TEXAS A&M UNIVERSITY
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Vehicular Teamwork: Collaborative Localization of Autonomous Vehicles

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IEEE International Conference on Intelligent Transportation 2021

Presentation Outline

- Motivation
- Introduction
  - Ultra-Wideband Technology
- Theory
  - Decentralized Collaborative Localization
- Results
  - Simulated
  - Experimental
- Conclusions

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Autonomous Vehicles

Sardari, LoKan, 2014, "Google self-driving car“ [6]

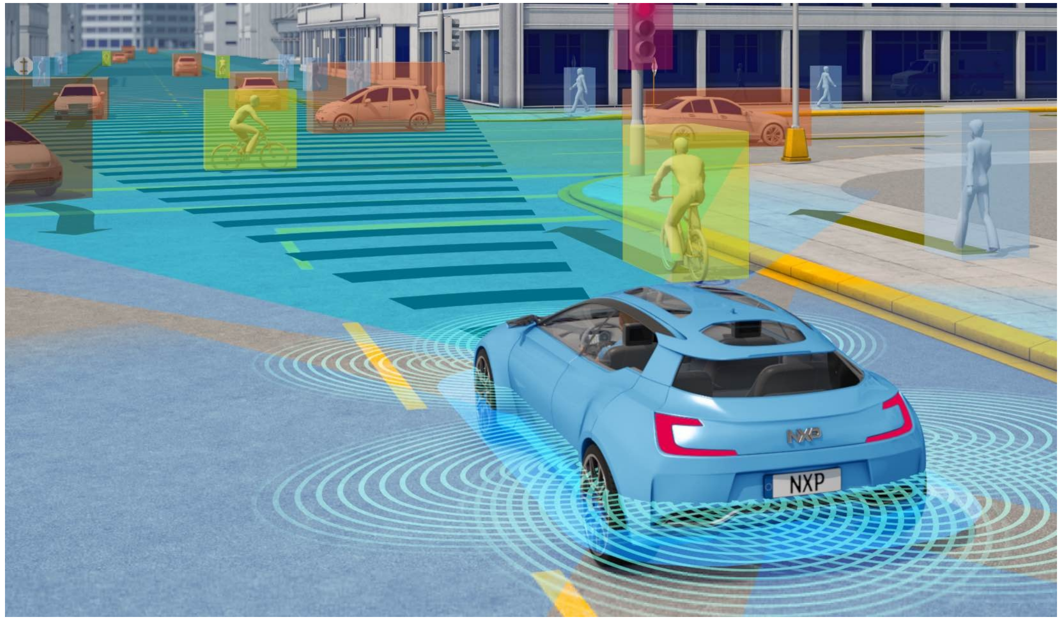
AV Sensors

Perception

- Radar
- Lidar
- Cameras
- Ultra Sonic

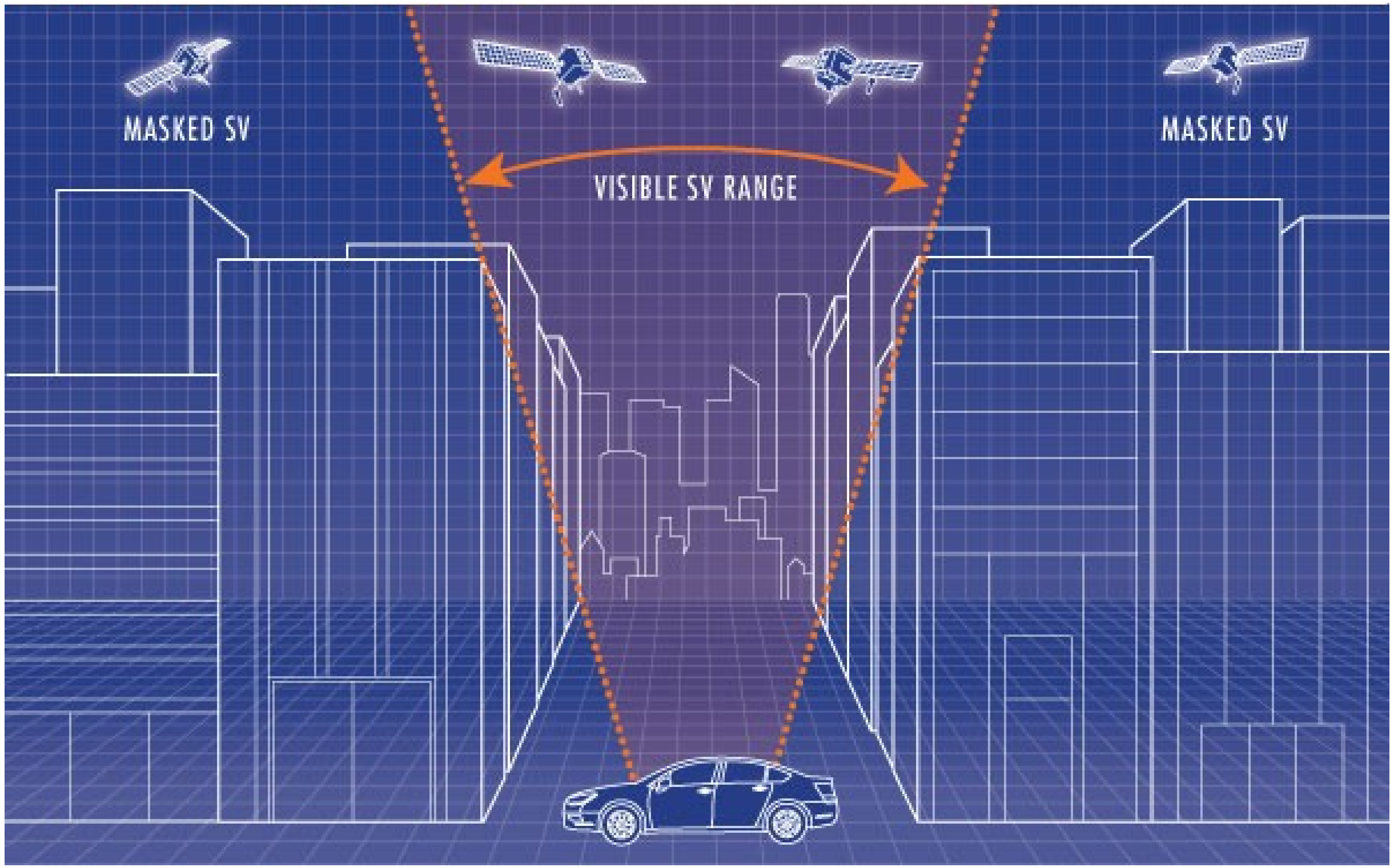
Localization

- Inertial Measurement Unit (IMU)
- Wheel and Steering Odometry
- Global Navigation Satellite System (GNSS)



Electronics Weekly, 2017, *CES Autonomous cars and the sensors to make them safe* [9]

Urban Canyons



Kumar, Muthukumar, 2014, *GNSS Shadow Matching: Improving GNSS positioning in Urban Canyons* [10]

AV Limitations

Difficulty in transitioning to GPS-denied environments

iDigHardware, 2017, *Decoded: Securing Parking Garages* [11]

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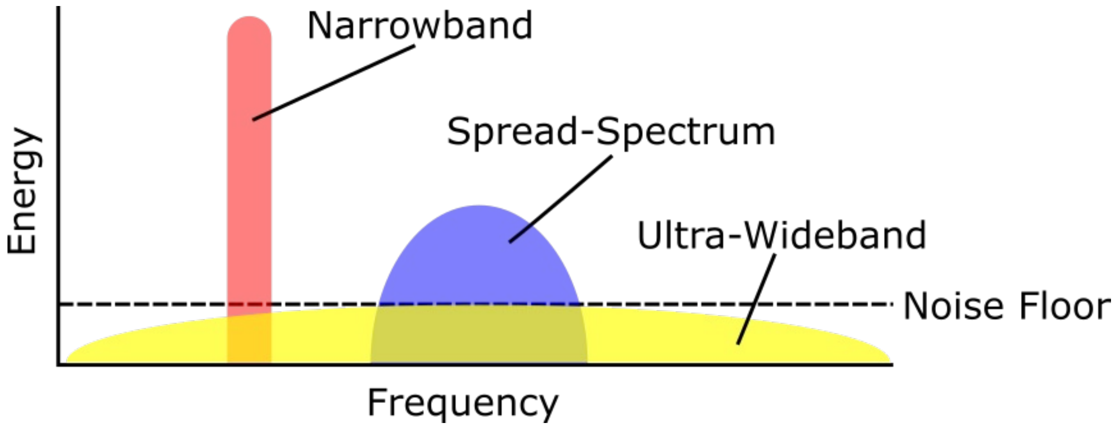
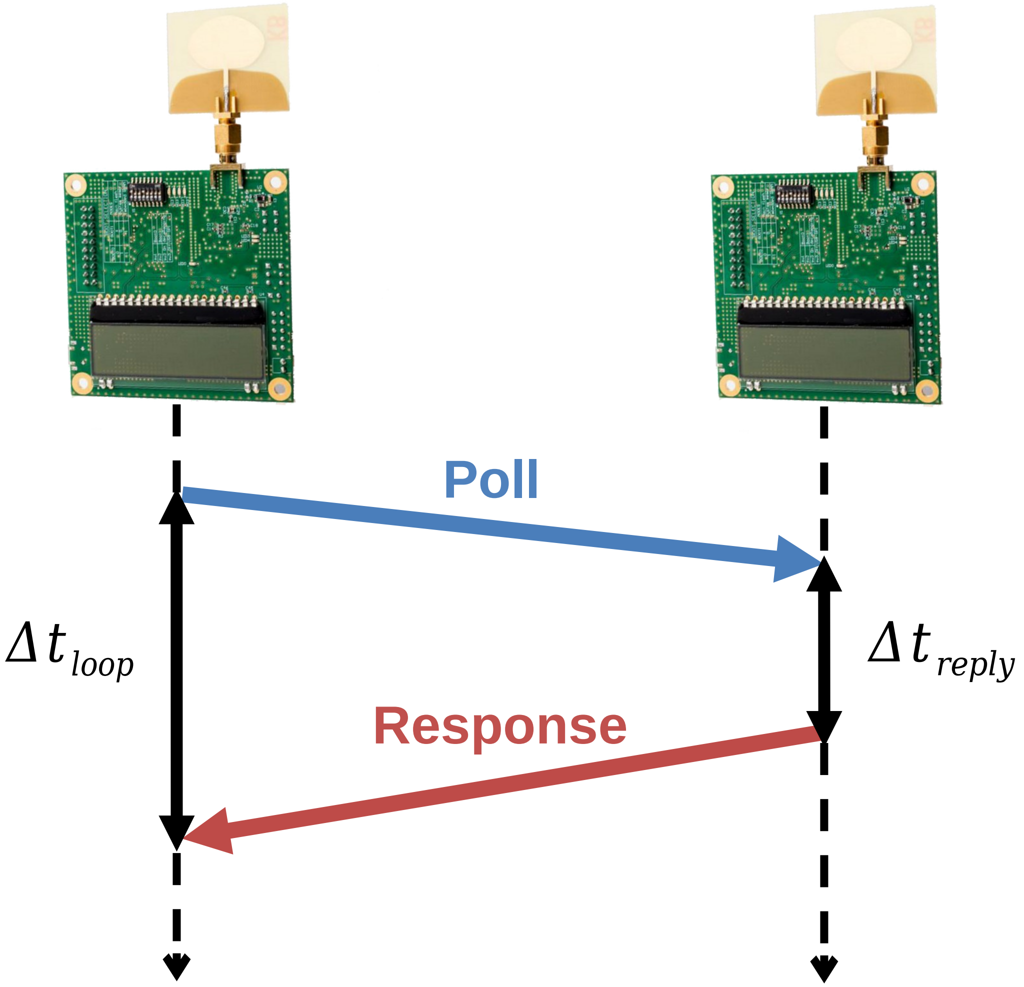
Ultra-Wideband Technology

- FCC first regulated in 2002 [1]
- Large Bandwidth (>500 MHz) Low Power Radio
- Pulses occupy entire UWB bandwidth
- Shared Spectrum
- Relative immunity to multipath errors



UWB Ranging



$$TimeofFlight = \frac{\Delta t_{loop} - \Delta t_{reply}}{2}$$

$$Distance = \frac{TimeofFlight}{c}$$

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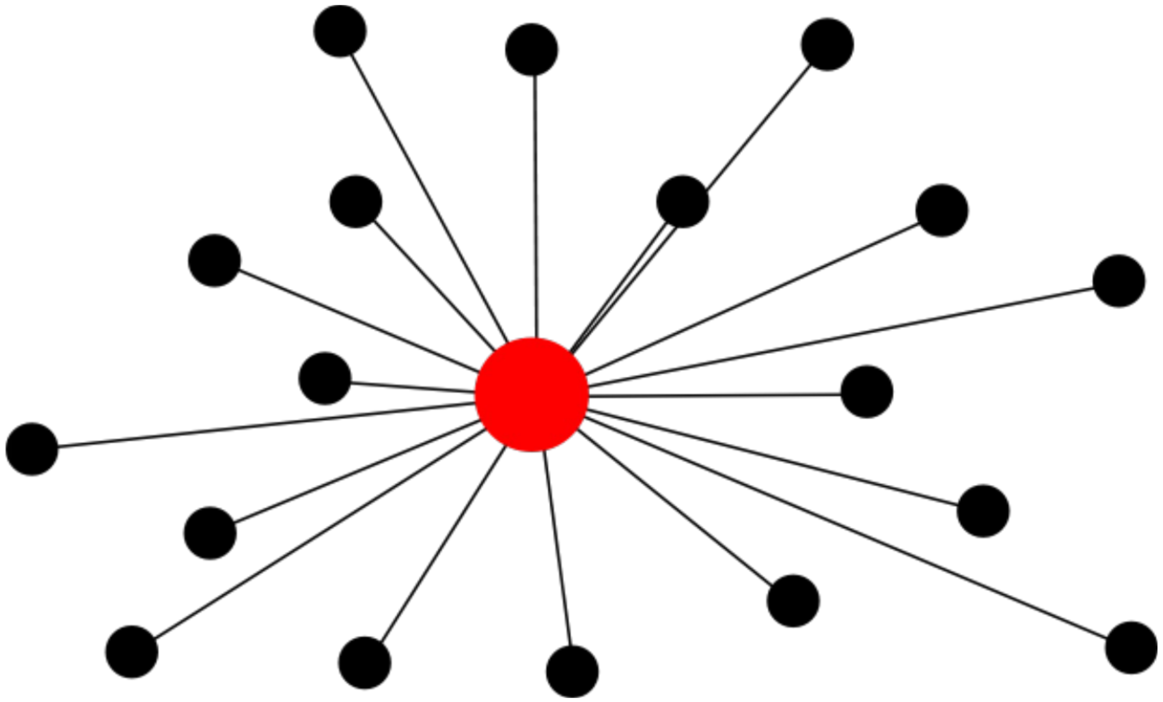
Collaborative Localization

"Traffic jam" by lynac is licensed under CC BY-NC 2.0 [16]

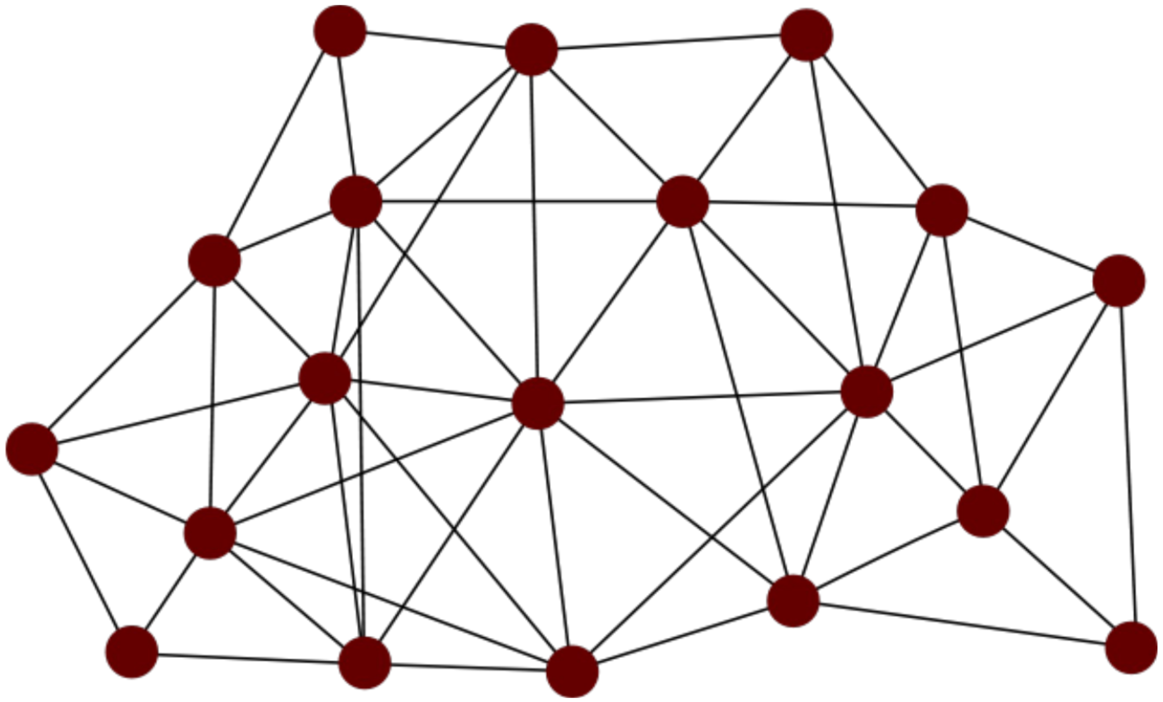
Collaborative Localization

- Centralized:



Collaborative Localization

- Decentralized



Kalman Filter

- Linear Quadratic Estimation
- Recursive Two-Step Process
  - Prediction step
  - Update step
- Commonly used for guidance and control problems
- Nonlinear measurement and process models
  - Linearized to form Extended Kalman Filter

DCL Algorithm

- Distributed Approximation of Extended Kalman Filter
- Derived by *Luft, L. et. al.* [4]
- Recursive Three-Step Process
  - Control (Prediction) Step
  - Private Update Step
  - Relative Update Step
- Number of relative nodes varies with time

DCL Algorithm

Joint State:

$$\hat{x}^t = \left[\hat{x}_1^t; ...; \hat{x}_N^t\right]$$

$$\Sigma^t = \left[\Sigma_{ij}^t\right]_{1 \leq i,j \leq N}$$

Initialization:

$$\hat{x}^0 = \left[\hat{x}_1^0; ...; \hat{x}_N^0\right]$$

$$\Sigma^0 = \begin{bmatrix} \Sigma_{11}^0 & & 0 \\ & \ddots & \\ 0 & & \Sigma_{NN}^0 \end{bmatrix}$$

Decomposition:

$$\Sigma_{ij}^{t+1} = \sigma_{ij}^{t+1} \left(\sigma_{ji}^{t+1}\right)^T$$

$$\sigma_{ij}^{t+1} = \Sigma_{ij}^{t+1}$$

$$\sigma_{ji}^{t+1} = I$$

DCL Algorithm

Control Step (Prediction)

EKF

$$\hat{x}^{t+1} = g(\hat{x}^t, u^t)$$

$$P^{t+1} = G^t P^t (G^t)^T + R^t$$

DCL

$$\hat{x}_i^{t+1} = g(\hat{x}_i^t, U_i^t)$$

$$\Sigma_{ii}^{t+1} = G_i^t \Sigma_{ii}^t (G_i^t)^T + R_i^t$$

$$\sigma_{ij}^{t+1} = G\sigma_{ij}^t$$

DCL Algorithm

Private Update

$$for\ Car\ i,\ \ j \in \{1, ..., N\} \backslash \{i\}$$

EKF

$$S^t = H^t \Sigma^t (H^t)^T + Q^t$$

$$K^t = \Sigma^t (H^t)^T S^{-1}$$

$$\hat{x}^{t+1} = \hat{x}^t + K^t \left(z^t - h(\hat{x}^t) \right)$$

$$\Sigma^{t+1} = (I - K^t H^t) \Sigma^t$$

DCL

$$S = H_i^t \Sigma_{ii}^t (H_i^t)^T + Q_i^t$$

$$K_i^t = \Sigma_{ii}^t (H_i^t)^T S^{-1}$$

$$\hat{x}_i^{t+1} = \hat{x}_i^t + K_i^t \left[z_i^t - h(\hat{x}_i^t) \right]$$

$$\left\{ \begin{array}{l} \Sigma_{ii}^{t+1} = (I - K_i^t H_i^t) \Sigma_{ii}^t \\ \sigma_{ij}^{t+1} = (I - K_i^t H_i^t) \sigma_{ij}^t \end{array} \right.$$

DCL Algorithm

Relative Update

$$for\ Cars\ i, j,\ k \in \{1, ..., N\} \backslash \{i, j\}$$

EKF

$$S^t = F^t \Sigma^t (F^t)^T + Q^t$$

$$K^t = \Sigma^t (F^t)^T S^{-1}$$

$$\hat{x}^{t+1} = \hat{x}^t + K^t \left(z^t - h(\hat{x}^t) \right)$$

DCL

$$\Sigma^t_{ij/ji} = \sigma^t_{ij/ji} (\sigma^t_{ji/ij})^T$$

$$S = \begin{bmatrix} F_i & F_j \end{bmatrix} \begin{bmatrix} \Sigma^t_{ii} & \Sigma^t_{ij} \\ \Sigma^t_{ji} & \Sigma^t_{jj} \end{bmatrix} \begin{bmatrix} F_i^T \\ F_j^T \end{bmatrix} + Q^t_{ij}$$

$$K = \begin{bmatrix} \Sigma^t_{ii} F_i^T & \Sigma^t_{ij} F_j^T \\ \Sigma^t_{ji} F_j^T & \Sigma^t_{jj} F_i^T \end{bmatrix} S^{-1}$$

$$\hat{x}^{t+1}_{i/j} = \hat{x}^t_{i/j} + K_{i/j} \left[z^t_{ij} - h(\hat{x}^{t+1}_i, \hat{x}^{t+1}_j) \right]$$

$$F^t_{i/j} = \frac{\partial f(x_i, x_j)}{\partial x_{i/j}} \left(\hat{x}^t_{i/j} \right)$$

DCL Algorithm

Relative Update

$$for\ Cars\ i, j,\ k \in \{1, ..., N\} \backslash \{i, j\}$$

EKF

$$\Sigma^{t+1} = (I - K^t F^t)\Sigma^t$$

DCL

$$\begin{cases} \Sigma^{t+1}_{ii/jj} = (I - K_{i/j}F_{i/j})\Sigma^t_{ii/jj} - K_{i/j}F_{j/i}\Sigma^t_{ji/ij} \\ \Sigma^{t+1}_{ij} = (I - K_i F_i)\Sigma^t_{ij} - K_i F_j \Sigma^t_{jj} \\ \sigma^{t+1}_{ij} = \Sigma^{t+1}_{ij} \\ \sigma^{t+1}_{ji} = I \\ \sigma^{t+1}_{ik/jk} = \Sigma^{t+1}_{ii/jj} \left(\Sigma^{t+1}_{ii/jj}\right)^{-1} \sigma^t_{ik/jk} \end{cases}$$

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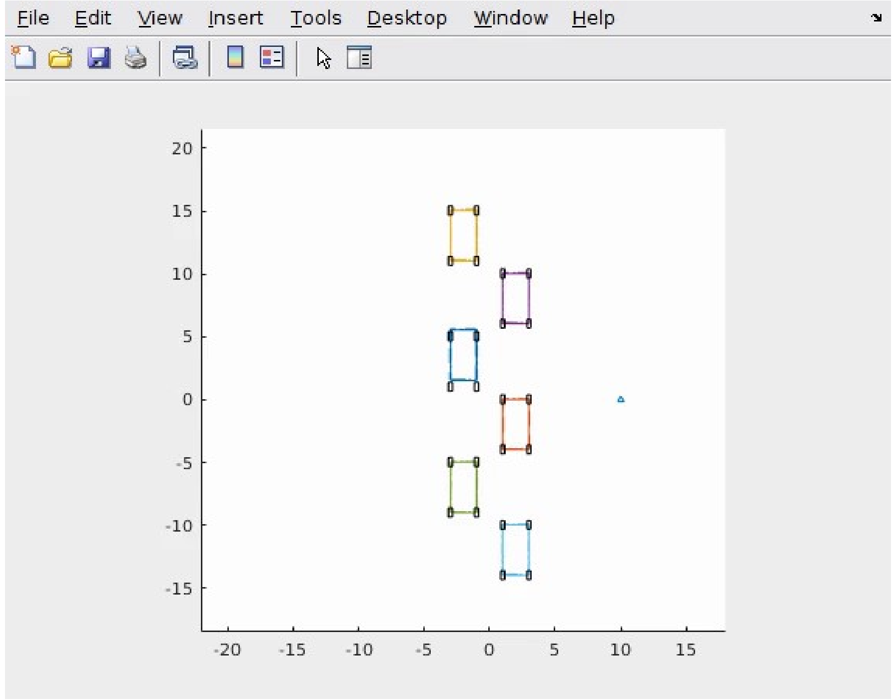
Simulation Environment

- Models *n*-vehicles with random sensor errors
- IMU, Odometry, GPS, and UWB
- Handles landmarks and collaboration
- Simulates estimation algorithms
  - Single Vehicle EKF
  - Centralized EKF with UWB
  - Decentralized EKF with UWB
- Programmed in MatLab
- Open Sourced

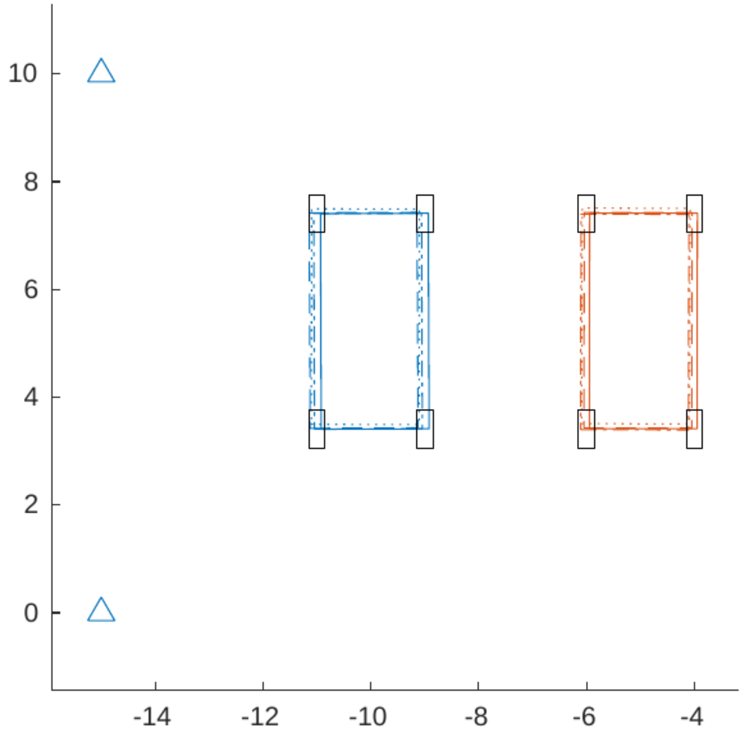


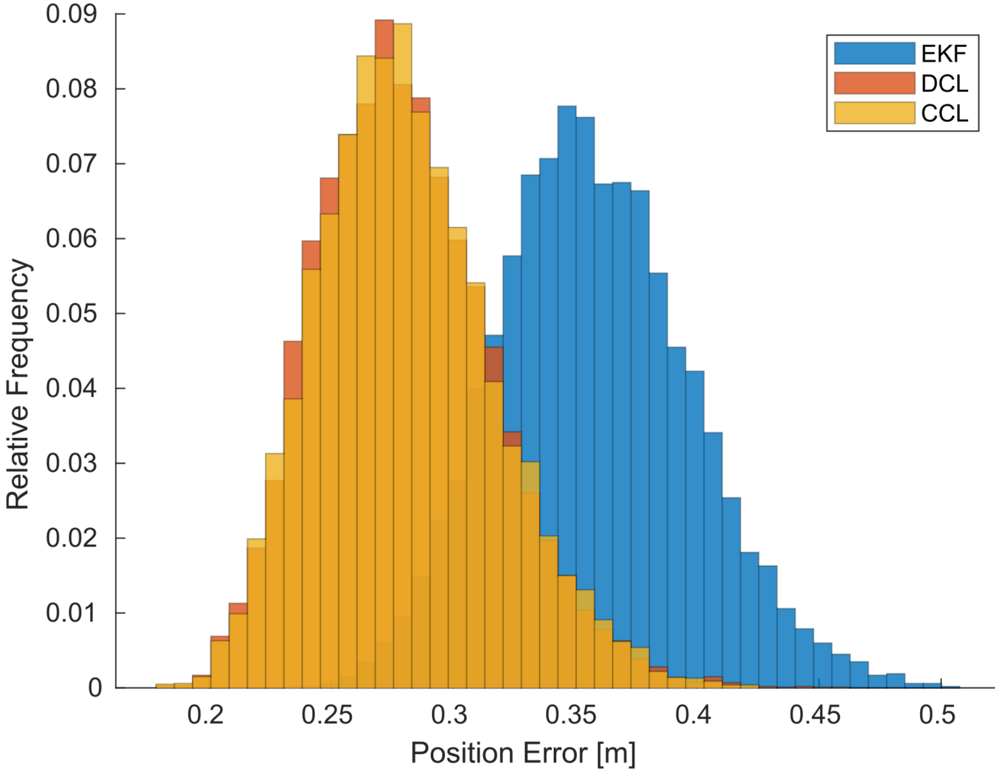
Monte Carlo Simulations

- Monte Carlo Simulation Parameters
  - 10,000 Runs Each
  - Parallelized for faster processing
  - With and Without UWB Landmarks
  - With and Without UWB Collaboration
  - Calculates RMS position error
  - 20 second simulations

Simulation Results

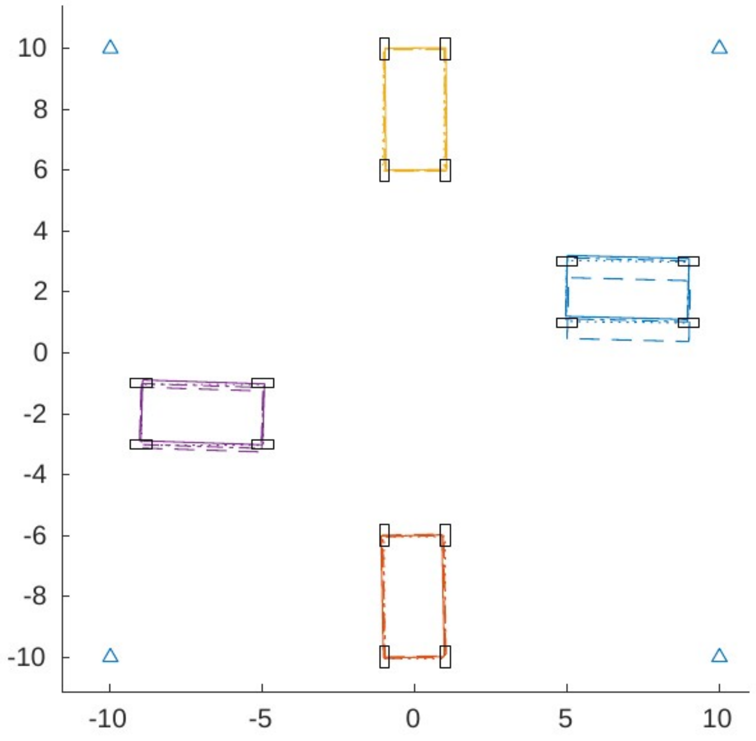
- Parallel Motion

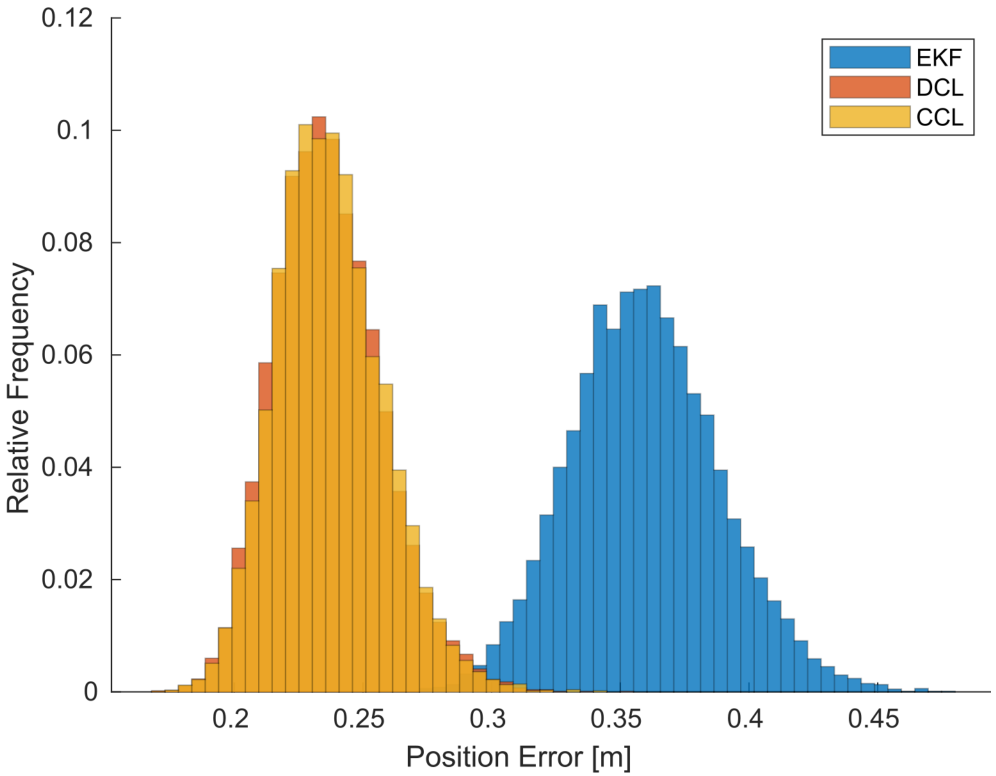




Simulation Results

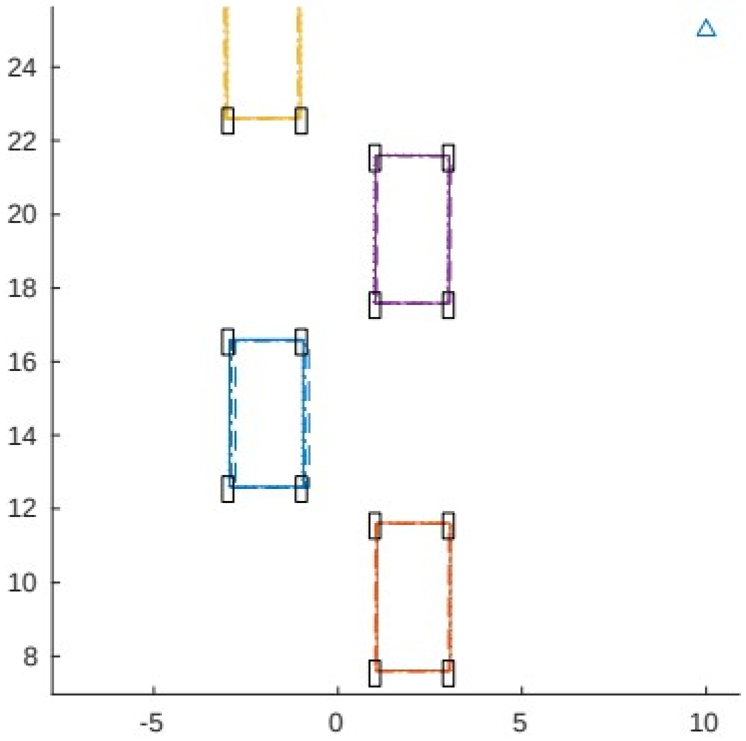
- Street Crossing

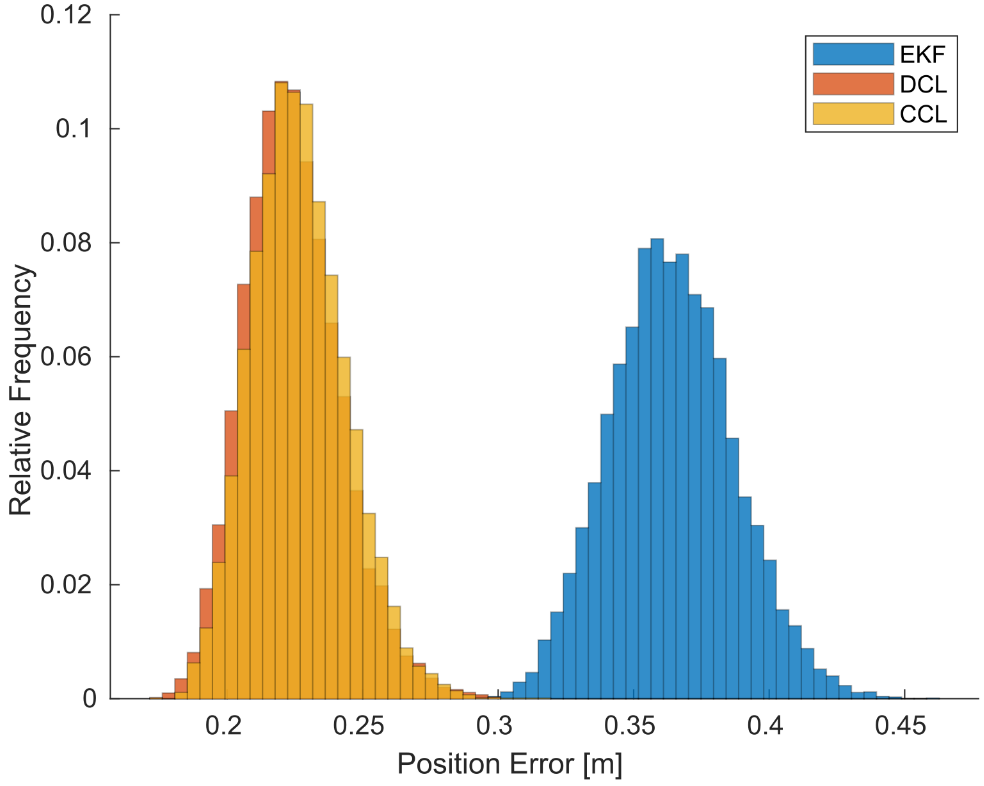




Simulation Results

- Tunnel Environment – No GPS with Landmarks





Simulation Results Summary

- UWB offers improvements with collaboration
- Larger vehicle networks increased accuracy
- Greater improvements seen from landmarks
- Largest impact in GPS-denied settings

Experiment	GPS	EKF	DCL	CCL
Parallel	Yes	0.37	0.28	0.28
Street Crossing	Yes	0.37	0.24	0.24
Tunnel	No	0.30	0.24	0.24

Experimentation

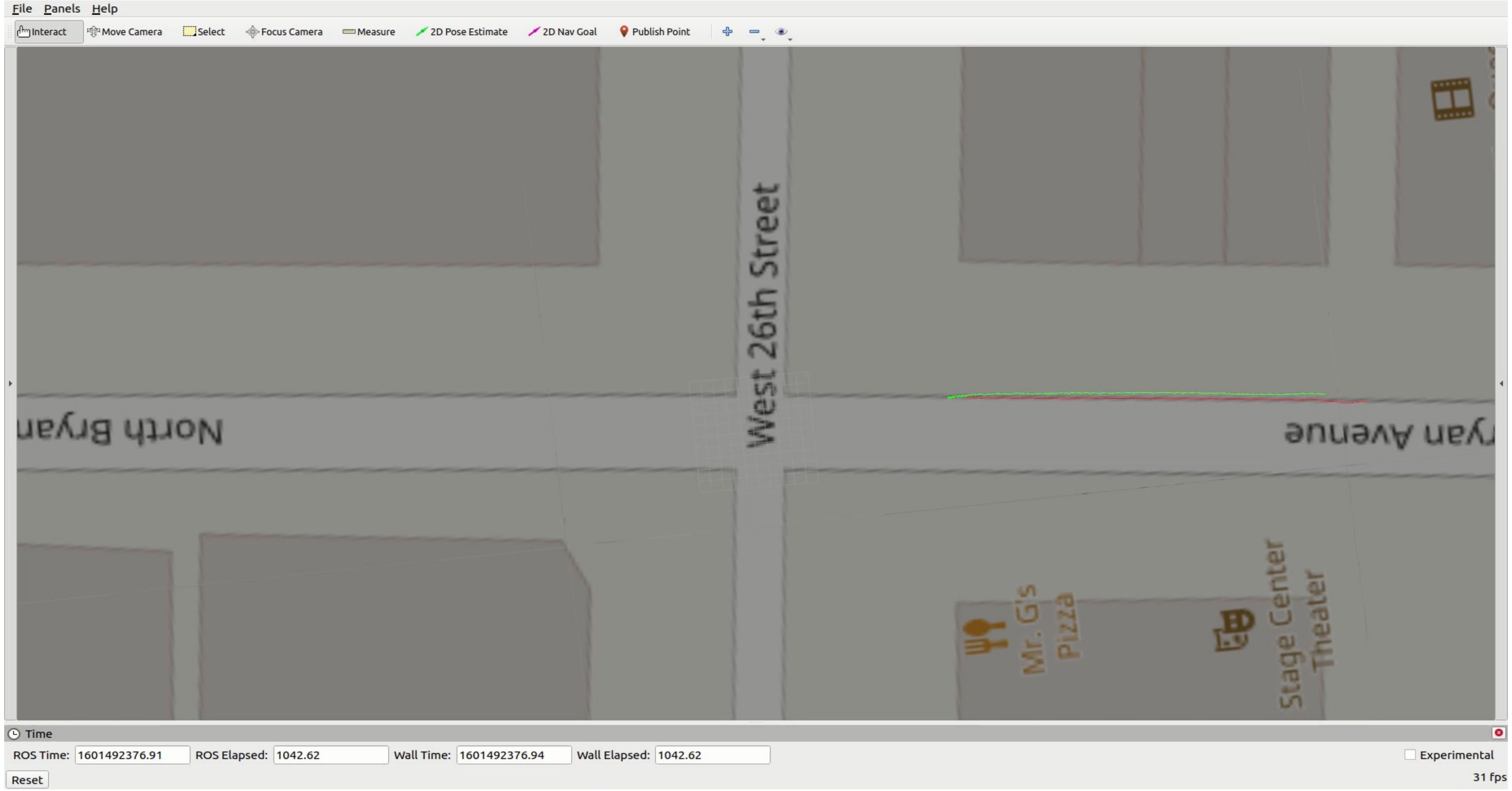
Texas Transportation Institute, 2018, *Self-Driving Vehicles Begin Operating in Downtown Bryan, Texas* [17]

Experimental Setup

- Unmanned Lab Autonomous Trolley
- Sensors:
  - IMU
  - Odometry
  - GPS (RTK corrections available)
  - UWB Ranging – Collaborative and Landmarks
- Localization Algorithms:
  - EKF
  - EKF with UWB landmark ranging
  - DCL with UWB vehicle ranging

Experimental Data - Crossing

Experimental Data - Tunnel



Experimental Results Summary

- UWB offers improvements with collaboration
- Greater improvements seen from landmarks
- Largest impact in GPS-denied settings

Experiment	GNSS	EKF	DCL	CCL
Parallel	No	2.06	1.81	1.81
Street Crossing	Yes	2.32	1.61	1.61
Tunnel	No	7.78	1.30	1.30

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Contributions

- Developed flexible collaborative simulation
  - Various scenes and vehicle parameters
  - Monte Carlo testing capability
- Decawave ROS driver package
- UWB error model validation
- Validations of Luft’s DCL algorithm

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