Event-Aided Time-to-Collision Estimation for Autonomous Driving

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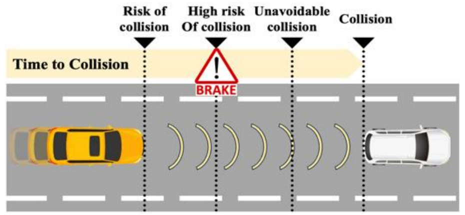
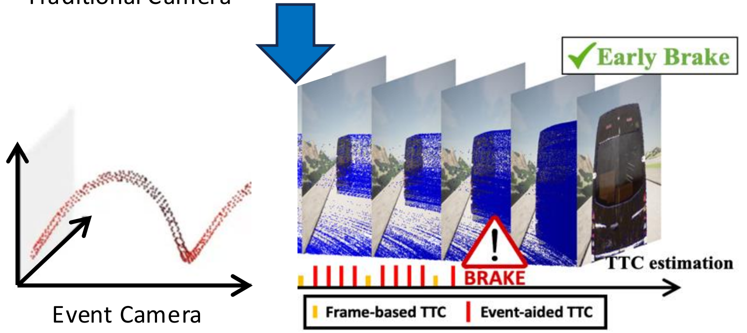
Introduction of TTC Problem



- Time-to-Collision is the time remaining before a potential collision, used to alert drivers and autonomous systems to decelerate.
- Accurate TTC estimation is crucial in high-speed driving scenarios.
- Traditional camera-based TTC estimation relies on consecutive images but is limited by frame rates, causing delays in high-speed scenarios.

Traditional Camera



Event Camera

Our goals:

To estimate the TTC **during the blind period of the standard camera** (i.e. the time interval between two successive exposures) using event data as input.

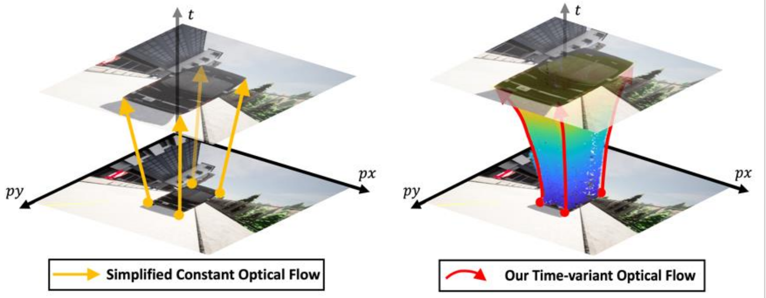
Our Contribution

A time-variant affine model

1. Visualization on general instantaneous optical flow

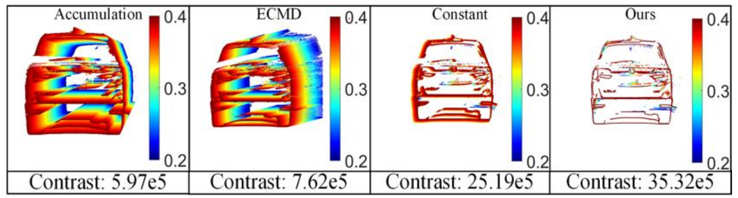
P: 3D contour points X: observation image point u: Optical Flow

2. The advantages of our time-variant optical flow



- strong assumption (constant) + captures the time-variant nature of flow field

3. Model comparison with constant and simplified affine models via ECMD[1]



$$\mathbf{p}(t_{\mathtt{ref}}) = \frac{1}{Z(t_{\mathtt{ref}})}\begin{bmatrix} -\nu_x + x(t_0)\nu_z \\ -\nu_y + y(t_0)\nu_z \end{bmatrix}(t_{\mathtt{ref}} - t_0) + \mathbf{p}(t_0)$$

$\mathcal{A}(\mathbf{p}(t_0);\ \boldsymbol{\nu}/Z(t_{\mathtt{ref}}))$

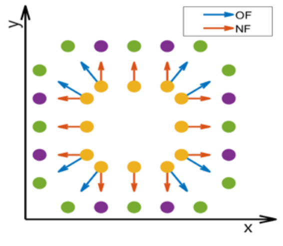
+ captures the true flow-field dynamic
+ leads to a more accurate geometric model
+ benefits to spatio-temporal registration

[1] McLeod, S, et al. "Globally optimal event-based divergence estimation for ventral landing." in European Conference on Computer Vision. (2022)

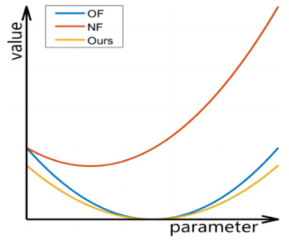
A robust linear solver initialization

- Novel geometric measurement overcoming partial observability in event-based normal flow (NF)
- Geometric Error
- Linear Solver

$$\frac{1}{Z_k}\begin{bmatrix} -\nu_x + x_k\nu_z \\ -\nu_y + y_k\nu_z \end{bmatrix}^{\mathsf{T}} \mathbf{n}_k = \mathbf{n}_k^{\mathsf{T}}\mathbf{n}_k \qquad \begin{bmatrix} n_{k,x} \\ n_{k,y} \\ (\delta t_k \mathbf{n}_k - \mathbf{p}_k)^{\mathsf{T}}\mathbf{n}_k \end{bmatrix}^{\mathsf{T}} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = -\mathbf{n}_k^{\mathsf{T}}\mathbf{n}_k$$



Visual Comparison

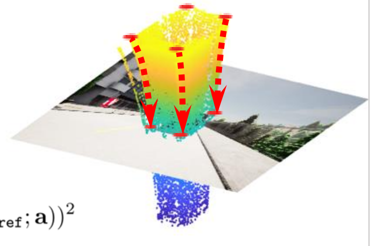


Error Surface Comparison

A nonliner solver via Spatio-Temporal Registration

- Model Fitting
- Objective Function

$$\mathbf{a}^{\star} = \arg\min_{\mathbf{a}} \sum_{\mathbf{e}_k \in \mathcal{E}} (\bar{\mathcal{T}}_{\mathtt{ref}}(W(\mathbf{p}_k, t_k, t_{\mathtt{ref}}; \mathbf{a}))^2$$



Spatio-Temporal Space

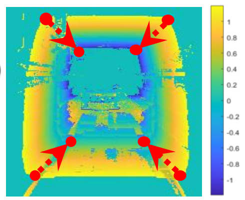
- Warping Function

$$W(\mathbf{p}_k, t_k, t_{\mathtt{ref}}; \mathbf{a})) \doteq \mathcal{A}(\mathbf{p}_k; \mathbf{a})(t_{\mathtt{ref}} - t_k)$$

$\mathbf{a} = \frac{\boldsymbol{\nu}}{Z(t_{ref})} = [a_x, a_y, a_z]^{\mathsf{T}}$: geometric affine model

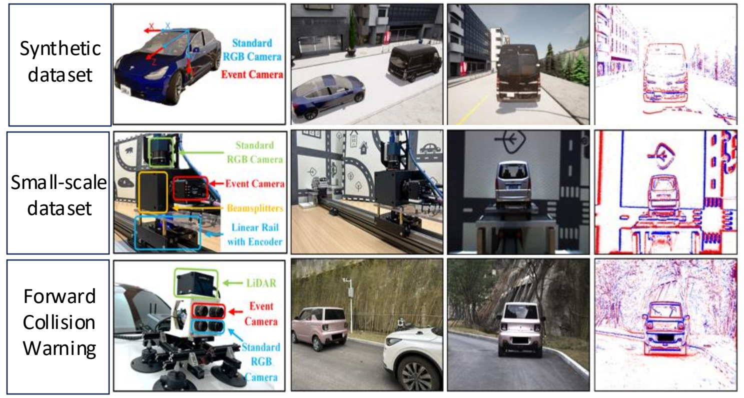
$\mathbf{e}_k = (\mathbf{x}_k, t_k, p_k)$: single event data

$\mathcal{E}_{\mathbf{x}}$: event set triggered at $\mathbf{x}$

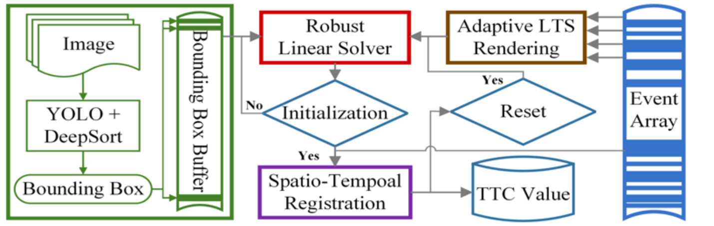


Linear Time Surface

Experiments



Data Generation & Collection



Flowchart of the proposed FCW system

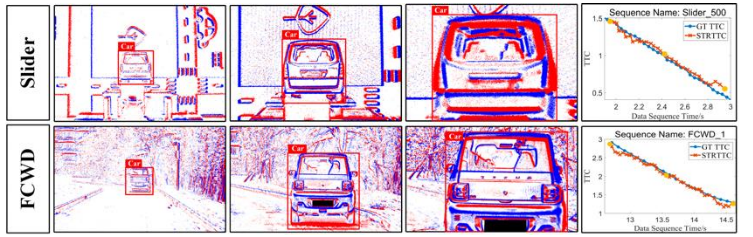
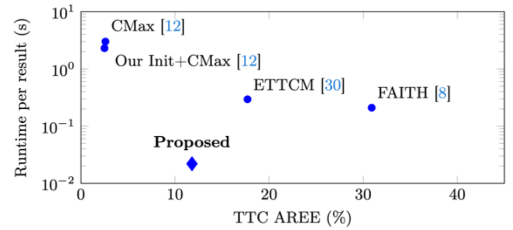


Illustration of the input (event data and the bounding box) and a continuous estimation results of TTC



Runtime and Accuracy Comparison

Project Page

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