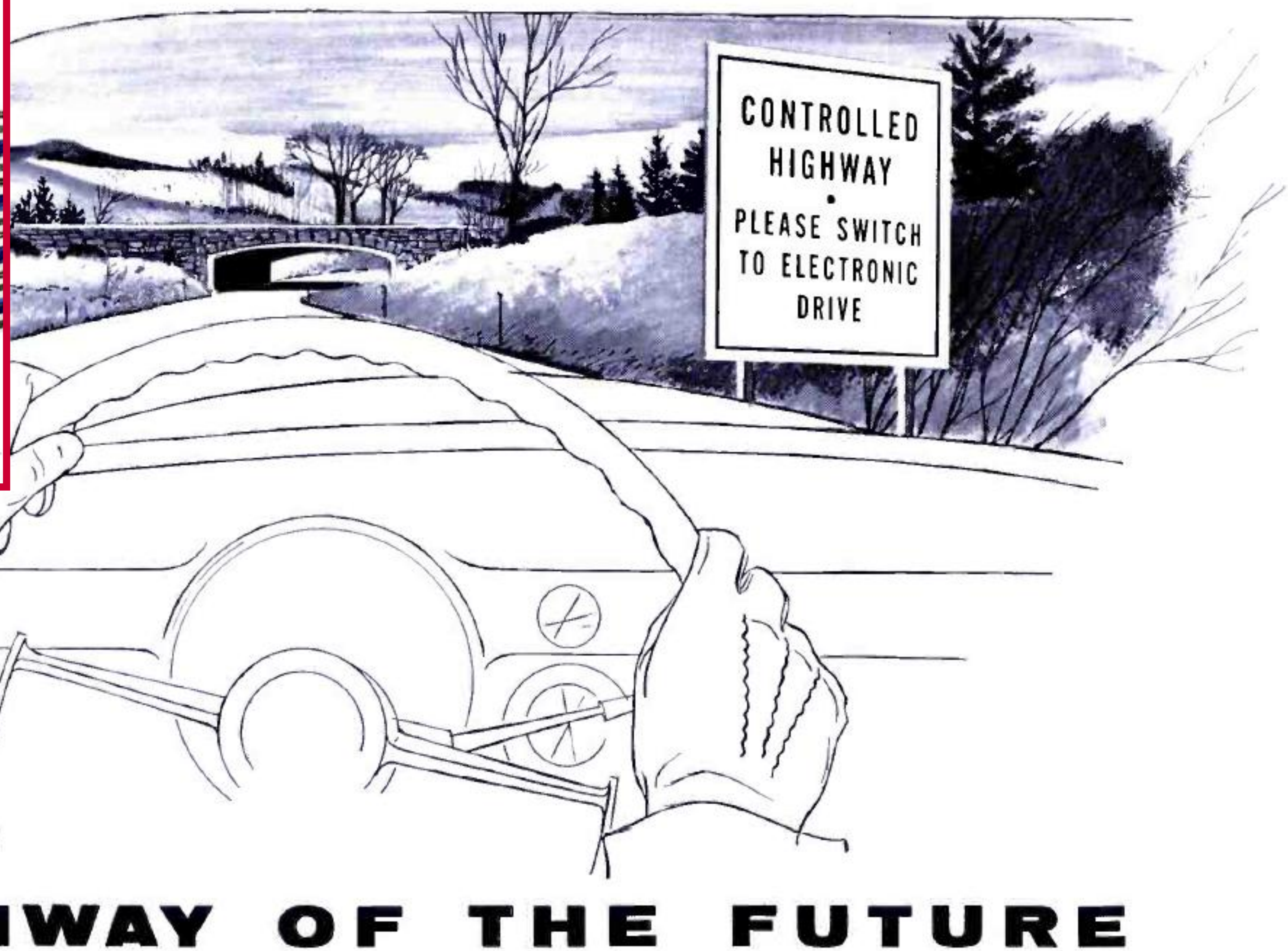
Quantifying Navigation Safety of Autonomous Passenger Vehicles (APVs)

Mathieu Joerger, *The University of Arizona*
joerger@email.arizona.edu

Matthew Spenko, *Illinois Institute of Technology*

APVs Were Just Around the Corner … in 1958

1958



[IEEE Spectrum] Evan Ackerman , "Self-Driving Cars Were Just Around the Corner—in 1960", IEEE Spectrum Magazine, September 2016

Stepping Stones to APVs: DGPS/INS, laser, radar

- DARPA Grand Challenge (2005)
  - 150 miles across Mojave desert
  - 4 teams completed the course while averaging ~20 mph
- DARPA Urban Challenge (2007)
  - 60 miles in urban areas,
  - obey traffic regulations and negotiate obstacle, traffic, pedestrian
  - 3 teams completed course while averaging ~13 mph

Stanford's Stanley

https://cs.stanford.edu/group/roadrunner/stanley.html

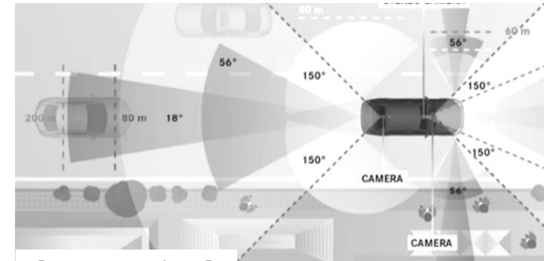
Tartan Racing's Boss **(*Carnegie Mellon*)**

http://www.tartanracing.org/index.html

Scope of Current APV Research Efforts

- Google and most car manufacturers have autonomous car prototypes

- The National Highway Traffic Safety Administration (NHTSA) classification:
  - Level 1: **Function-specific Automation**
  - Level 2: **Combined Function Automation**
  - Level 3: **Limited Self-Driving Automation**
    driver expected to take over at any time
  - Level 4: **Full Self-Driving Automation**



[Haueis ‘15]

[NHTSA ‘13] NHTSA, “Preliminary statement of policy concerning automated vehicles,” online, 2013
[Haueis ‘15] Haueis, “Localization for automated driving,” ION GNSS+ 2015

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Example Experimental Testing Campaigns

- My understanding of Google's approach
  - testing with trained operators ready to take over, on select roads
  - soon to reach **2 million miles** driven in autonomous mode [Google '16]

- My understanding of Tesla's approach
  - 'Model S' autopilot available on the market, **restricted to highway**
    - ➢ constant reminders: "Always keep your hands on the wheel, be prepared to take over at any time"
  - 70,000 'Model S' Autopilots are claimed to have driven **130 million miles** [Rogowsky]

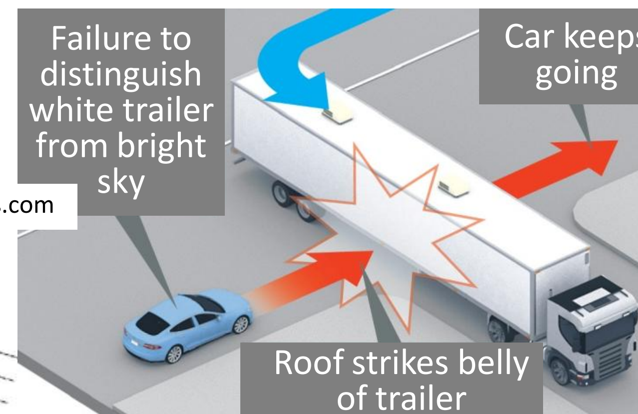
[Google '16] Google, "Google Self-Driving Car Project Monthly Report", available online, August 2016

[Rogowsky] Rogowsky, "The Truth About Tesla's Autopilot Is We Don't Yet Know How Safe It Is" , *Forbes*, 2016

APV Accident Reports

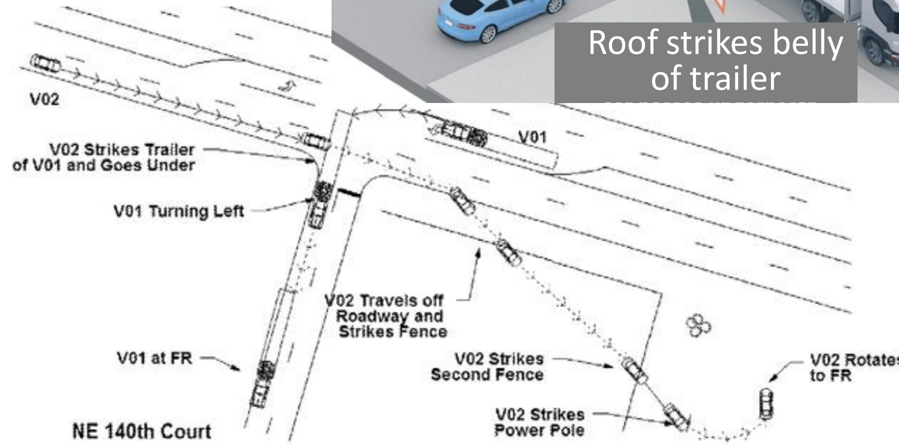
- In 2015, Google reported:
  - 13 ‘contacts’ avoided by operator, Google car at fault in 10 of them [Google ‘15]
- February 14 2016 in Mountain View, CA :
  - first crash where Google car was at fault
- May 7 2016 in Williston, FL:
  - Tesla autopilot caused a fatality

http://jalopnik.com/



www.straitstimes.com

[Florida Highway Patrol]



[Google ‘15] Google, “Google self-driving car testing report on disengagements of autonomous mode”, available online, December 2015

How do these APVs Compare to Human Drivers?

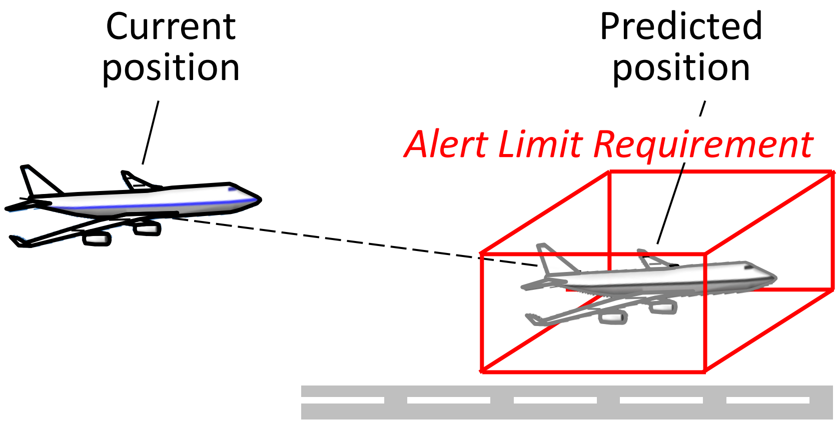
- In the U.S., car accidents cause over 30,000 deaths/year, 90% of which are due to human error [NHTSA '14]
  - 3 trillion miles driven per year
    - **1 fatality per 100 million mile driven (MMD)**

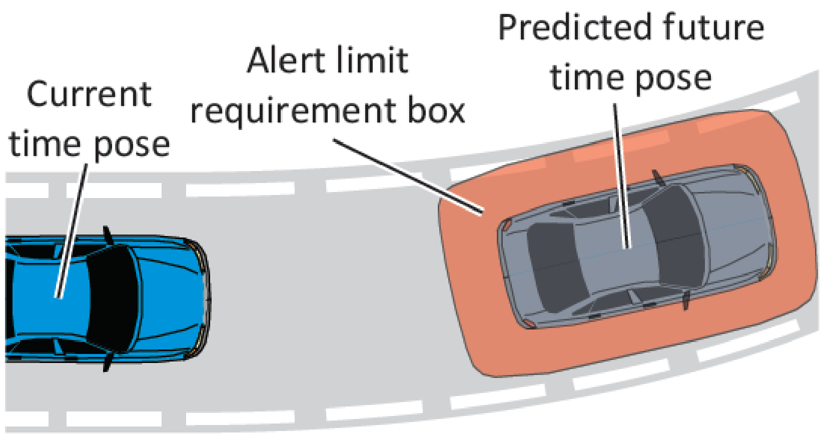
- Not enough data yet to prove safety (or lack thereof) of Tesla / Google APVs

- A purely **experimental** approach is **not sufficient**
    - in response, **leverage analytical methods** used in aircraft navigation safety

[NHTSA '14] fars.NHTSA.dot.gov, "Fatality analysis reporting system. Technical report, National Highway Traffic and Safety Administration," 2014

Leveraging Analytical Methods Used in Aviation Safety





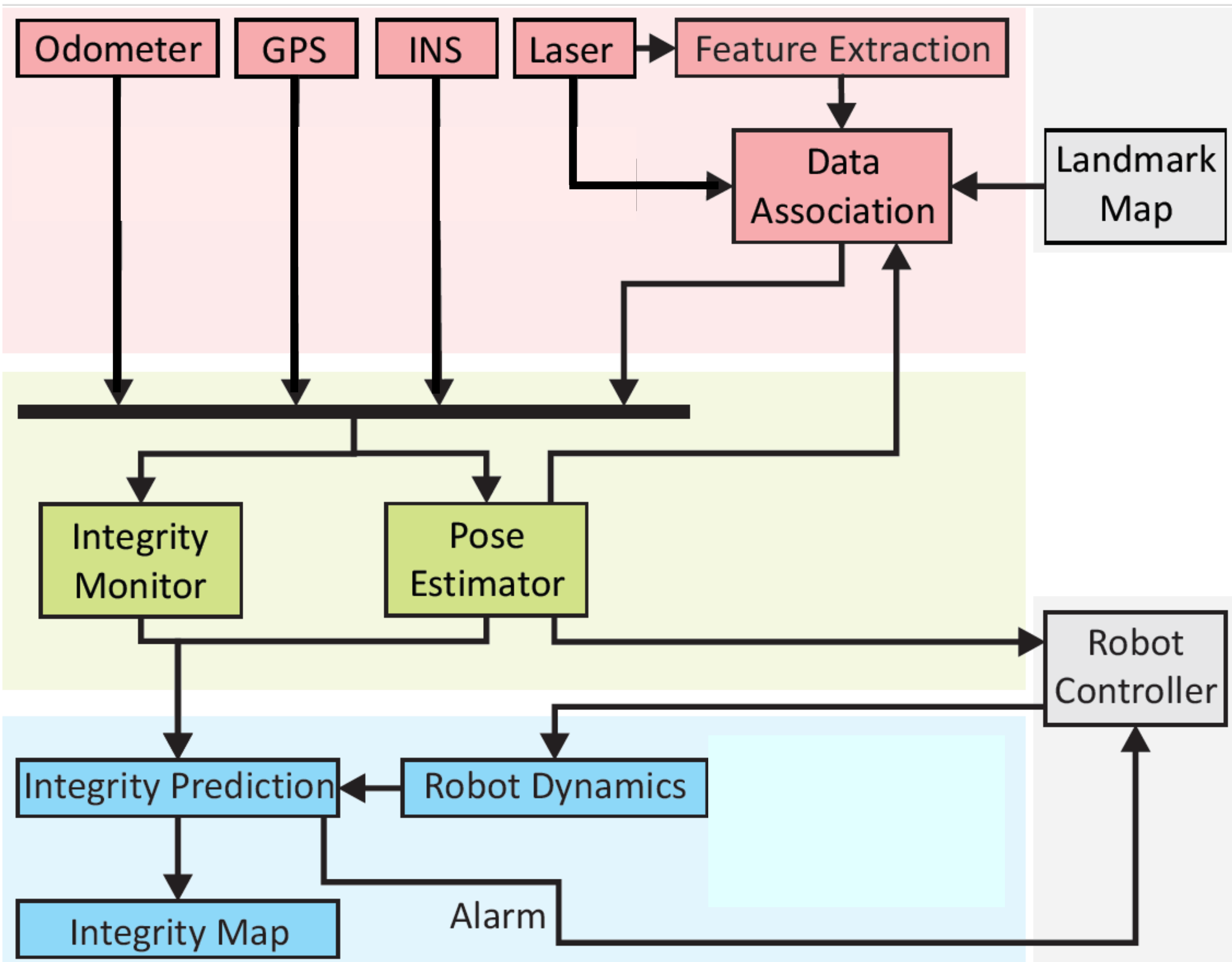
- It took decades of R&D to bring alert limit down to 10 m [LAAS]

- Challenges in bringing aviation safety standards to APVs
  - GPS-alone is insufficient → **multi-sensor** system needed
  - not only peak in safety risk at landing → **continuous risk monitoring**
  - unpredictable meas. availability → **prediction** in dynamic APV environment

[LAAS] RTCA SC-159, "Minimum Aviation System Performance Standards for the Local Area Augmentation System (LAAS)," Doc. TCA/DO-245, 2004.

Example Three Step Approach for APV Safety Evaluation

- Evaluate safety risk contribution of **each system component**



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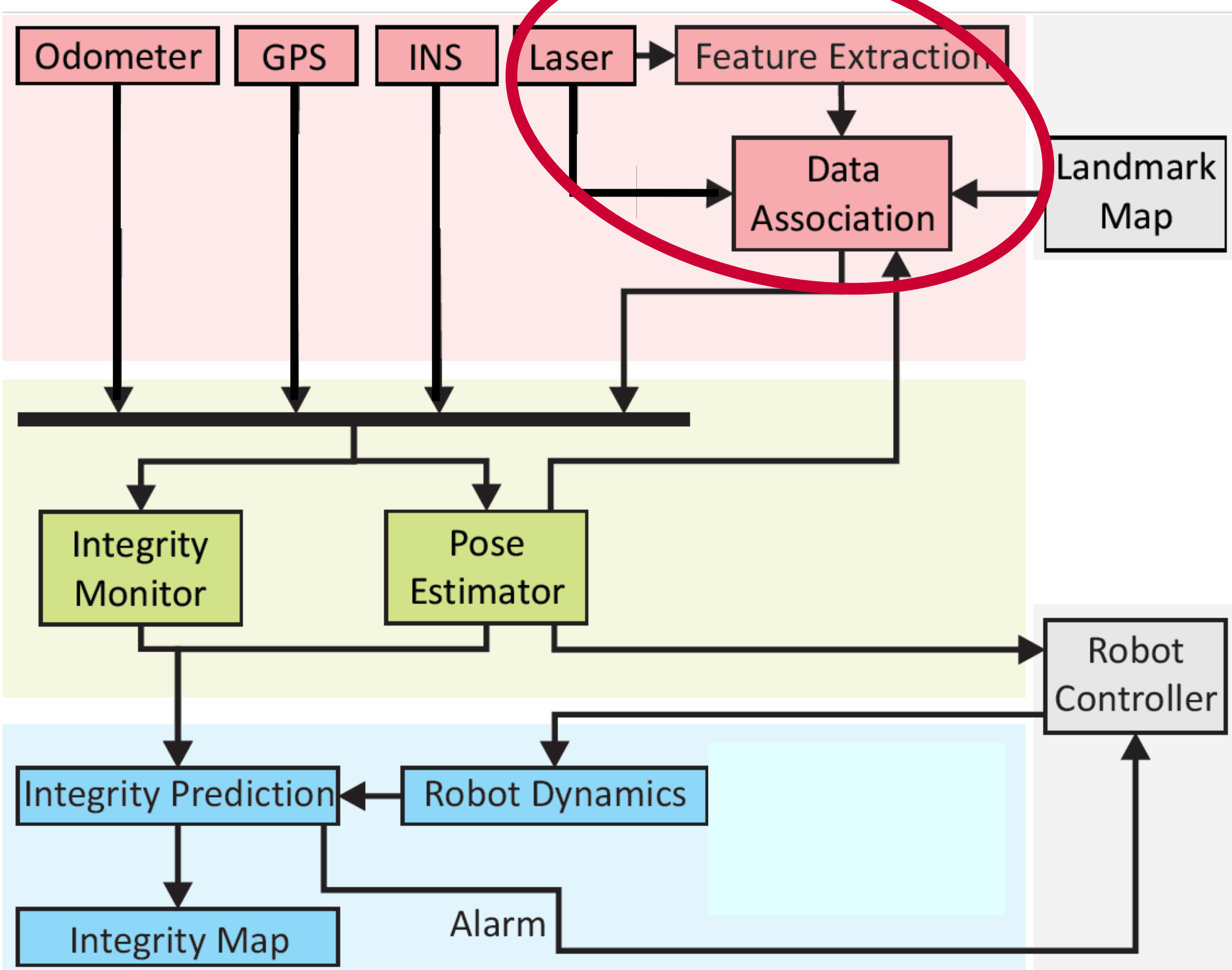
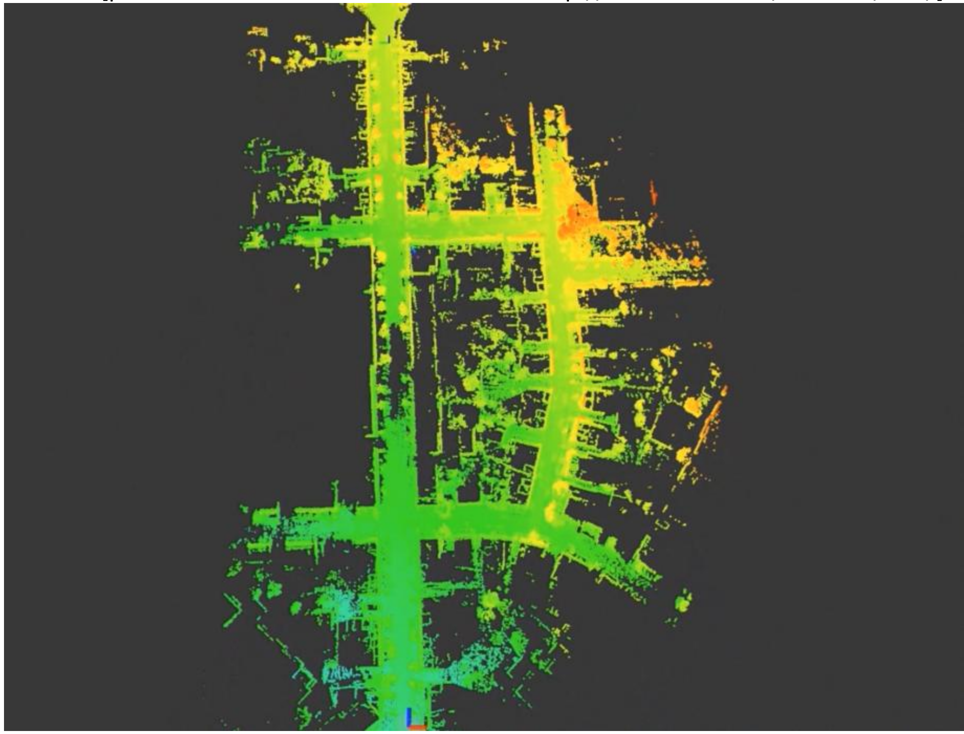


Laser Data Processing

[processed data from the KITTI dataset: http://www.cvlibs.net/datasets/kitti/]



- Each individual laser (radar) data point provides little information

- Feature extraction
  - find few **distinguishable**, and **repeatedly identifiable** landmarks

- Data association
  - from one time step to the next, find correct **feature in stored map corresponding to extracted landmarks**

[1958] Spenko and Joerger: “Receding Horizon Integrity—A New Navigation Safety Methodology for Co-Robotic Passenger Vehicles”

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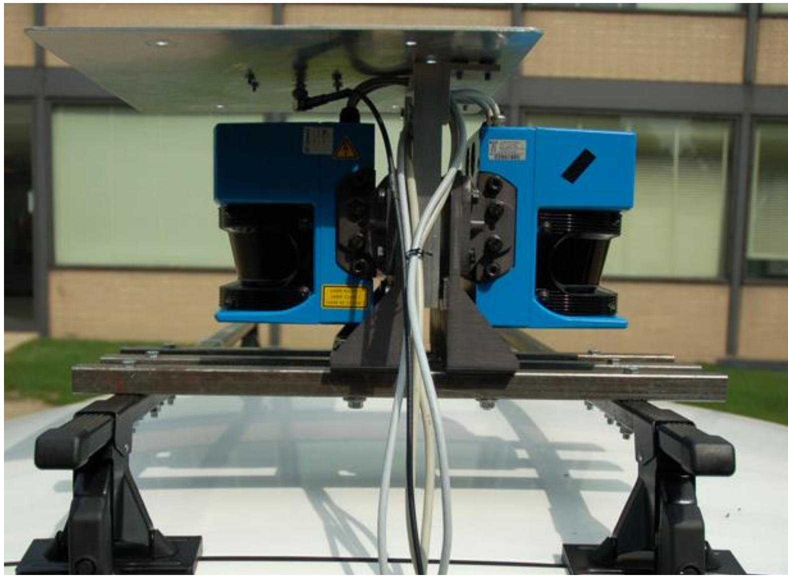
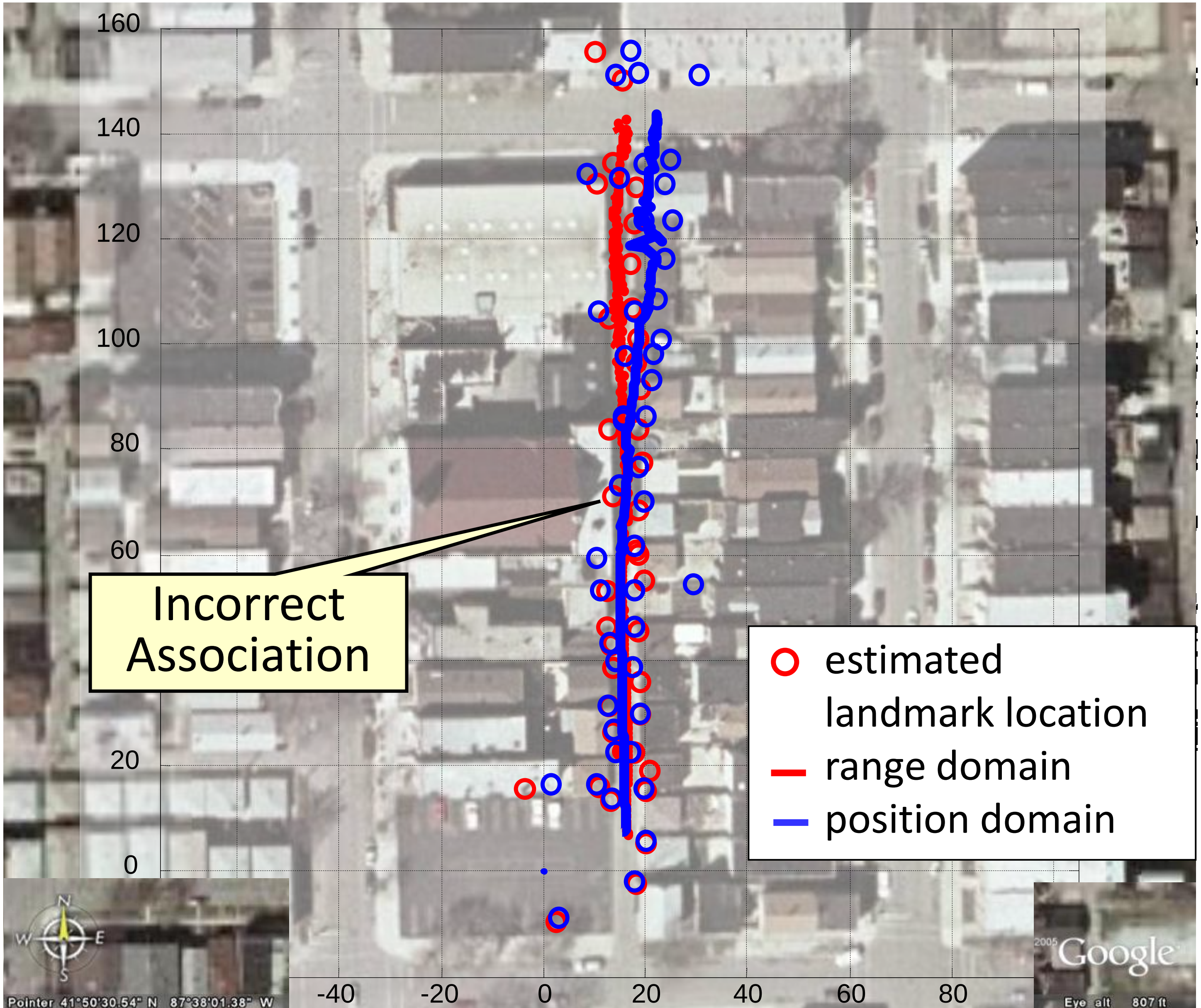
Experimental Setup



True Trajectory and Landmark Location



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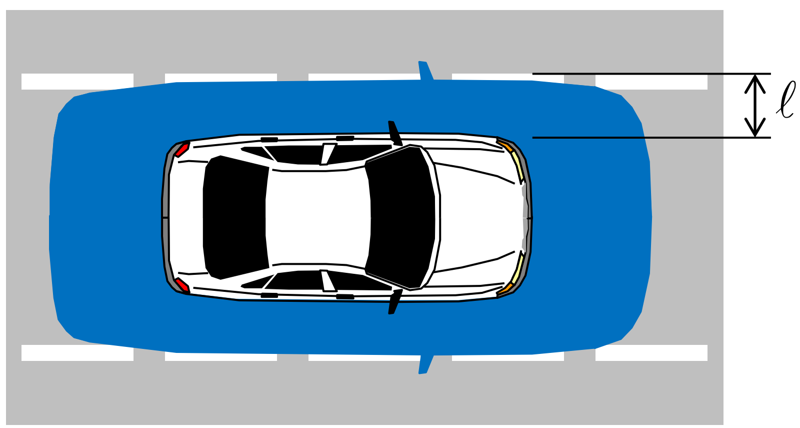
Integrity Risk Definition

- We define the integrity risk at time step k,
  or probability of hazardously misleading information (HMI)

$$P(HMI_{\underbrace{k}_{\text{at time } k}}) = P\left(|\overbrace{\hat{\varepsilon}_k}^{\text{estimation error}}| > \overbrace{\ell}^{\text{specified alert limit}}\right)$$



Integrity Risk Evaluation

- We define the integrity risk at time step k,
  or probability of hazardously misleading information (HMI)
  - considering a two mutually exclusive, exhaustive hypotheses

$$P(HMI_{\underset{\text{at time } k}{k}}) = P\left(|\overbrace{\hat{\varepsilon}_k}^{\text{estimation error}}| \overbrace{> \ell}^{\text{specified alert limit}}\right) = P(HMI_k,\ \underbrace{CA_K}_{\text{correct association}}) + P(HMI_k,\ \overbrace{IA_K}^{\text{incorrect association}})$$

K : times 1 to k

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at time k

K : times 1 to k

- We establish an easy-to compute upper-bound in [PLANS '16] :

$$P(HMI_k) \leq 1 - [1 - \underbrace{P(HMI_k \mid CA_K)}_{\text{derived from EKF variance}}]P(CA_K)$$

[PLANS '16] Joerger et al. "Integrity of Laser-Based Feature Extraction and Data Association", *PLANS 2016*

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  - and, over time [PLANS '16]

$$P(CA_K) = P(CA_1,\ CA_2, \ldots,\ CA_k) = \prod_{j=1}^{k} P(CA_j \mid\ CA_{J-1})$$

[PLANS '16] Joerger et al. "Integrity of Laser-Based Feature Extraction and Data Association", *PLANS 2016*

Probability of Correct Association

- In [PLANS 2016], we presented an innovation-based method

[BarShalom '88]

$$\boldsymbol{\gamma}_i = \underbrace{\mathbf{z}}_{\substack{\text{measurement} \\ [z_1\ z_2\ z_3]^T}} - \underbrace{\mathbf{h}_i(\bar{\mathbf{x}})}_{\substack{\text{predicted} \\ \text{(depends on} \\ \text{ordering A,B,C)}}}$$

$$\min_{i=0,\ldots,\,n_L!-1} \boldsymbol{\gamma}_i^T \underbrace{\mathbf{Y}_i^{-1}}\boldsymbol{\gamma}_i$$

$\mathbf{Y}_i$: covariance matrix of innovation vector γ_i

- We derived an integrity risk bound accounting for all possible incorrect associations:

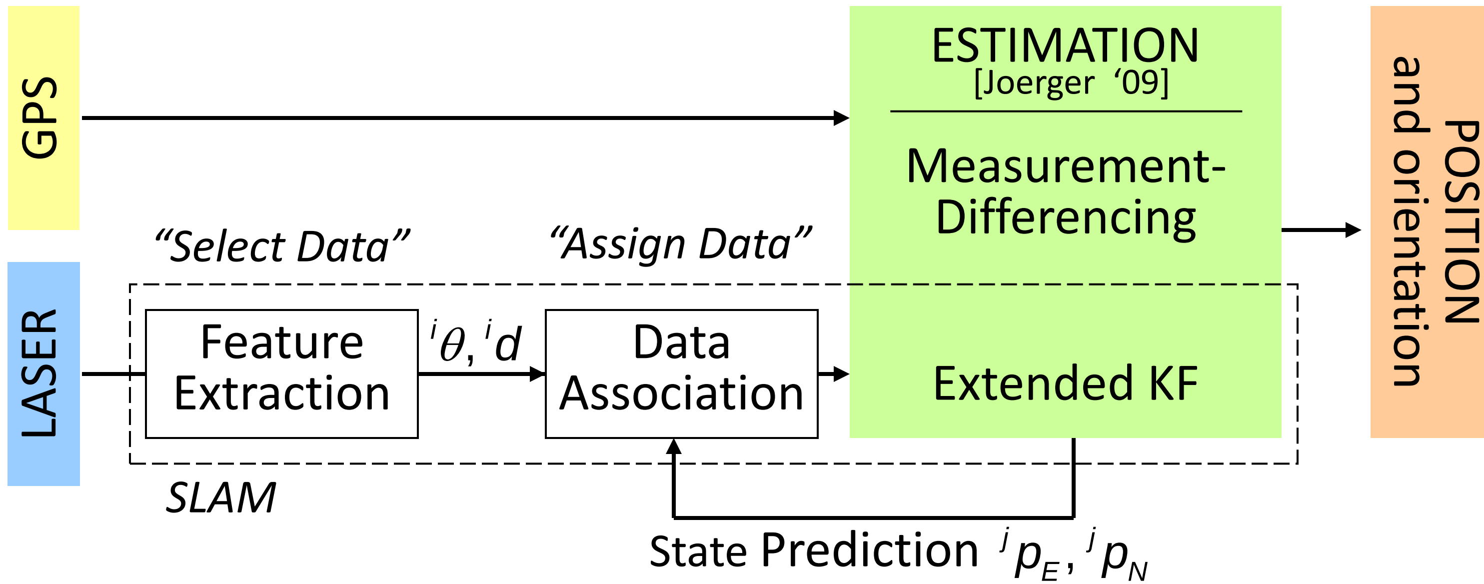
$$\boxed{P(HMI_k) \leq 1 - [1 - P(HMI_k \mid CA_K)]\prod_{j=1}^{k} P(CA_j \mid CA_{J-1}) + \underbrace{I_{FE,ALLOC}}_{}}$$

risk allocation for feature extraction… for example, 10^{-8}

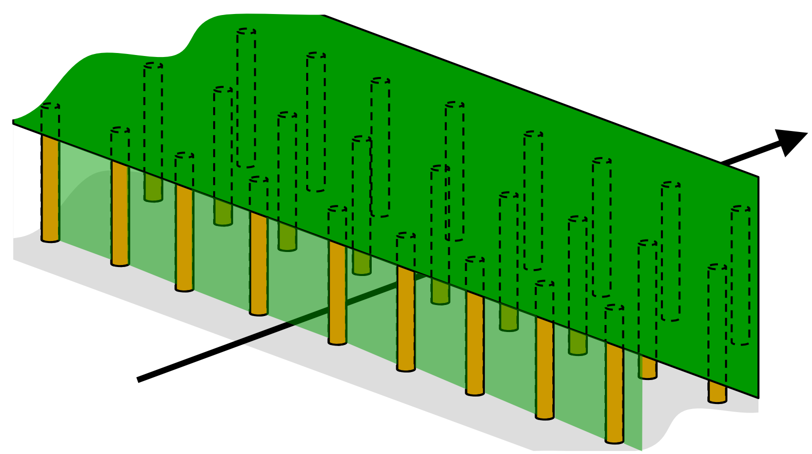
[BarShalom '88] Y, Bar-Shalom, and T. E. Fortmann, "Tracking and Data Association," *Mathematics in Science and Engineering*, Vol. 179, Academic Press, 1988.

[PLANS '16] Joerger et al. "Integrity of Laser-Based Feature Extraction and Data Association", *PLANS 2016*

Multi-Sensor GPS/Laser System



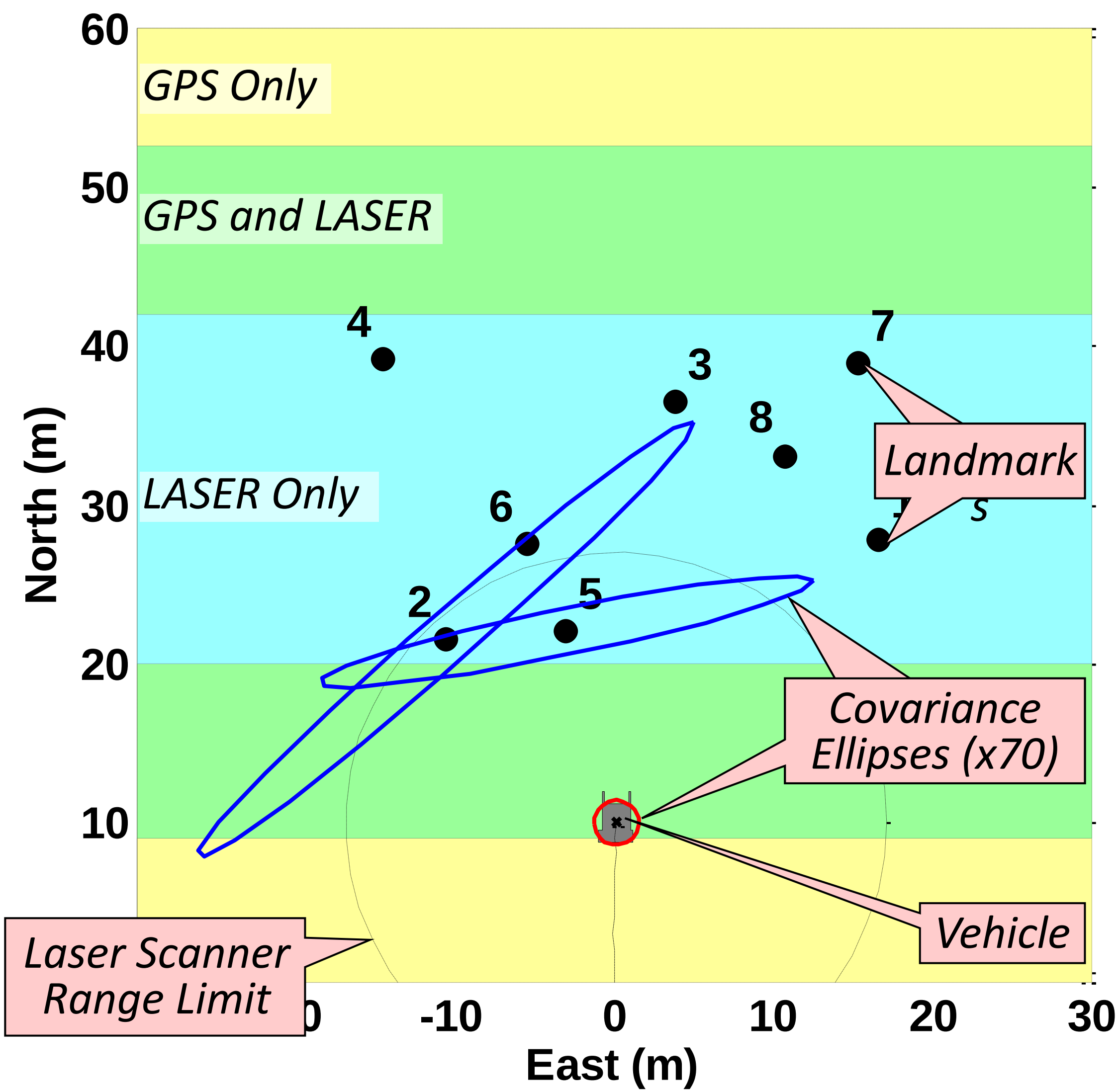
Simulation Scenario:
Vehicle Driving through Forest

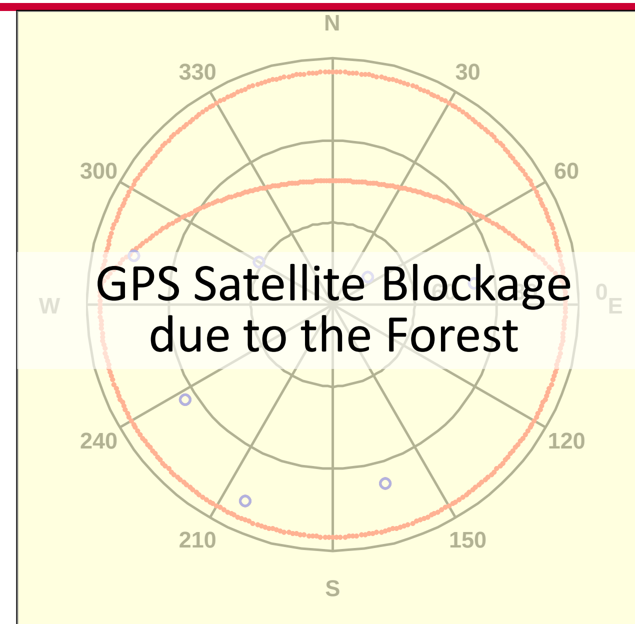


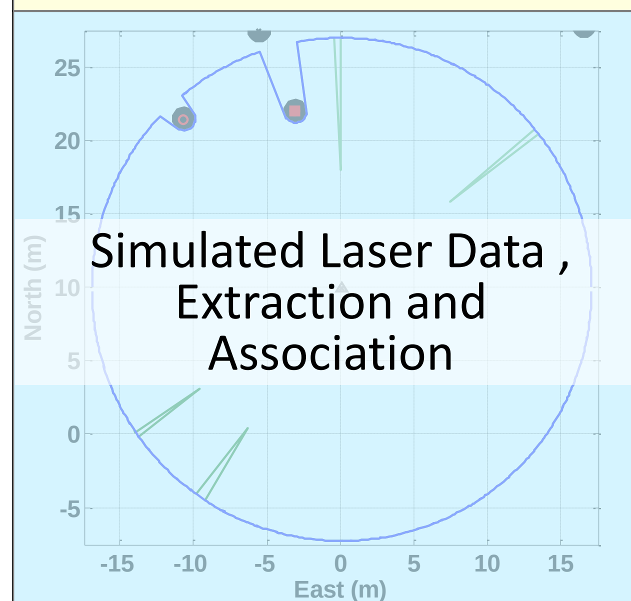
[Joerger '09] Joerger, and Pervan. "Measurement-Level Integration of Carrier-Phase GPS and Laser-Scanner for Outdoor Ground Vehicle Navigation." *ASME J. of Dynamic Systems, Measurement, and Control*. 131. (2009).

Direct Simulation of SLAM

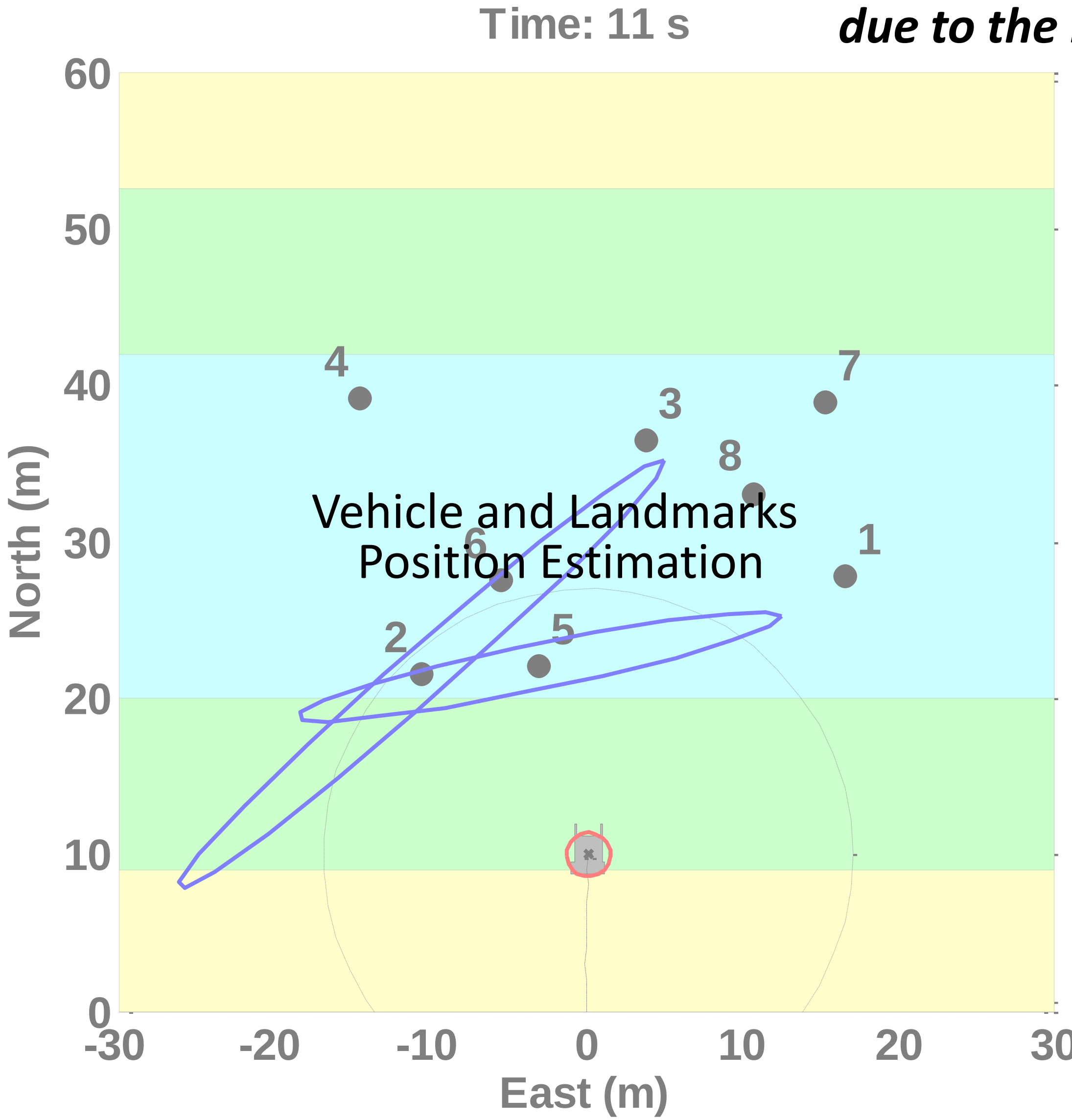
Vehicle and Landmarks Position Estimation



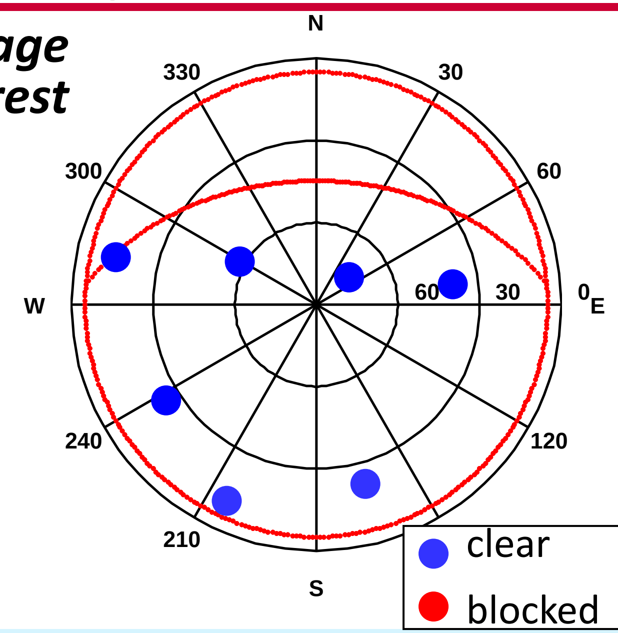


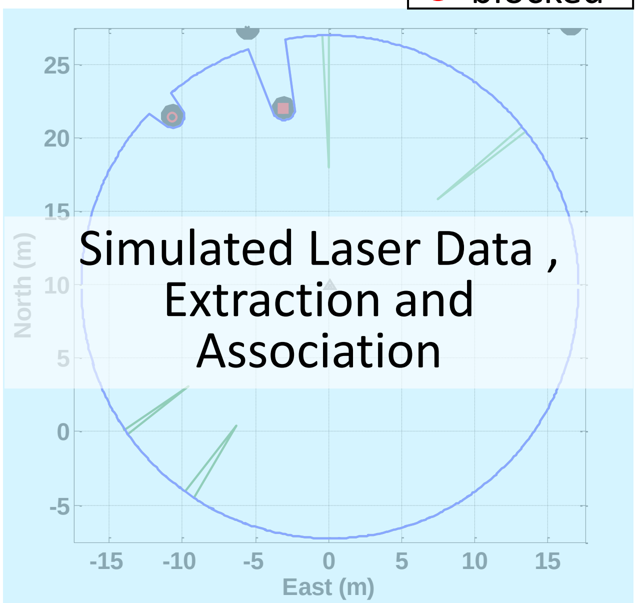


Forest Scenario: Direct Simulation



GPS Satellite Blockage due to the Forest





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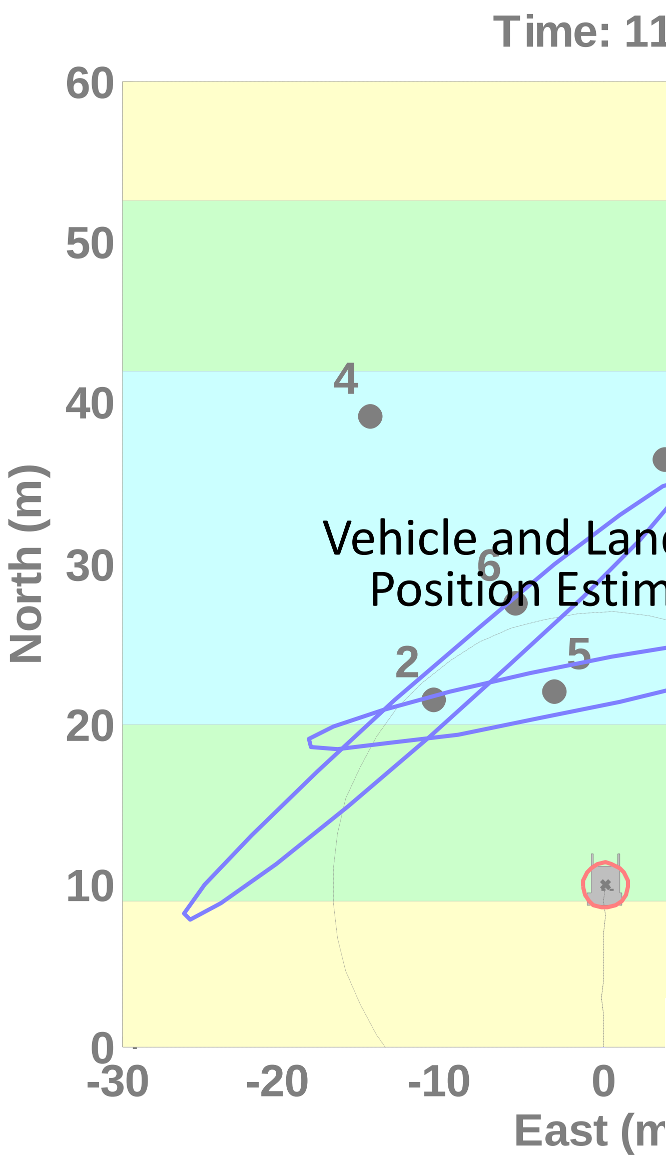
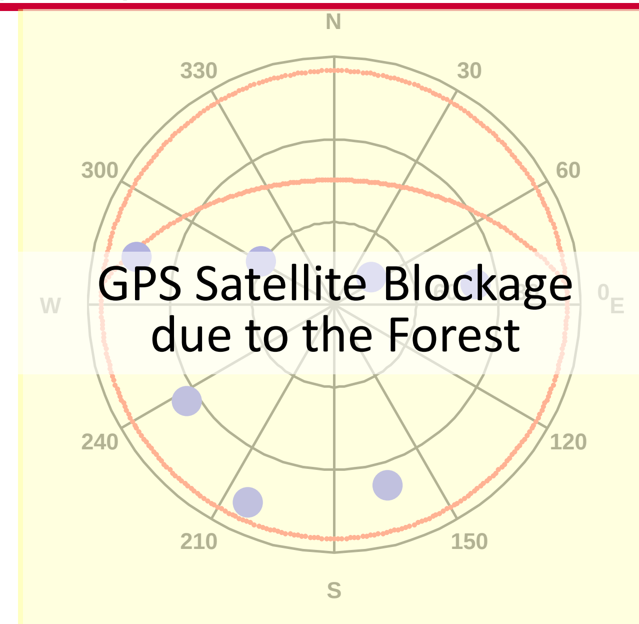
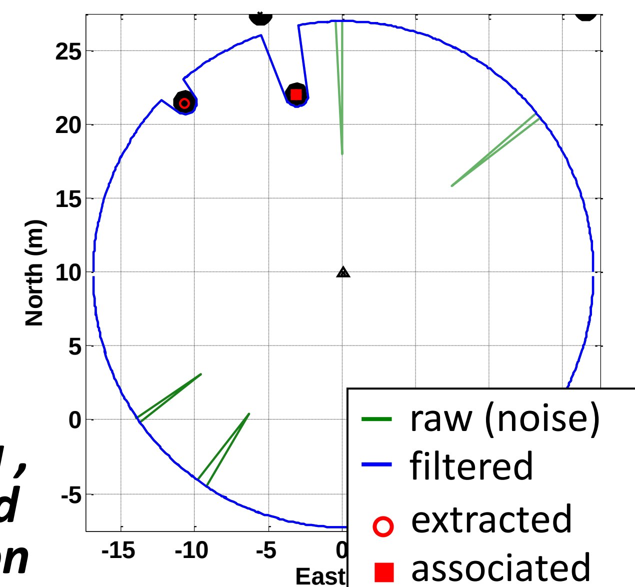
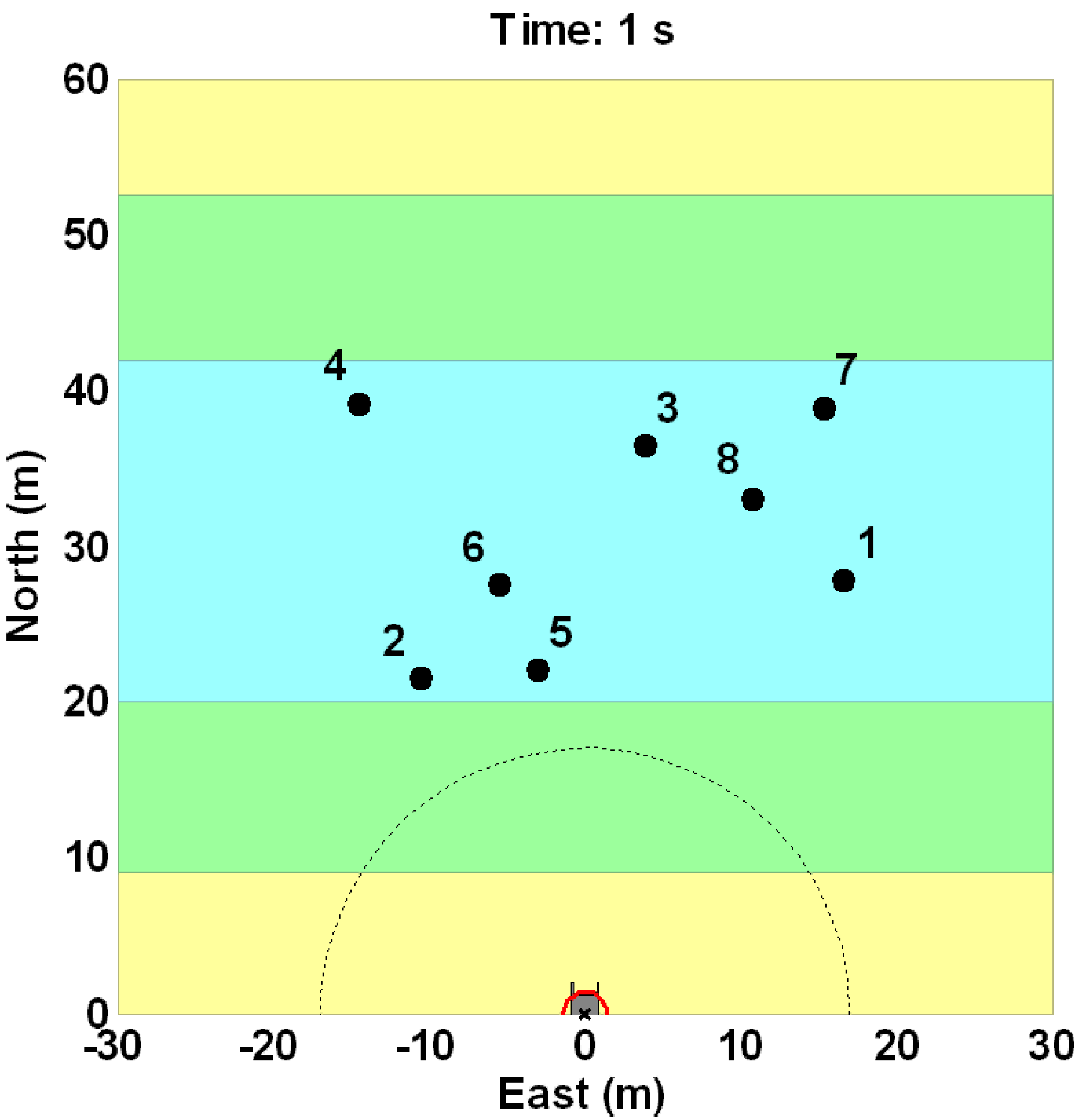


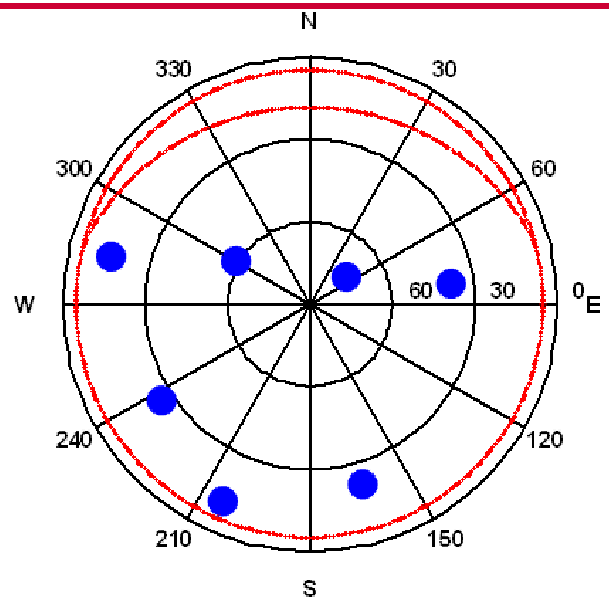


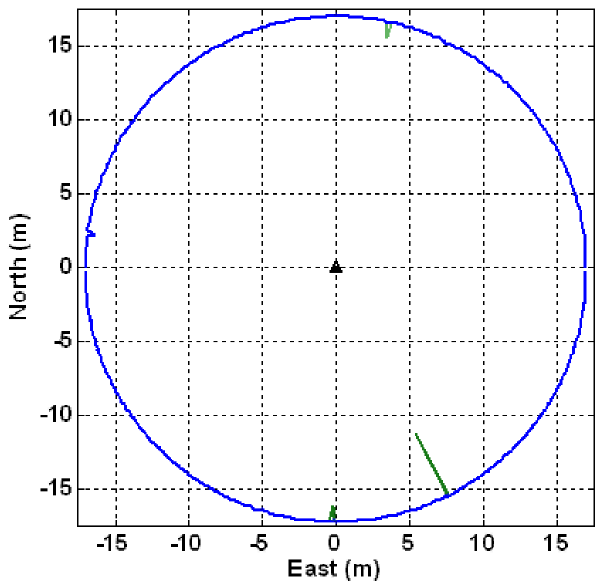


Simulated Laser Data , Extraction and Association

Direct Simulation of SLAM

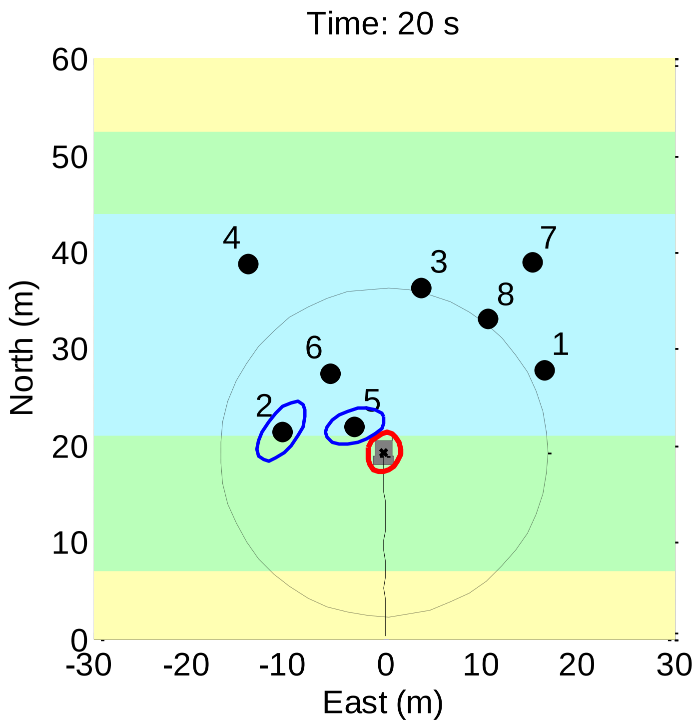


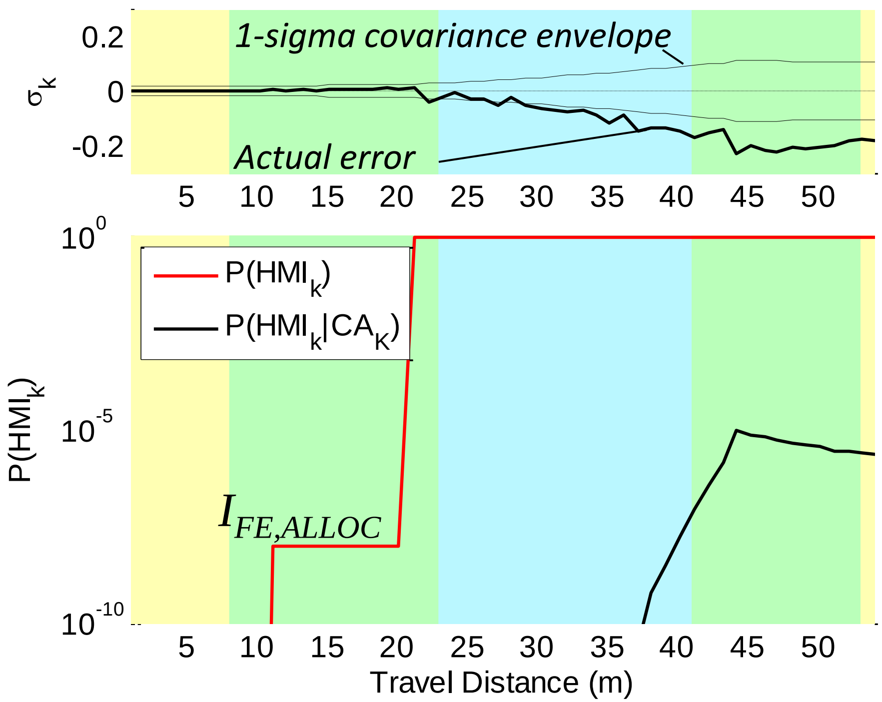




Integrity Risk Evaluation

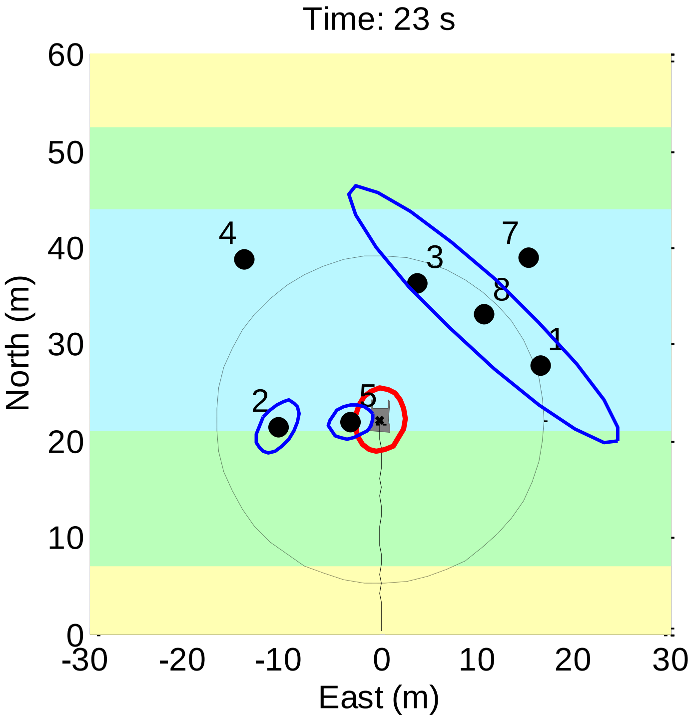
- The integrity risk bound accounting for possibility of IA is much larger than risk derived from covariance only
  - IA occur for landmark 6, which appears after being hidden behind 5

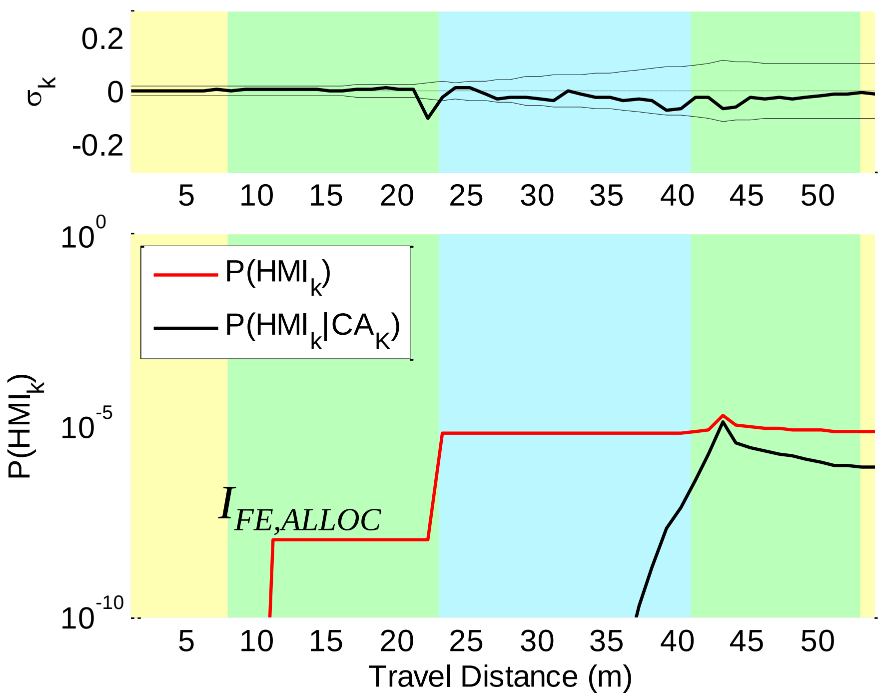




Leveraging Feature Extraction to Improve Integrity

- The paper uses a 'design parameter' to select landmarks:
  - **Key tradeoff: Fewer extracted features improve integrity** by reducing risk of incorrect association, but **reduce continuity**
  - Future work: **quantify continuity risk** due to feature selection





Conclusions

- Major challenges to analytical quantification APV navigation safety include
  - **safety** evaluation of **laser, radar, and camera**-based navigation
  - **multi-sensor** pose estimation, fault detection, and integrity monitoring
  - pose **prediction** in dynamic APV environment

- Analytical solution to APV navigation safety risk evaluation
  - could be used to set **safety requirements on individual sensors**
  - would provide design guidelines to **accelerate development of APVs**
  - would establish clear sensor-independent **certification** metrics

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Acknowledgment

- National Science Foundation (NSF)
  National Robotics Initiative (NRI)

  Award #1637899:
  “Receding Horizon Integrity—A New Navigation Safety Methodology for Co-Robotic Passenger Vehicles”