Receding Horizon Integrity: A New Navigation Safety Methodology for Co-Robotic Passenger Vehicles

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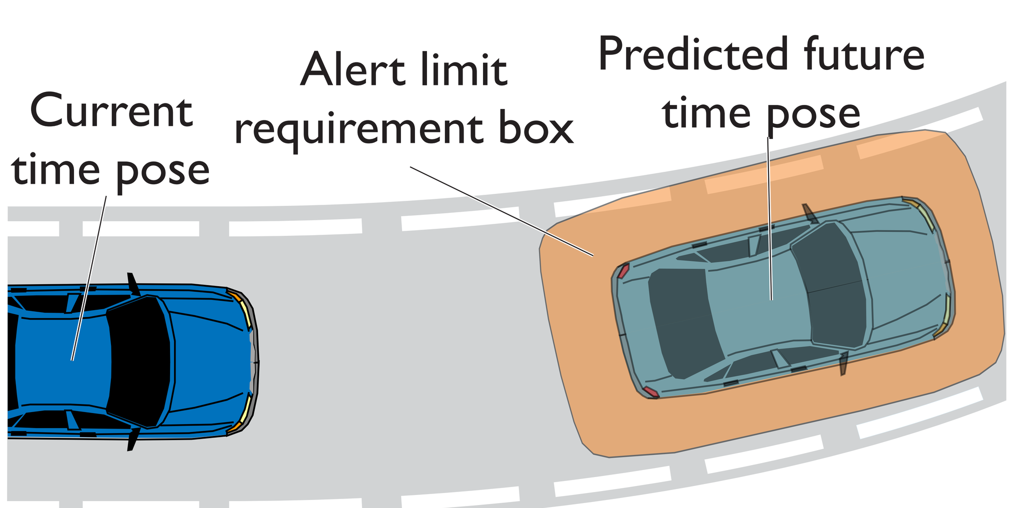
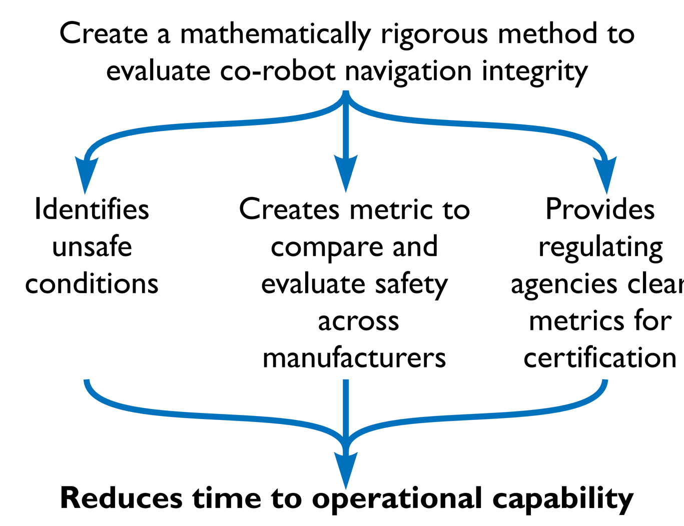
Goal: Quantify Co-Robot Safety

- Evaluate and guarantee localization **integrity**, a measure of **trust** in sensor information, valid even in the presence of **undetected faults**
- Used in aviation for decades (proven safety record)
- Quantifiable, sensor- and platform-independent



Impact: Accelerate Co-Robot Development

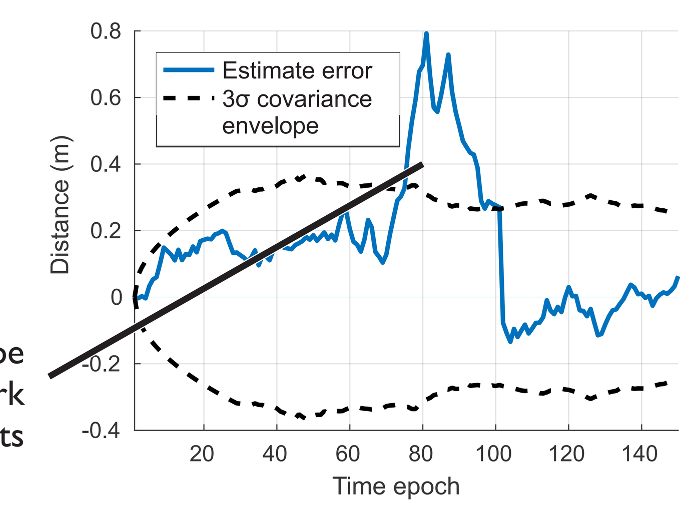
- Reduce accident rate, congestion, and emissions
- Current, experimental approaches to prove safety rely on billions of miles driven and require experiments to restart whenever significant changes in sensor or algorithm occur
- In contrast, our approach leverages analytical methods used in aviation safety



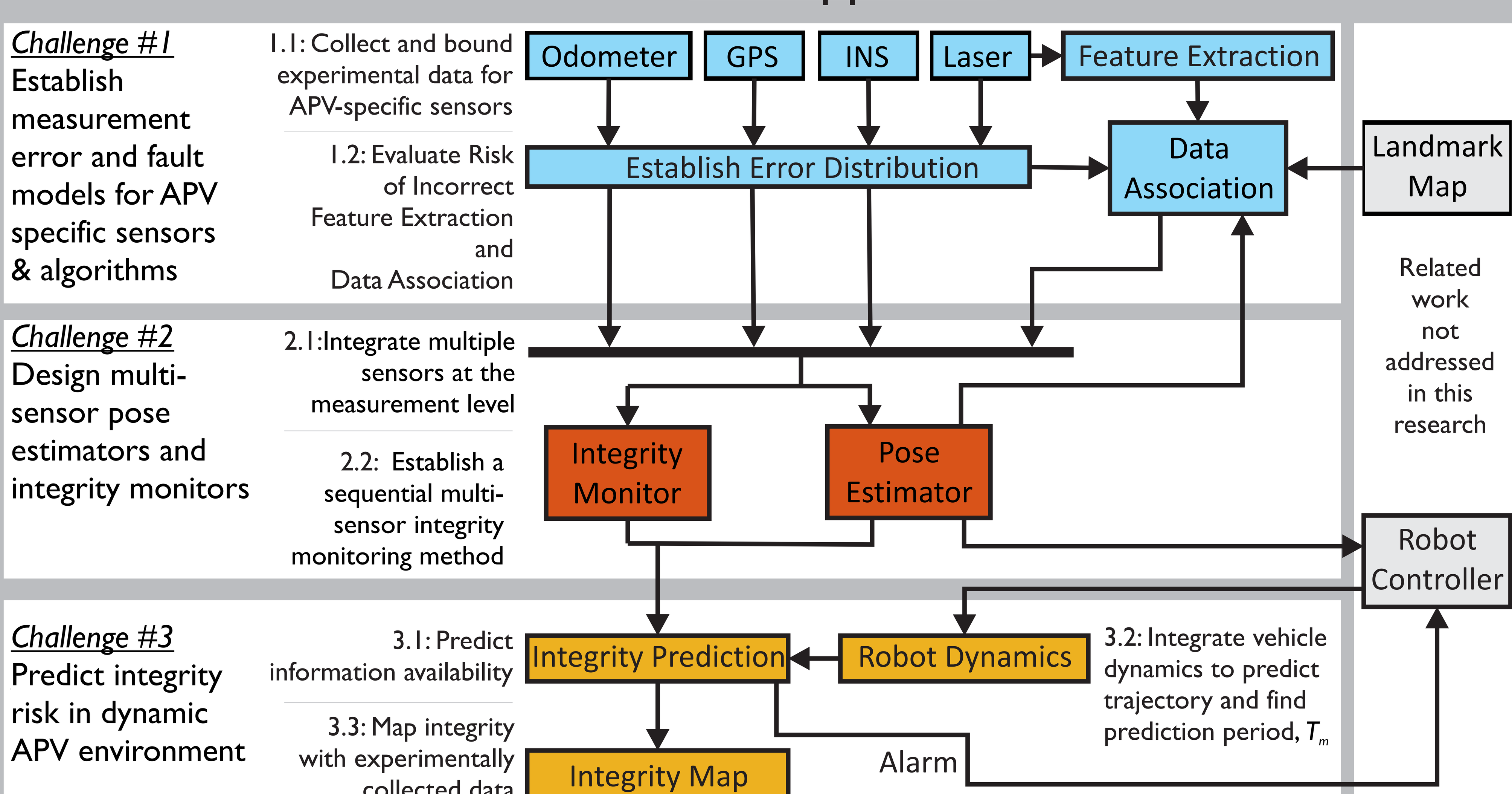
Unexplored Areas and Scope

- Quantify pose estimation performance in the presence of faults - contrast to traditional covariance matrix or particle spread
- Multi-sensor integrity monitors to evaluate impact of undetected sensor fault on safety risk
- Experimental integrity risk prediction in dynamic environments

Traditional covariance envelope fails to capture feature/landmark association faults



The Approach



Background

- Safety risk ≡ risk of Hazardous Misleading Information (HMI):

$$HMI_k \equiv \left\{\boldsymbol{\alpha}^T \hat{\boldsymbol{\epsilon}}_k > \ell\right\} \cap \left\{q_D < T_D\right\}$$

Time; Selects state of interest; Pose error; Specified *alert limit* defines acceptability on error; Detector; Specified *detector threshold*

- Evaluated under fault-free and faulted conditions:

$$P\left(HMI_k\right) = P\left(HMI_k, NF\right) + P\left(HMI_k, F\right)$$

Probability of HMI and having no faults; Probability of HMI and having at least one fault

- Impossible to solve $P(HMI)$, therefore upper bound:

$$P\left(HMI\right) \leq \check{P}\left(HMI\right) \leq I_{REQ}$$

A predefined integrity risk requirement

Current Work - Bound the Integrity Risk of Missassociations in the Feature Extraction/Data Association Process

Calculated using estimate error variance

$$P\left(HMI_k\right) \leq 1 + \left(P\left(HMI_k | CA_K\right) - 1\right) P\left(CA_K\right)$$

Probability of a correct association

In this portion of the work, we account for missassociations in the data association process between extracted features and landmarks on a map (e.g. feature A gets associated with landmark B and feature B gets associated with landmark A).

Bound on the probability that the lower bound on the separation between landmarks is larger than the actual separation

Accounts for the separation among landmarks - more separation increases $P(CA)$

$$P\left(CA_K | CA_{K-1}\right) \geq 1 - n_{FoV} + \left(1 - \frac{I_y}{n_{FoV}}\right) \sum_{l=1}^{n_{FoV}} \chi^2_{m+m_F} \left[\frac{1}{4} \left\|\mathbf{y}_l^*\right\|^2_{\mathbf{Y}_{i_l}^{-1}}\right]$$

Number of landmarks in the field of view - more landmarks decreases the probability of correct association

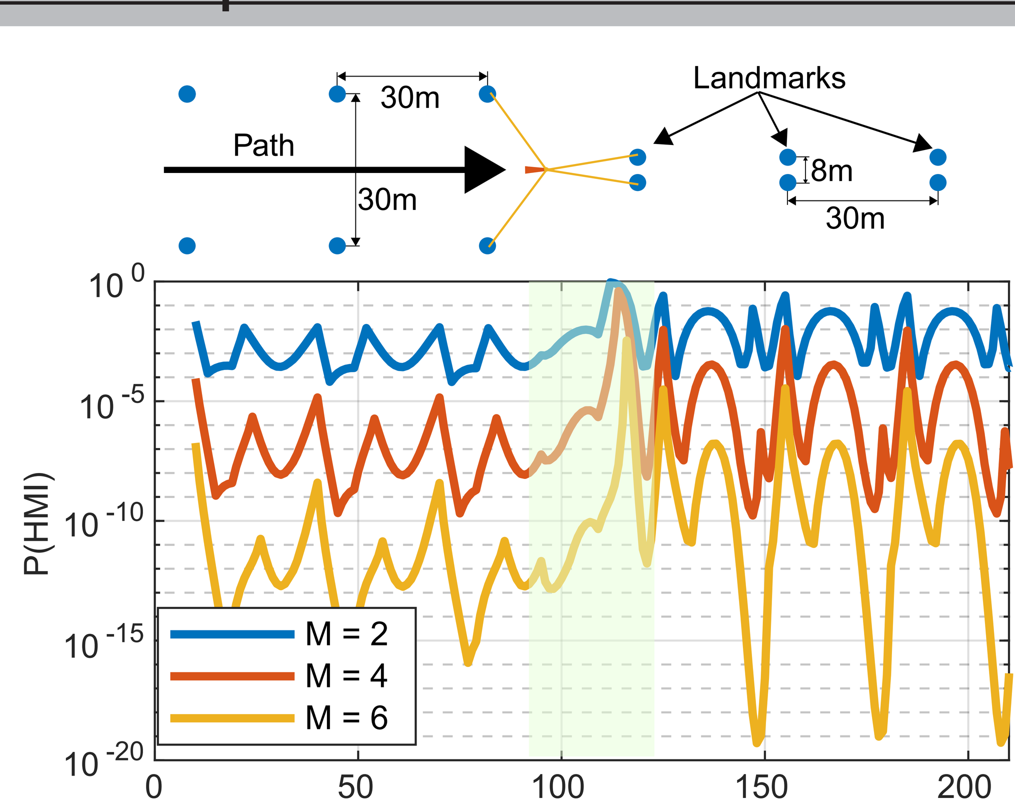
More landmarks increases $P(CA)$

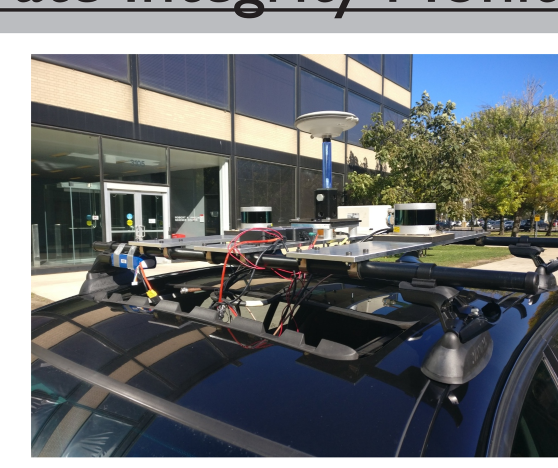
Chi-squared distribution emerges from the Gaussian sensor and Kalman filter noise

Current Work - Simulation and Experimental Results Demonstrate Integrity Monitoring and Integrity-Risk Constrained MPC

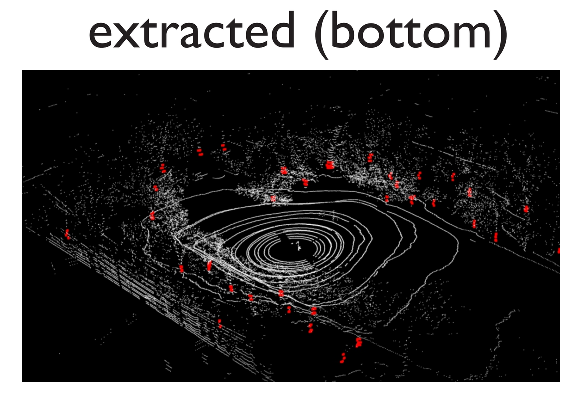
Here, we use a preceding horizon and a fault detector to monitor wrongly extracted features.

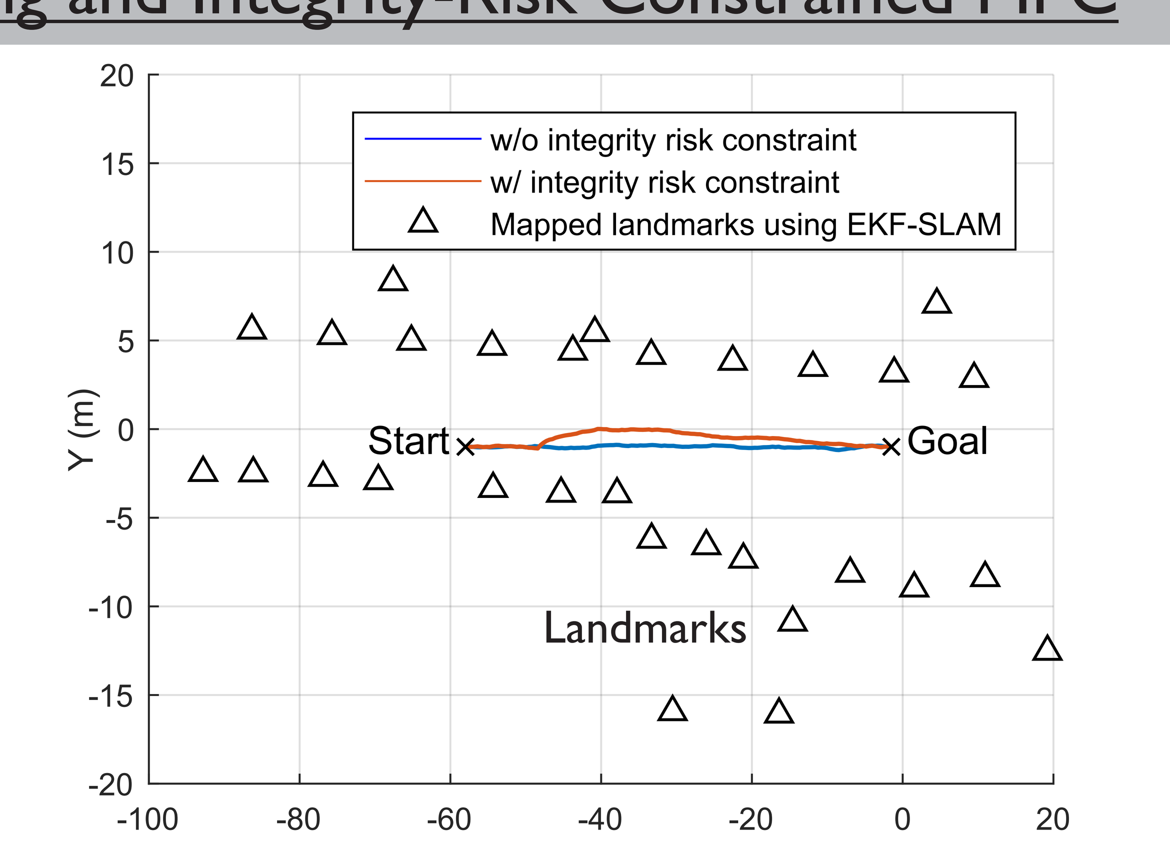
Simulation results show a robot moving from left to right in a map with two sections: landmarks laterally spaced 30m and 8m apart. The lateral pose integrity risk for three preceding horizon sizes shows the smallest horizon (M=2) has the largest integrity risk since a longer preceding horizon offers better fault monitoring capabilities. Integrity risk peaks at the transition between the two sections, (epochs≈100–120), as the relative geometry cannot ensure lateral position with high confidence.





GPS, IMU, and lidar experimental setup (top) and example lidar point cloud with features extracted (bottom)





Integrity-risk constrained model predictive control (MPC) shows how a robot will decrease its integrity risk by moving away from landmarks that are ill-separated