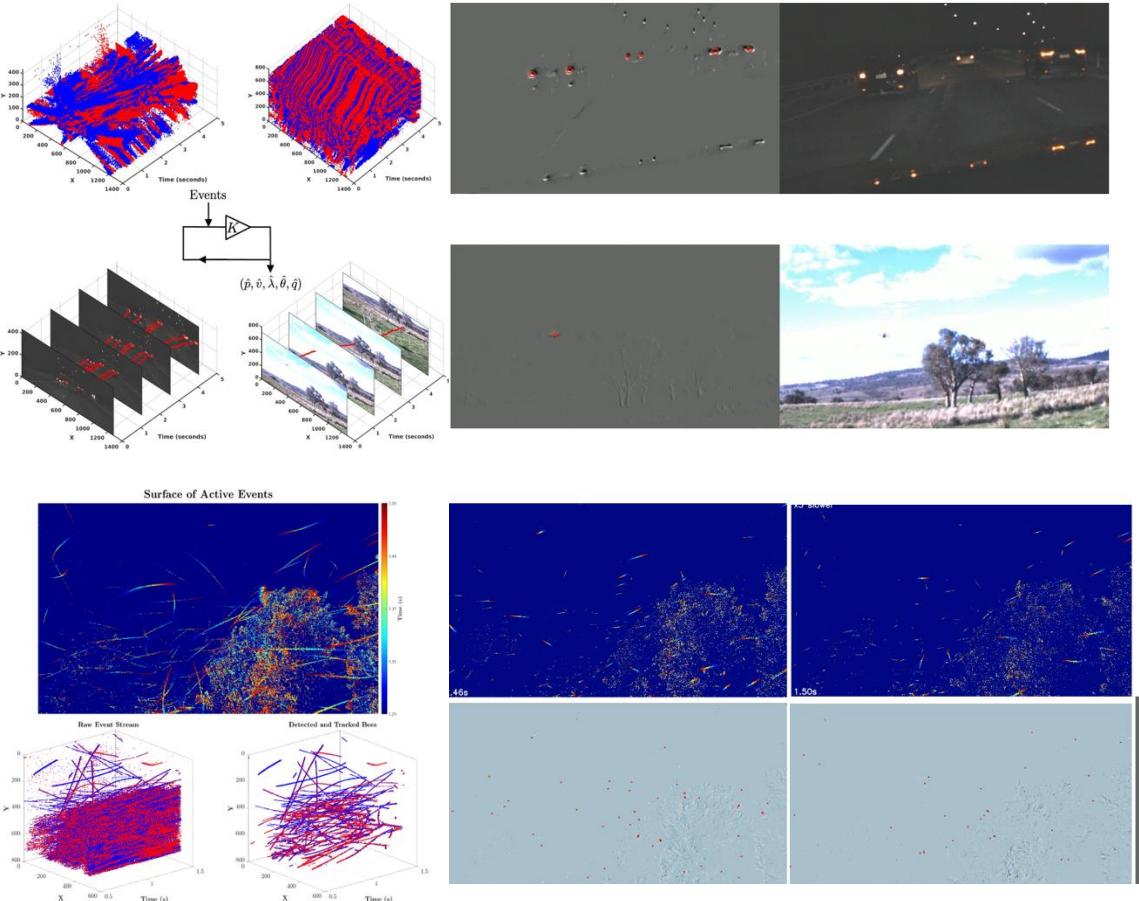
Smart Beacon: Decoding Transmission



Experiments



Thanks!

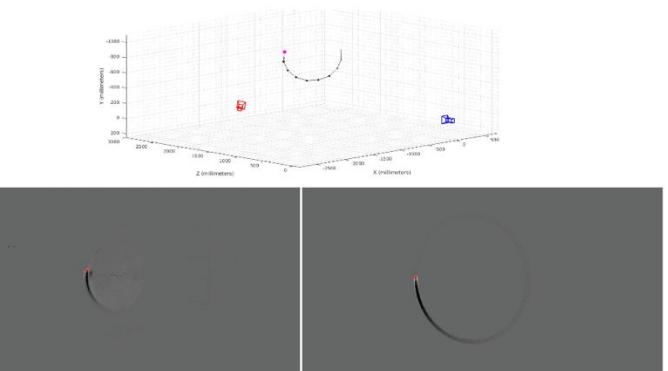
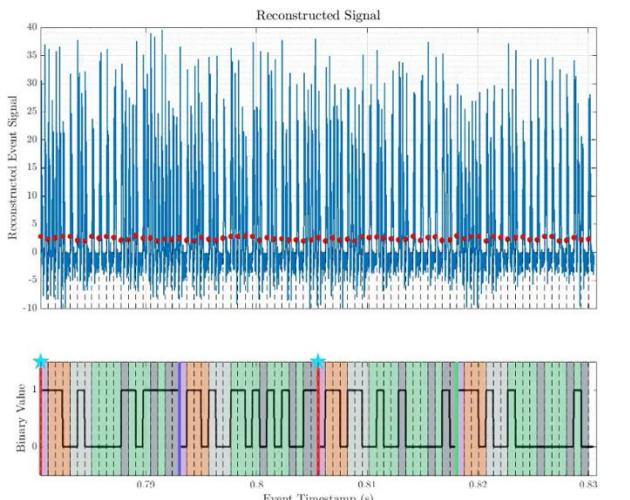


Australian
National
University

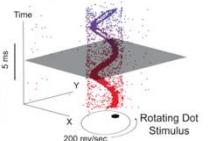


Systems Theory and
Robotics group

24/06/2025



Event-based Vision 2025
CVPR Nashville JUNE 11-15, 2025



Robert Mahony



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