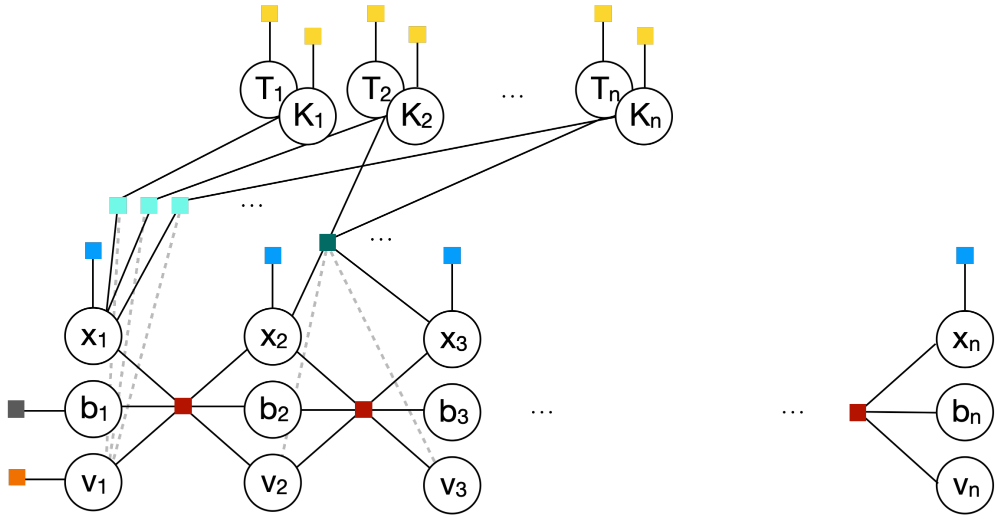
Multi-Sensor Sequential Calibration System at TuSimple

25 min

1. Introduction
2. Problem Constraints
3. Basic Model
4. Extensions
5. Evaluation

Truck

Model



Impact. Delivered in time for a demo of the autonomous driving technology.

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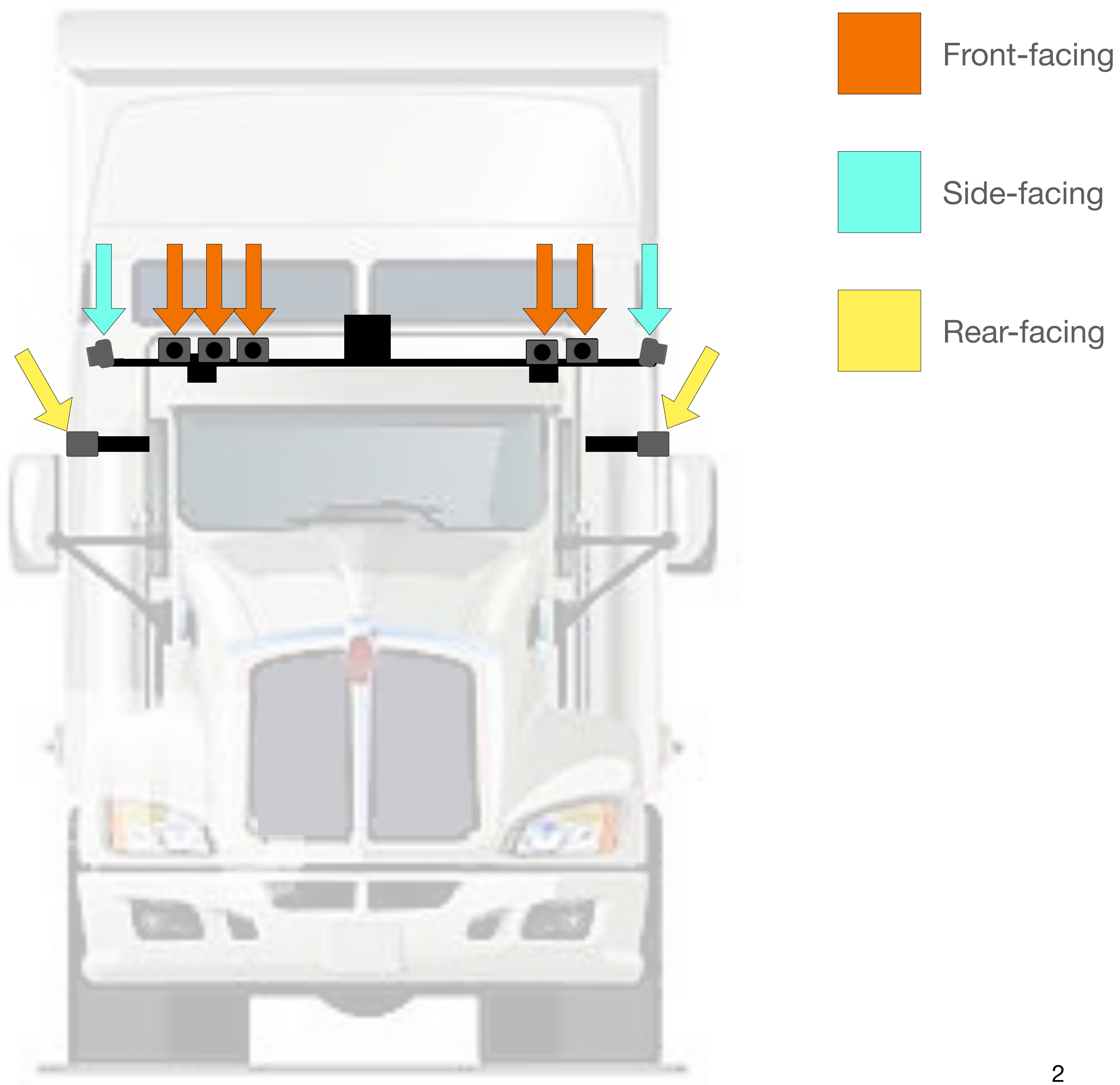
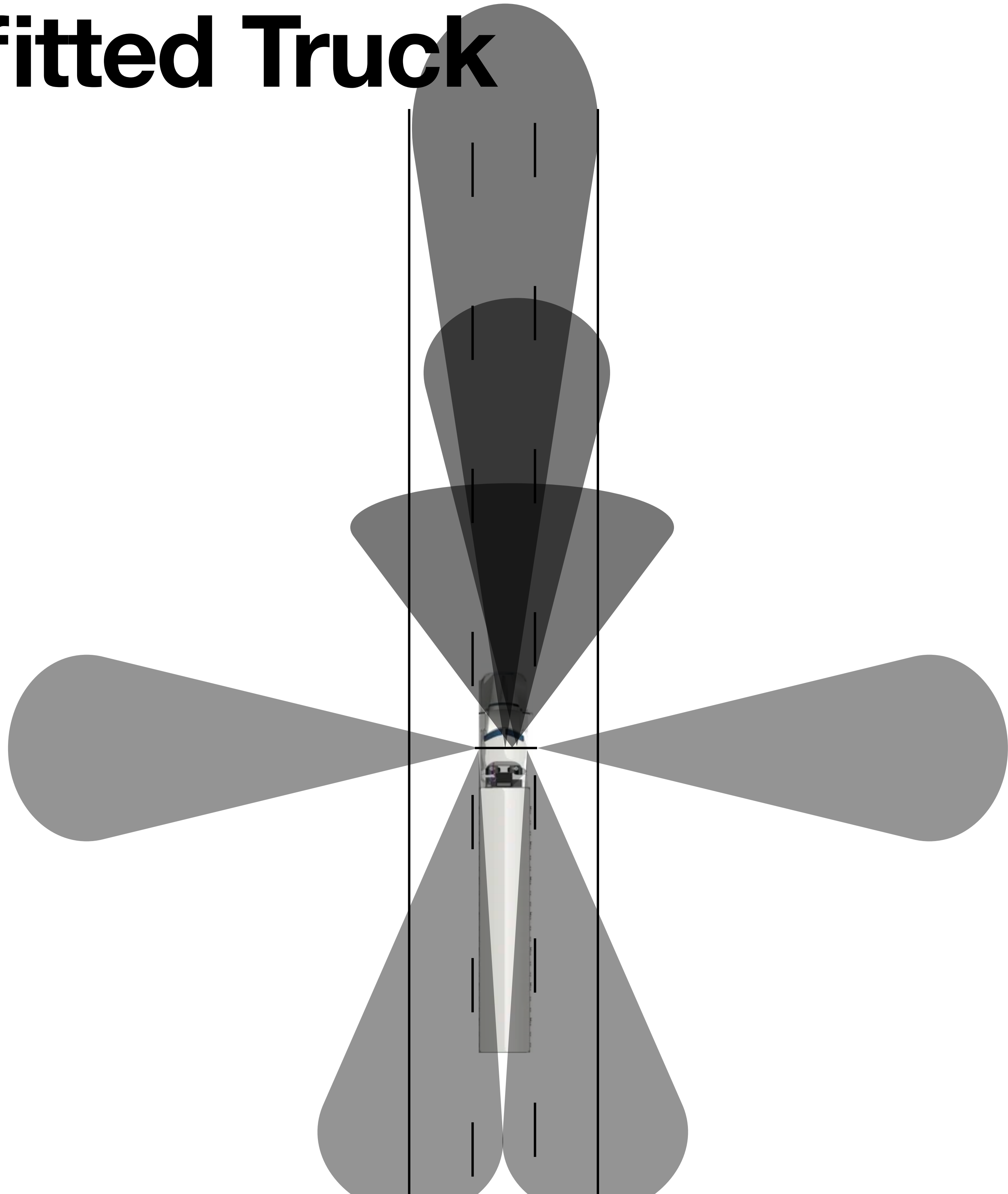
1. Introduction: 1. An Outfitted Truck





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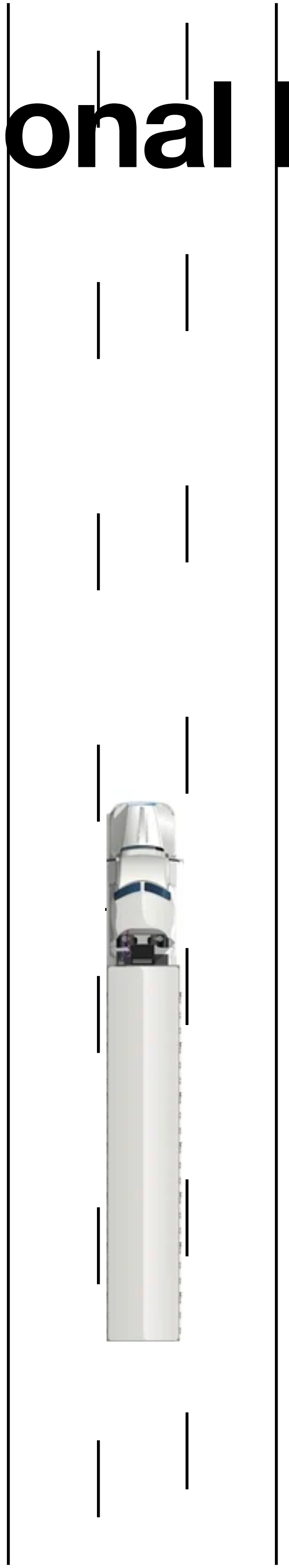
1. Introduction: 2. Operational Design Domain

- L4 autonomous truck
- Highway, limited urban driving
- Mapped roads
- Routes are known a priori
- The same routes are repeatedly driven



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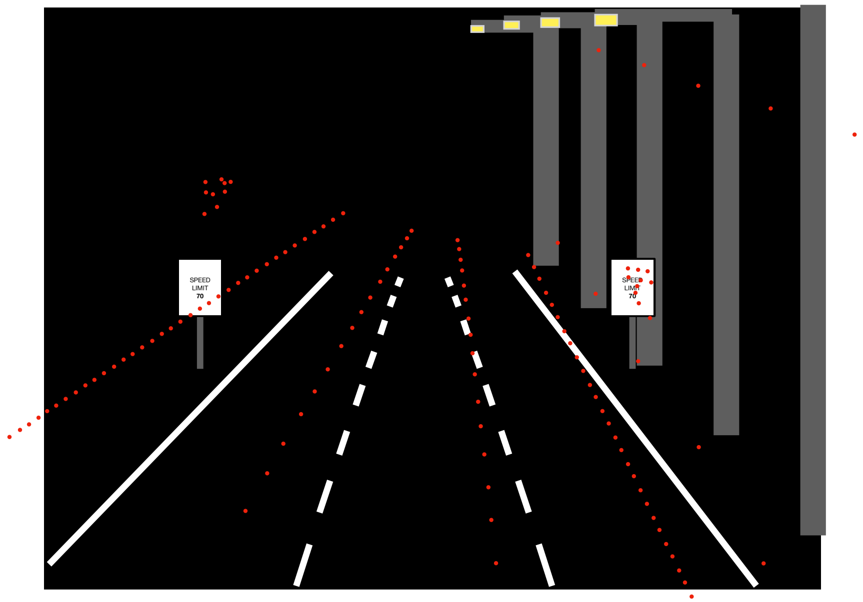
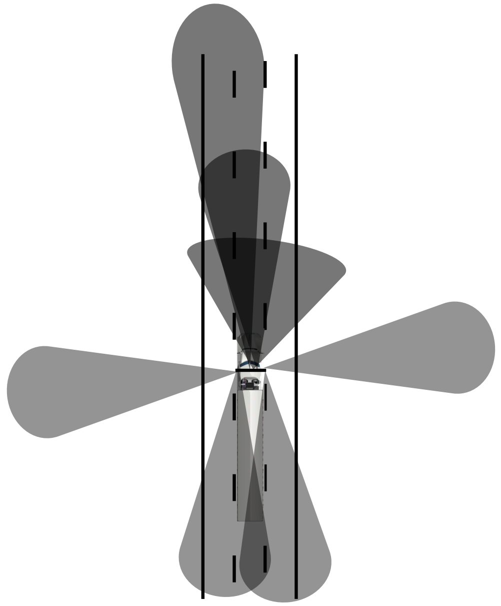
1. Introduction: 3. Extrinsic Camera Calibration

Projection of a prior map onto an image

Camera FOVs

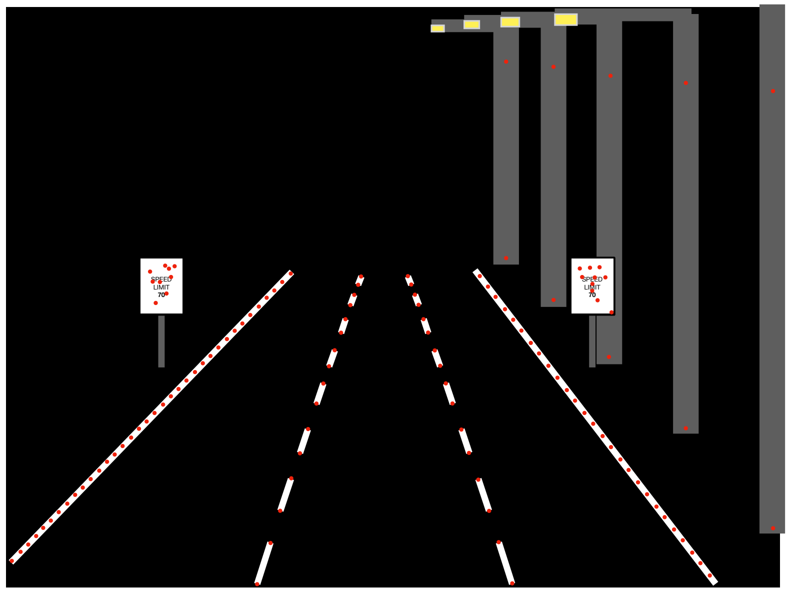
Uncalibrated

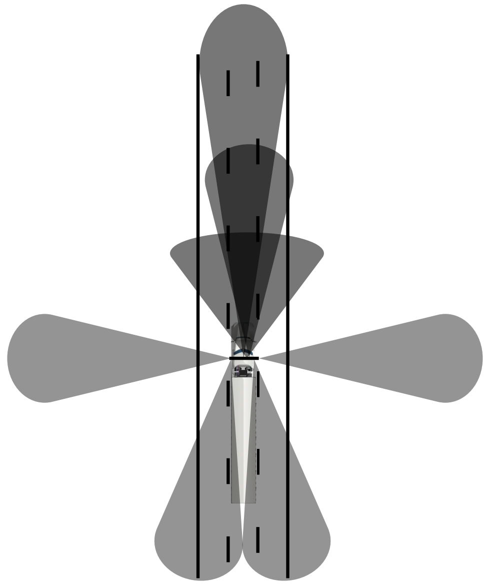




The goal is accurate SE(3) inter-sensor camera transforms

Calibrated





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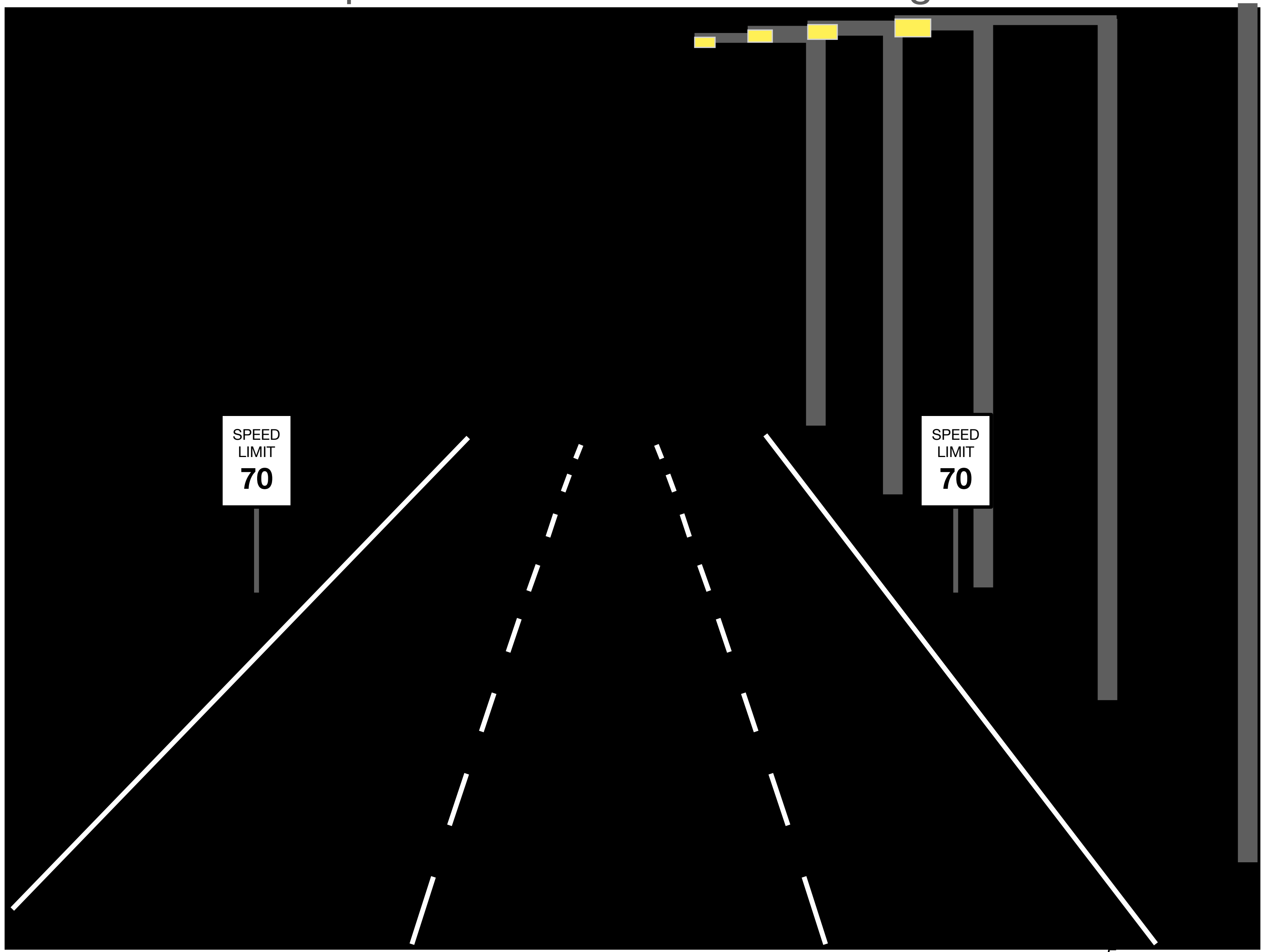
2. Problem Constraints: 1. Calibration Environment

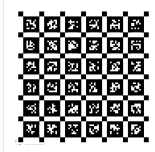
In-Situ Calibration
(this talk)

An example view from one front-facing camera

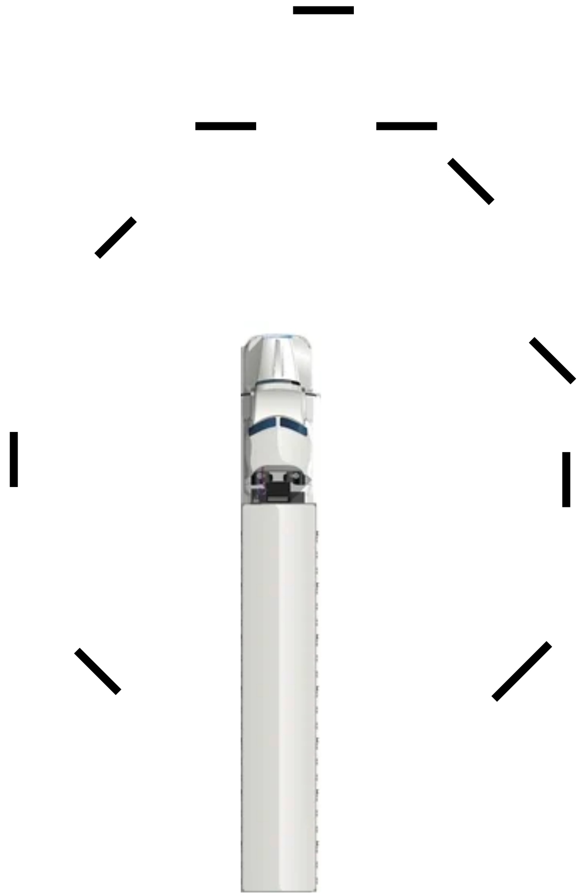


Warehouse calibration

AprilGRID
Calibration Board



Example layout



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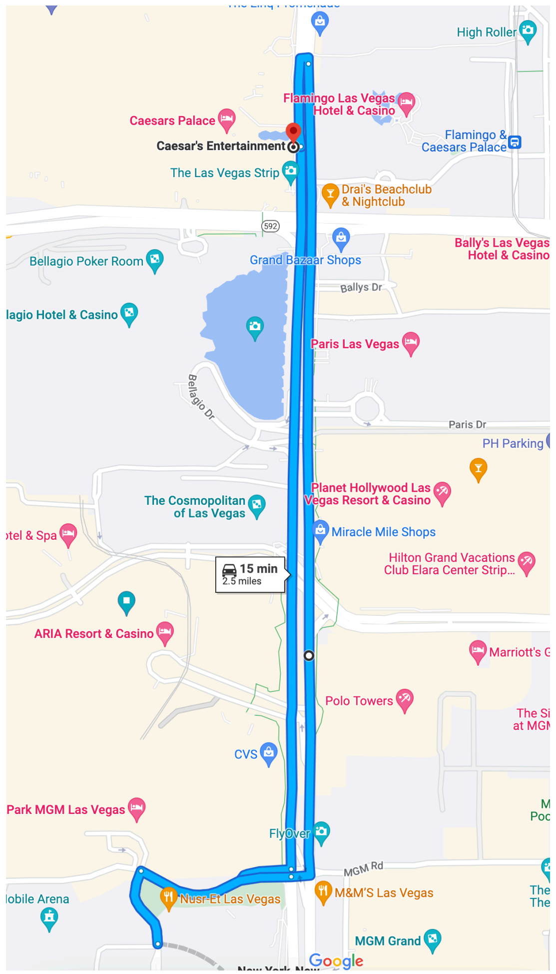
2. Problem Constraints: 2. Operations

Example route



- A defined, pre-mapped calibration route.
- The vehicle is operated by a licensed driver
- Data collection
- Offline, batch optimization for extrinsic calibration

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2. Problem Constraints: 3. Priors

Camera Extrinsic Priors

$$ {}^{cam_c}\hat{T}_{imu} \in SE(3) $$

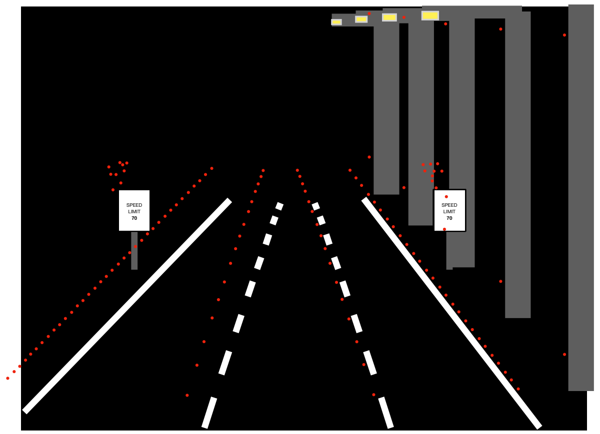
Camera Intrinsics

$$ K = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix} $$

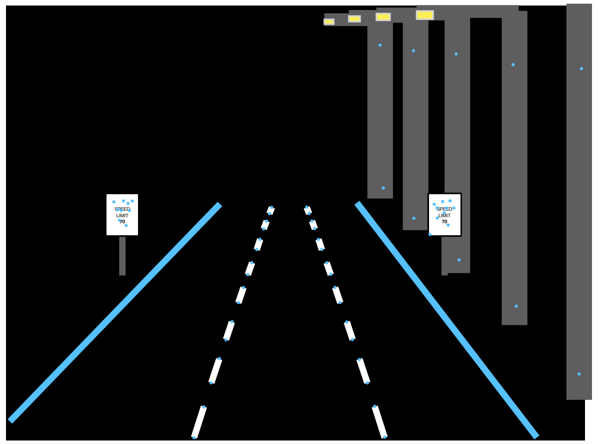
$$ D = k_1, k_2, k_3, k_4 $$

RTK GPS

Lane Map



Detections



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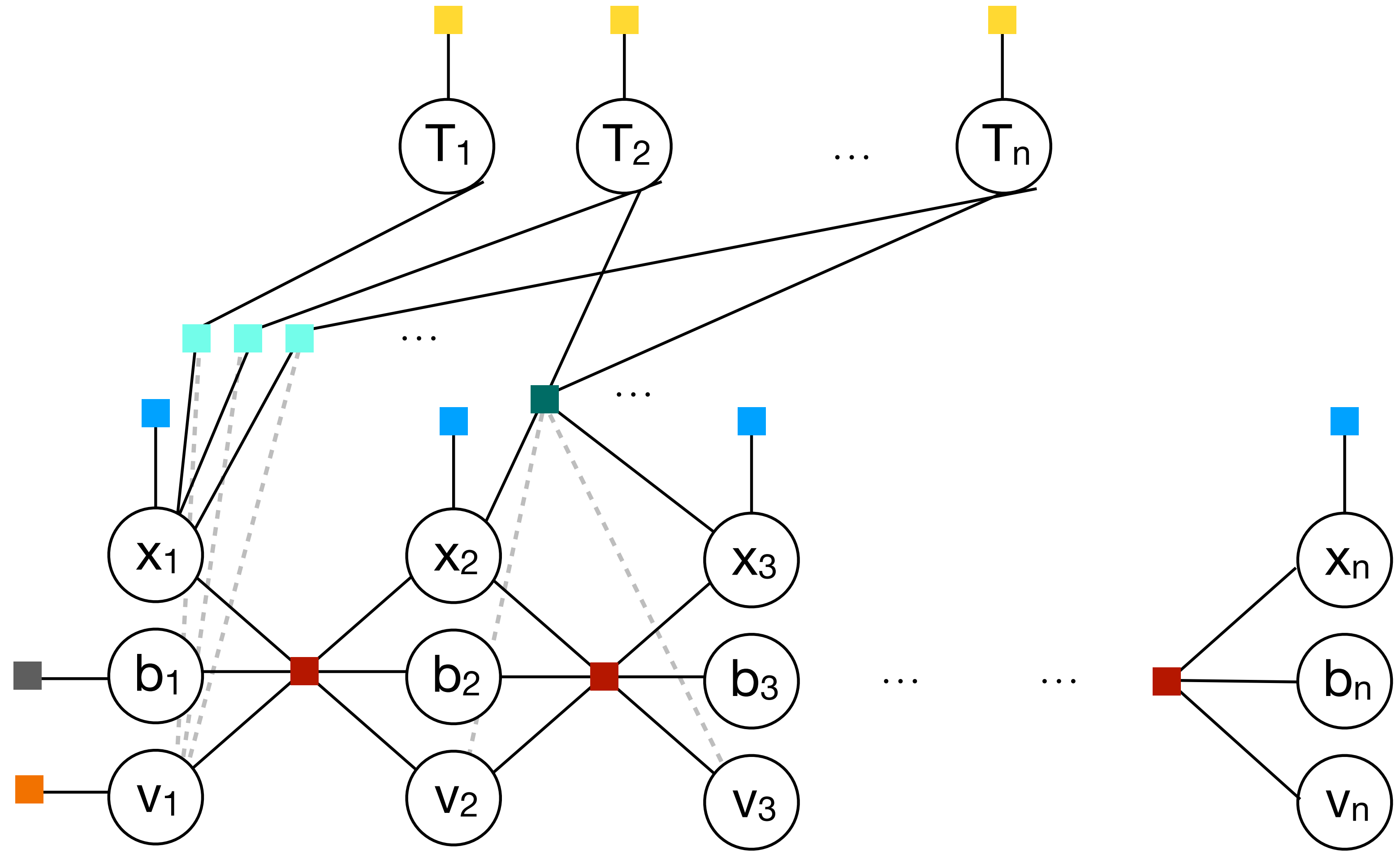
3. Basic Model: 1. Where we're headed



Variables

$T_c \in SE(3)$ camera extrinsic

$x_t \in SE(3)$ vehicle state

$b_t \in \mathbb{R}^6$ IMU bias

$v_t \in \mathbb{R}^3$ velocity

Factors

- Identity prior
- GNSS pose prior
- velocity prior
- camera extrinsic priors
- IMU preintegration
- 3D-2D projection
- 2D-2D epipolar line

- - - - used for rolling shutter compensation

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3. Basic Model: 2. Mathematical Description

Projection Equation

$$p_m^c = K \quad {}^{cam_c}T_{veh} \quad {}^{veh}T_{enu} \quad P_m$$

$P_m \in \mathbb{R}^3$ map point

${}^{veh}T_{enu} \in SE(3)$ vehicle pose

${}^{cam_c}T_{veh} \in SE(3)$ camera extrinsic

$K \in \mathbb{R}^{3\times 3}$ pinhole camera intrinsic

$p_m^c \in \mathbb{R}^2$ projected map point

Residual

$$p_d^c - p_m^c$$

$p_d^c \in \mathbb{R}^2$ detected 2D point

From e.g., nearest neighbors data association

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3. Basic Model: 3. Stationary Formulation

$$\underset{(T_c)_{c \in C}}{argmin} \sum_{c \in C} \sum_{(d,m)_c} \frac{1}{2} | p_d^c - h_m(T_c) |^2_{\Sigma_m}$$

$^{cam_c}T_{veh} \longrightarrow T_c$ shorthand notation

Σ_m measurement covariance

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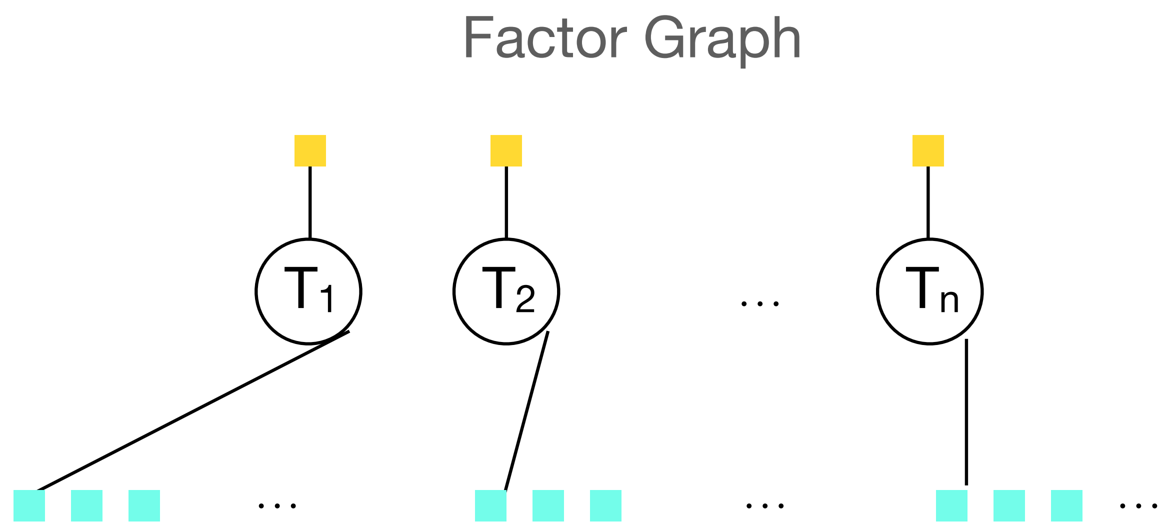
3. Basic Model: 4. Factor Graph



Variables

T_c

Factors

extrinsic prior

3D-2D projection

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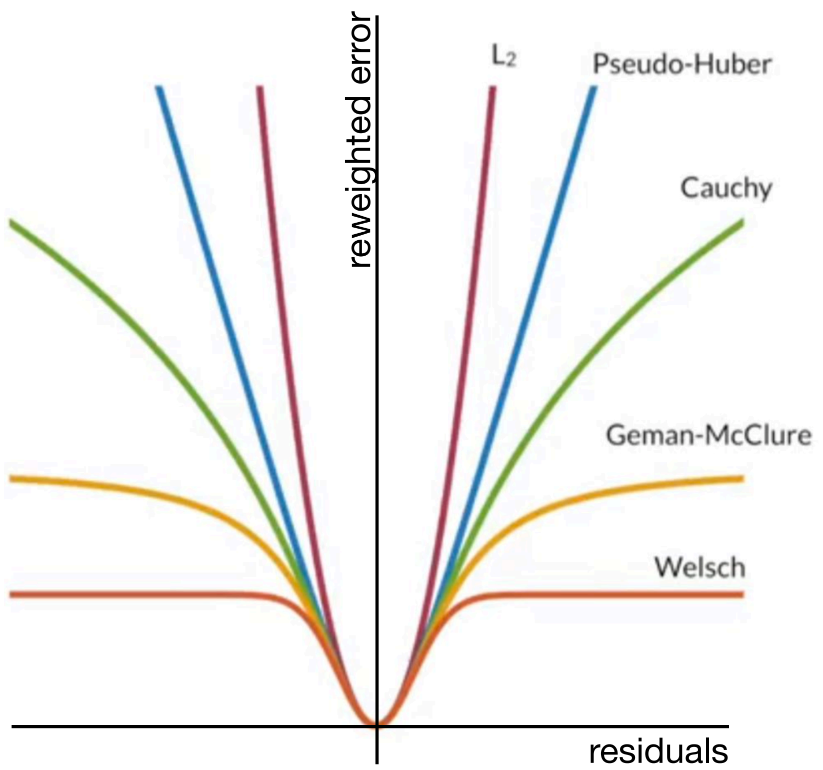
4. Extensions: 1. Robust Noise Model

$$\underset{(T_c)_{c \in C}}{argmin} \sum_{c \in C} \sum_{(d,m)_c} \tau(\,|p_d^c - h_m(T_c)|_{\sum m})$$

$\tau()$ robust loss function

Reweighting functions



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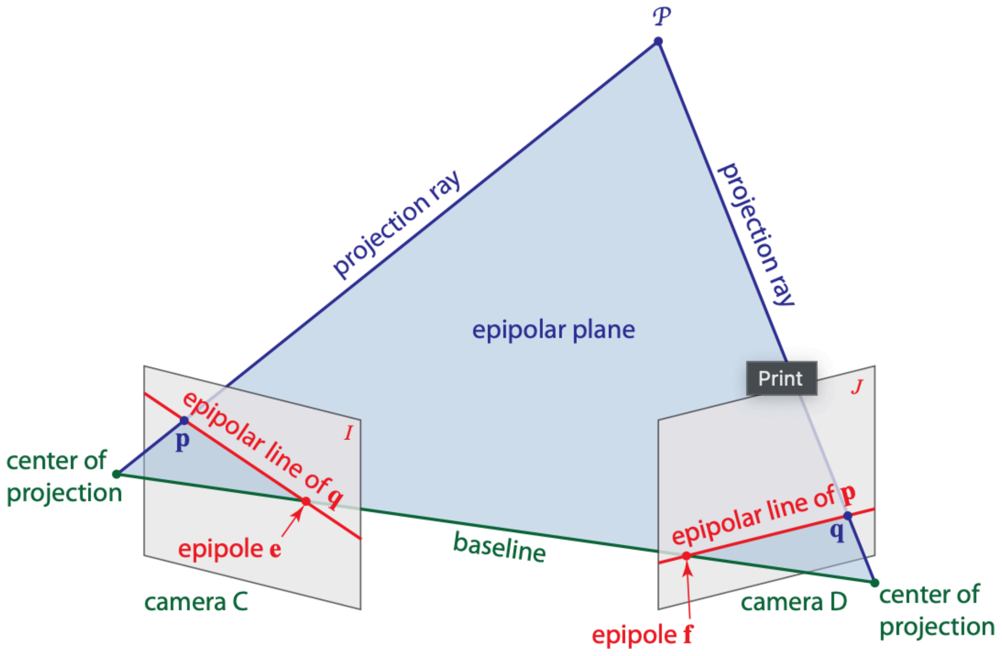
4. Extensions: 2. Epipolar Constraint

Geometric Interpretation



Essential Matrix Constraint

$$0 = p_d^{'c1}\ E\ p_d^{'c2}$$

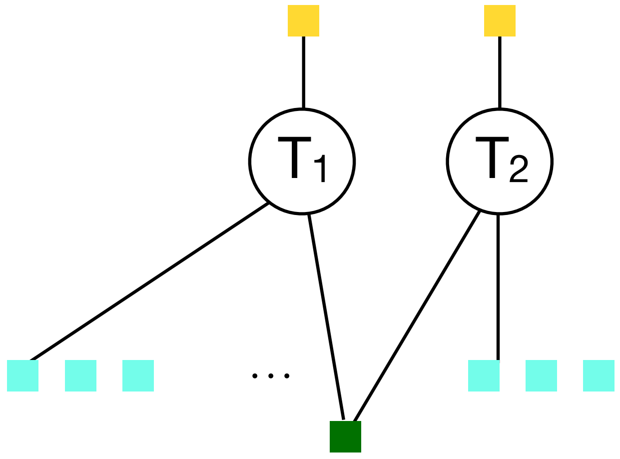
$p_d^{'c}$ normalized pixel coordinate

$$E = [t]_x R$$

$$t_x = \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix}$$

$${}^{cam_{c1}}T_{cam_{c2}} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix}$$

Factor Graph



Factors

extrinsic prior

2D-2D constraint

2D-2D epipolar line

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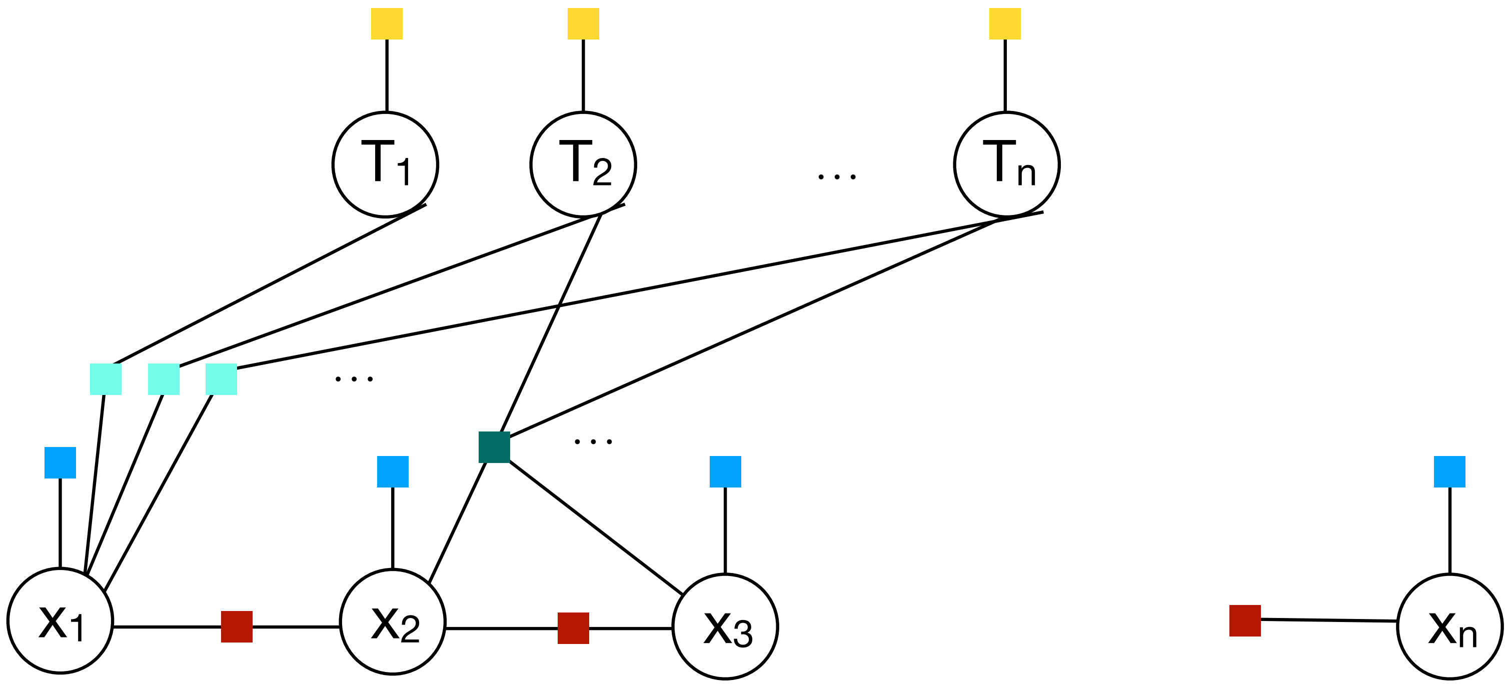
4. Extensions: 3. Sequential Model

- Essential matrix constraint between front and rear facing cameras.
- Capture more data from different viewpoints.
- Add vehicle state variables for robustness to GPS noise and bias.



Variables

$T_c \in SE(3)$ camera extrinsic

$x_t \in SE(3)$ vehicle state

Factors

GNSS pose prior

camera extrinsic priors

odometry (placeholder)

3D-2D projection

2D-2D epipolar line

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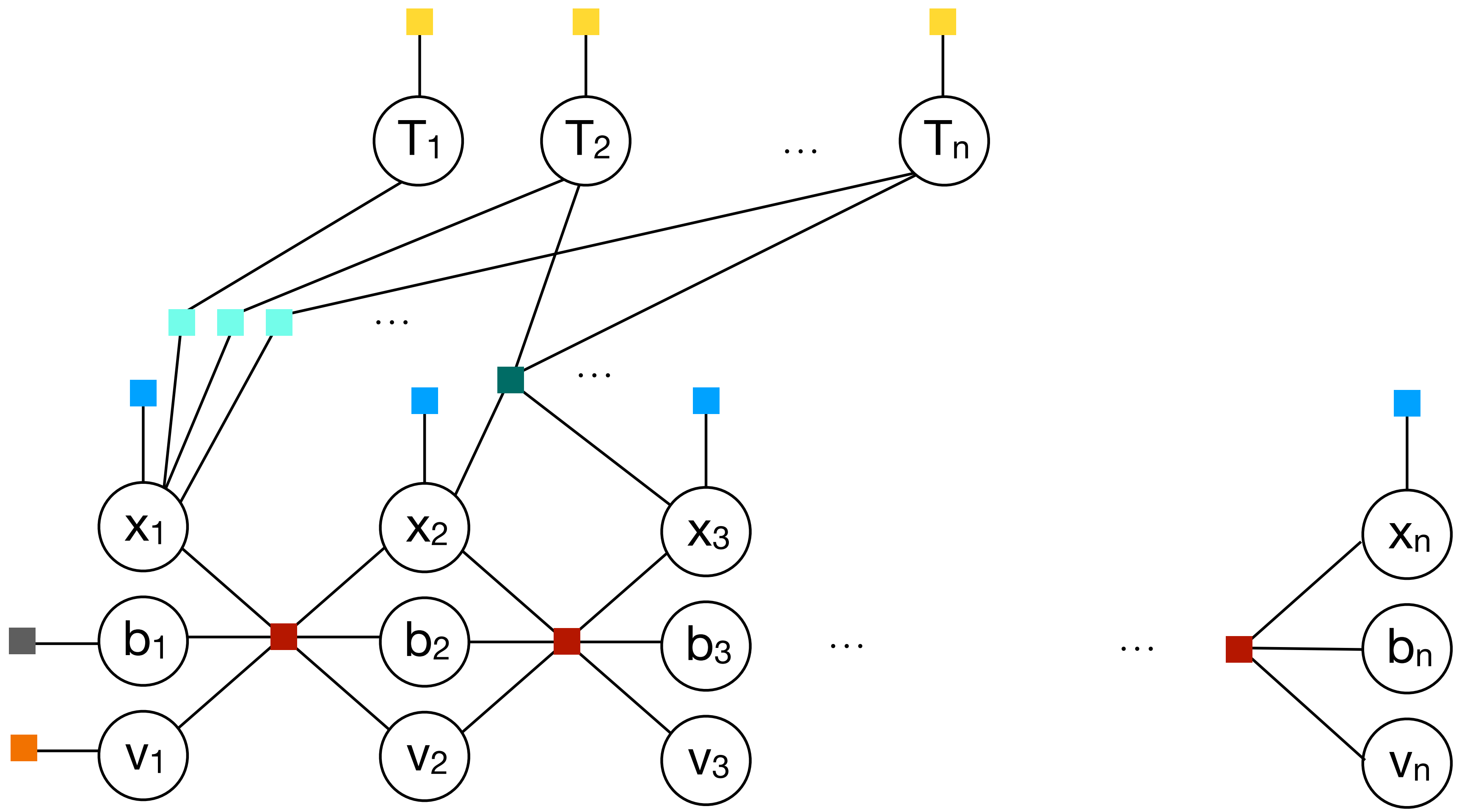
4. Extensions: 4. IMU Preintegration

- “Preintegration” avoids recomputing the update for each linearization point
- The IMU bias and the vehicle velocity are added to the model.



Variables

$T_c \in SE(3)$ camera extrinsic

$x_t \in SE(3)$ vehicle state

$b_t \in \mathbb{R}^6$ IMU bias

$v_t \in \mathbb{R}^3$ velocity

Factors

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- velocity prior
- camera extrinsic priors
- IMU preintegration
- 3D-2D projection
- 2D-2D epipolar line

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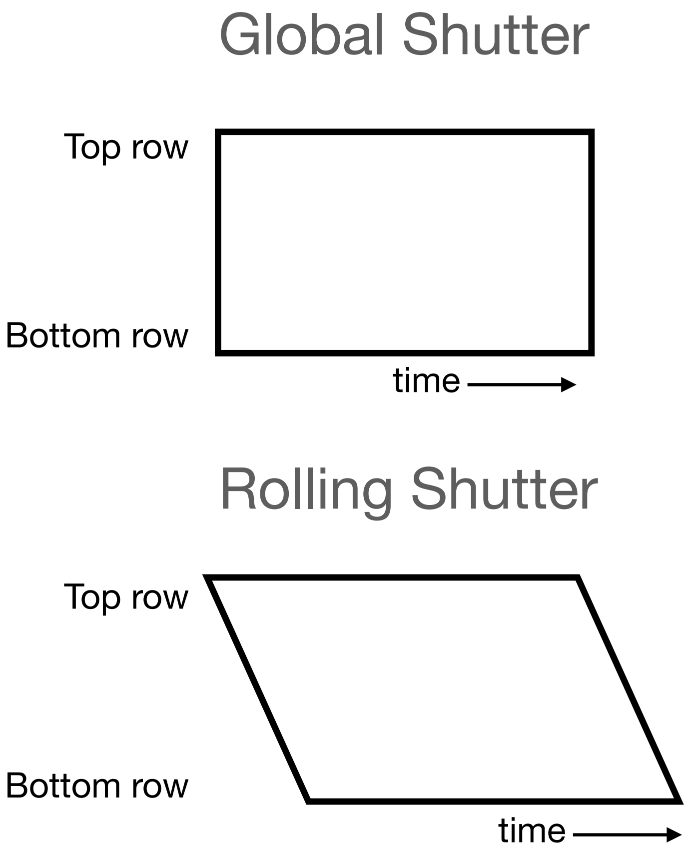
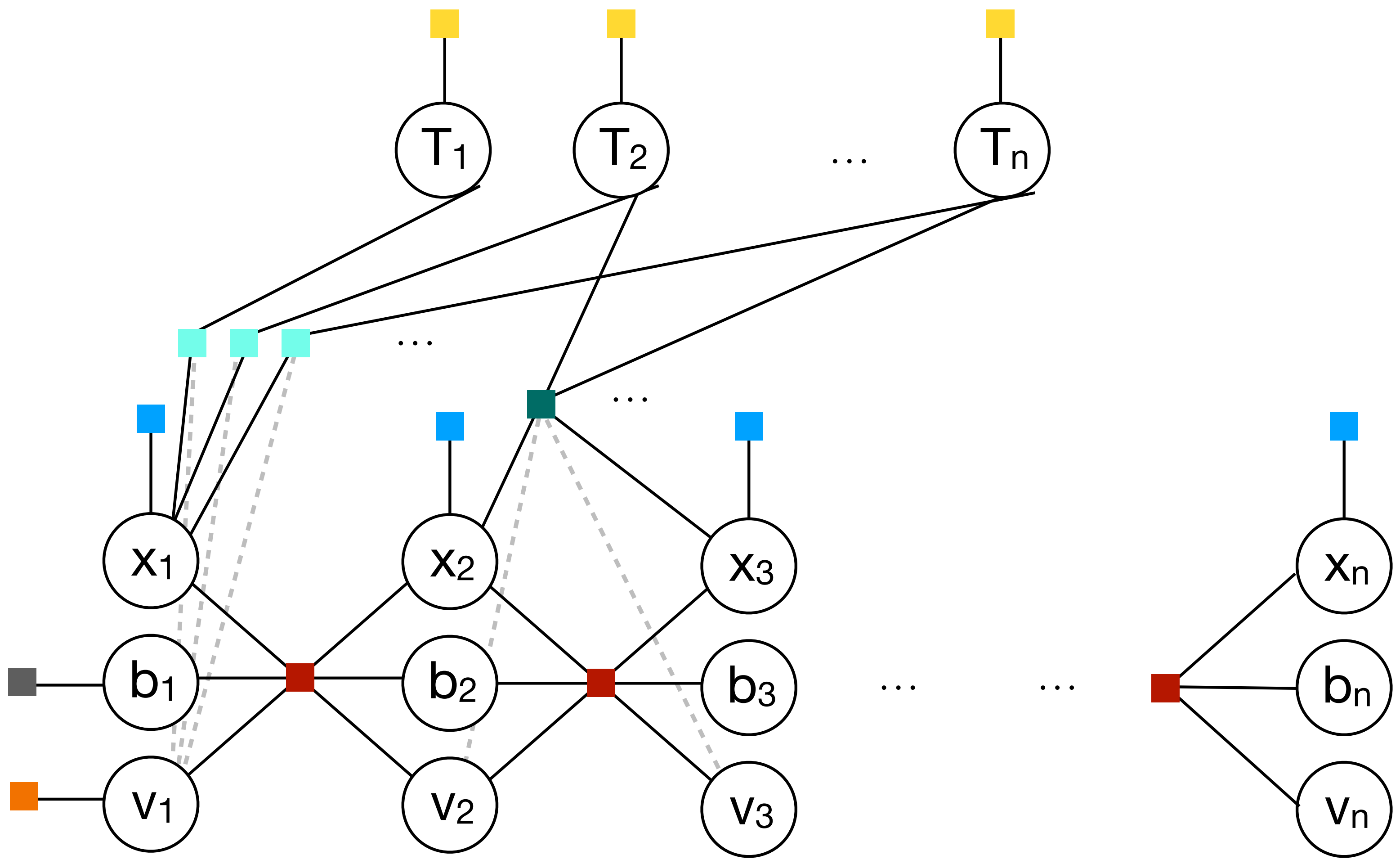
4. Extensions: 5. Rolling Shutter Compensation





- Calculate the scan line time using the readout offset and the exposure.
- Interpolate the camera pose for the scan line time for each constraint

Variables

$T_c \in SE(3)$ camera extrinsic

$x_t \in SE(3)$ vehicle state

$b_t \in \mathbb{R}^6$ IMU bias

$v_t \in \mathbb{R}^3$ velocity

Factors

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5. Evaluation: 1. Metrics

- Residuals. Low in terms of the number of residuals.
- Visual inspection. Accurate alignment quality of multiple cameras.
- Runtime. Two orders of magnitude faster than the previous approach due to the use of an optimization library that exploits sparsity.
- Amount of data. Use the subset of data required for the extrinsic calibration to stabilize.
- Extensible software design. The same implementation was seamlessly applied to different trucks with different camera configurations.

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5. Evaluation: 2. Limitations

- Different accuracy in roll, pitch, and yaw
- Data association can be difficult in the long-range camera.
- Multiple sources of error
    - Detection accuracy
    - GPS accuracy
    - Fidelity in map points
    - Perceptual aliasing in data association
    - Extrinsic jitter due to vehicle motion

Questions?