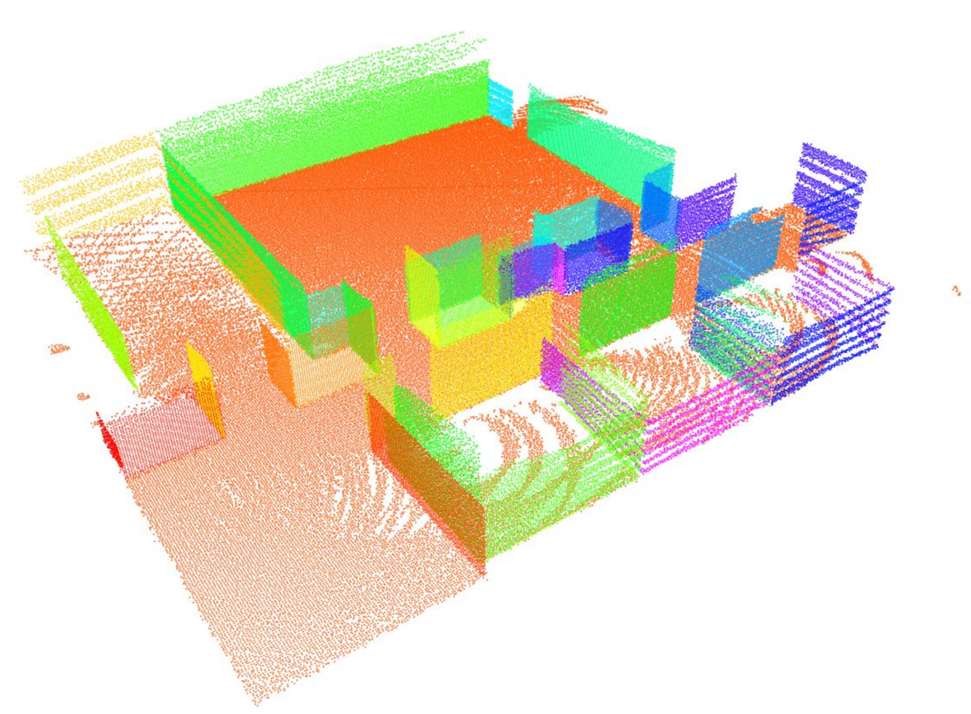
LIPS: LiDAR-Inertial 3D Plane SLAM

Patrick Geneva, Kevin Eckenhoff, Yulin Yang, and Guoquan Huang

University of Delaware, USA

Motivation

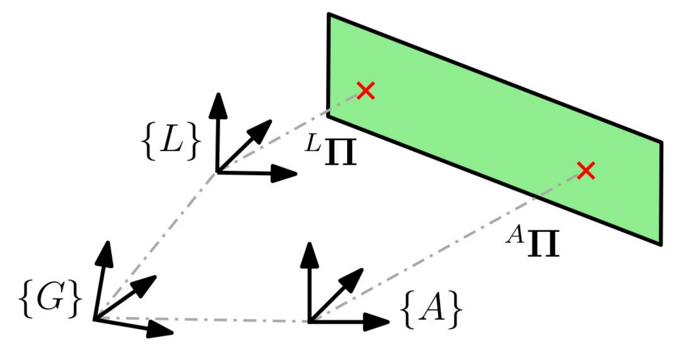
- Want to combine higher level primitives (e.g., planes) in structured environments
- Take advantage of LiDAR and IMU sensors
- Address representation for plane primitives



Closest Point Rep.

$$^G\mathbf{\Pi} = {}^G\mathbf{n}\, {}^Gd$$

$$\begin{bmatrix} {}^G\mathbf{n} \\ {}^Gd \end{bmatrix} = \begin{bmatrix} {}^G\mathbf{\Pi}/\|{}^G\mathbf{\Pi}\| \\ \|{}^G\mathbf{\Pi}\| \end{bmatrix}$$



$$^L\mathbf{\Pi}(\mathbf{x}) = \left({}^L_A\mathbf{R}\, {}^A\mathbf{n}\right)\left({}^Ad - {}^A\mathbf{p}_L^\top\, {}^A\mathbf{n}\right)$$

- Represent plane as the "closest" point on the plane to the current frame
- Minimal error state (3D point) is in Euclidean space
- Map from a frame {A} to frame {L} using the Hesse representation

Plane Compression

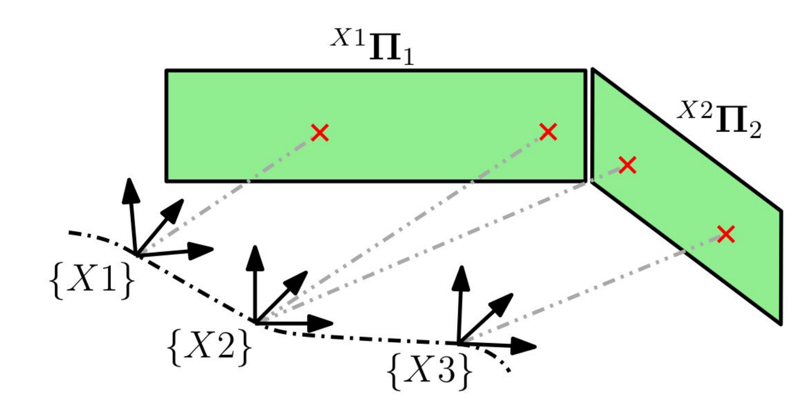
$$^L\mathbf{p}_{mi} = {}^L\mathbf{p}_i + \mathbf{n}_p, \quad \mathbf{n}_p \sim \mathcal{N}(0, \mathbf{R}_d)$$

$$^L\mathbf{\Pi}^* = \underset{^L\mathbf{\Pi}}{\text{argmin}} \sum_i \left\| \frac{^L\mathbf{\Pi}^\top}{\|^L\mathbf{\Pi}\|}\, {}^L\mathbf{p}_{mi} - \|^L\mathbf{\Pi}\| \right\|^2_{W_i^{-1}}$$

- Compress a set of points that correspond to a planar surface into a closest point plane
- This gives us the measurement $^L\hat{\mathbf{\Pi}}$ which is a direct reading of the plane from the current local frame {L}
- Compression allows for us to also get the covariance of the measurement for SLAM

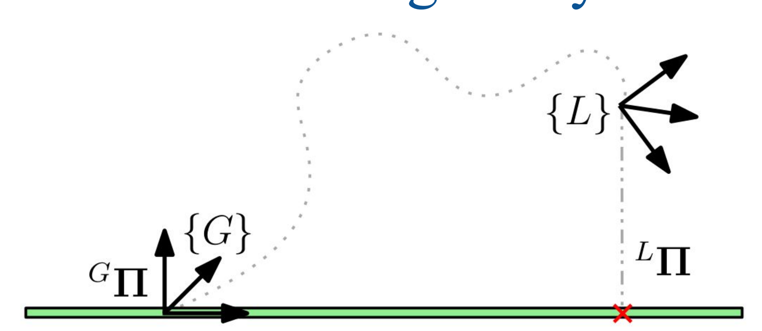
$$\mathbf{P}_\Pi = \left(\sum_i \mathbf{J}_i^\top\, W_i\, \mathbf{J}_i\right)^{-1}$$

Anchor Plane Factor



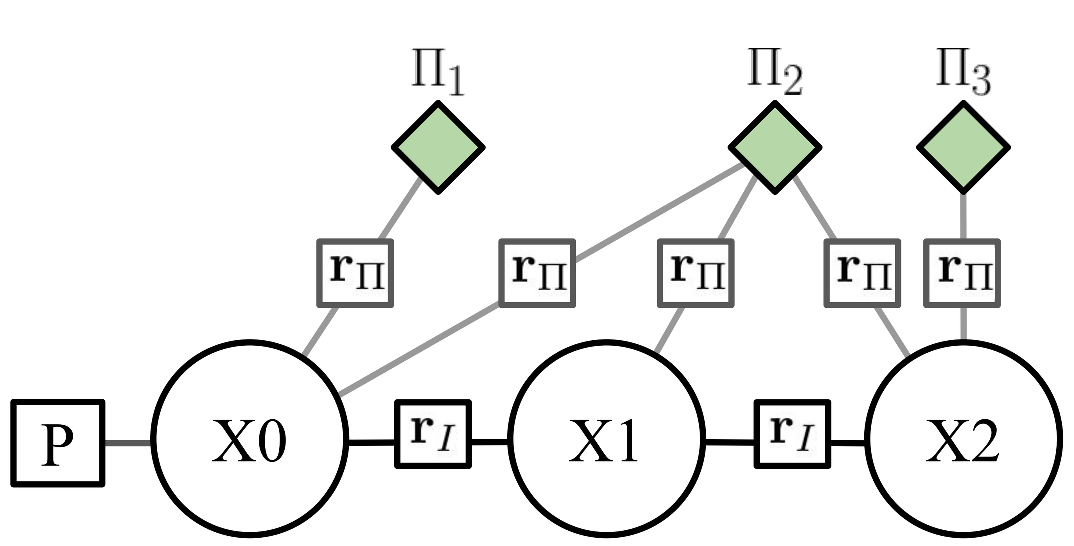
$$r_\Pi(\mathbf{x}) = {}^L\mathbf{\Pi}(\mathbf{x}) - {}^L\hat{\mathbf{\Pi}}$$

- Plane is represented from the frame it was first seen from (i.e., the "anchor" frame)
- This avoids the singularity when d=0



LiDAR Inertial Graph

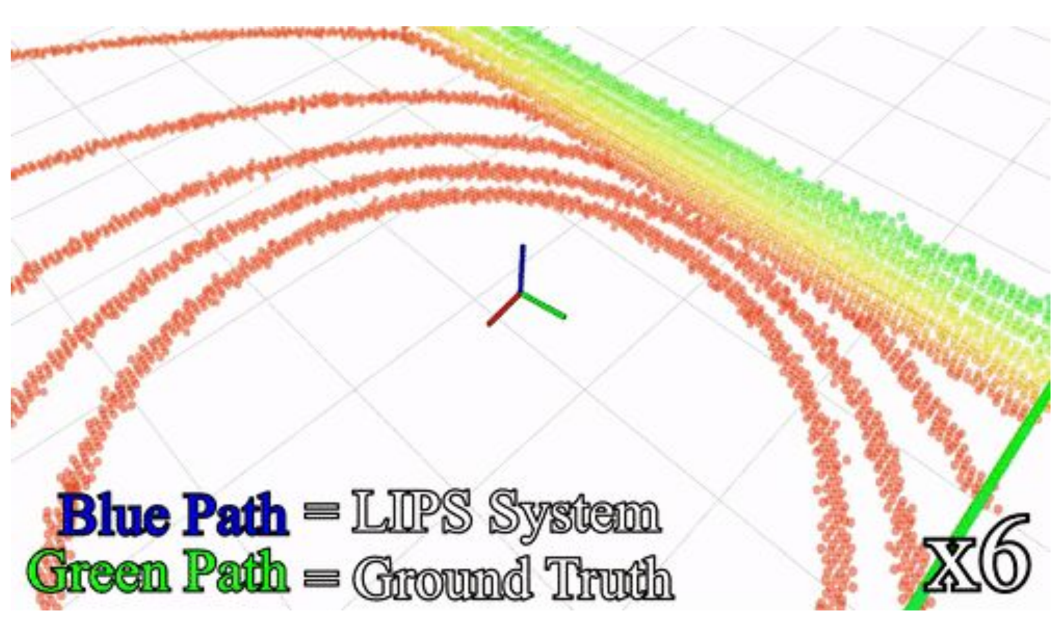
- Leveraged continuous IMU preintegration [Eckenhoff 2018]
- Open Sourced: https://github.com/rpng/cpi
- Extracted planar pointclouds are compressed into the Closest Point (CP) representation
- Jointly optimized with iSAM2 [Kaess 2012]

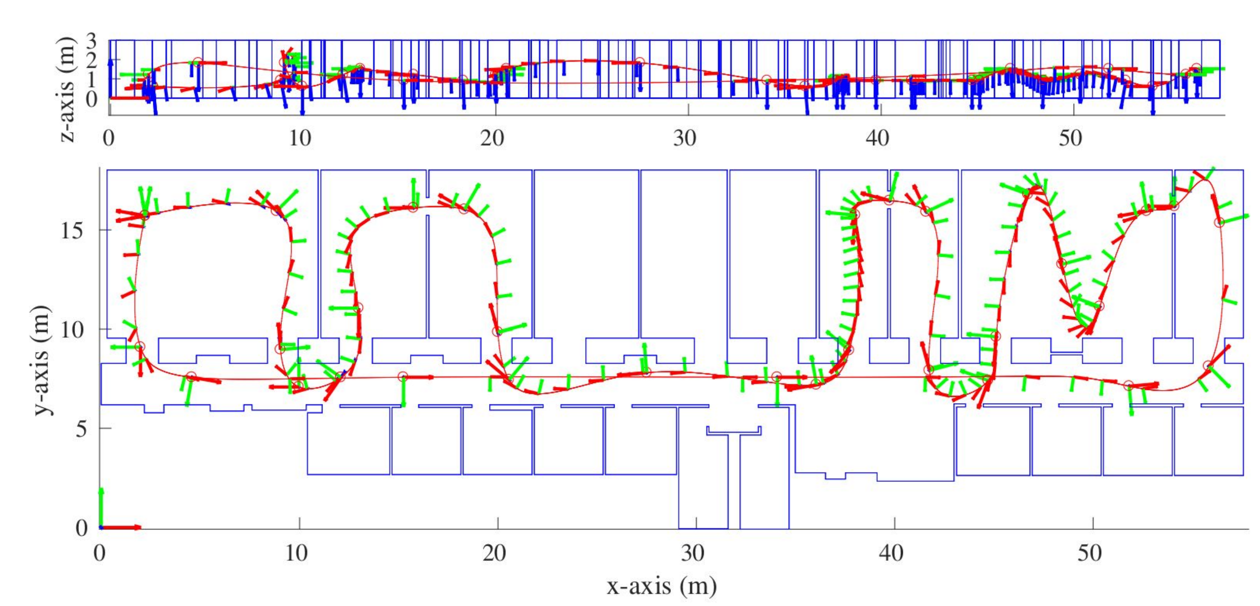


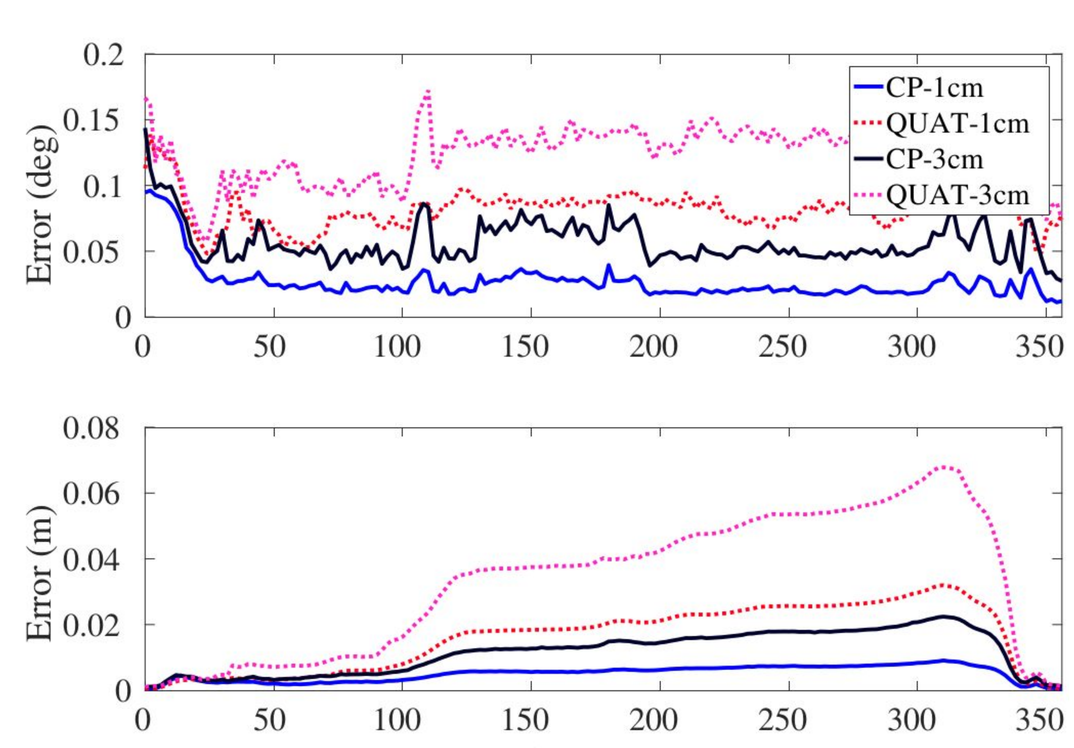
$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\text{argmin}} \left[\sum_i \|\mathbf{r}_{Ii}(\mathbf{x})\|^2_{\mathbf{R}_{Ii}} + \sum_j \|\mathbf{r}_{\Pi j}(\mathbf{x})\|^2_{\mathbf{R}_{\Pi j}} \right]$$

Continuous Preintegration — Closest Point Anchor Factors

Simulation Results

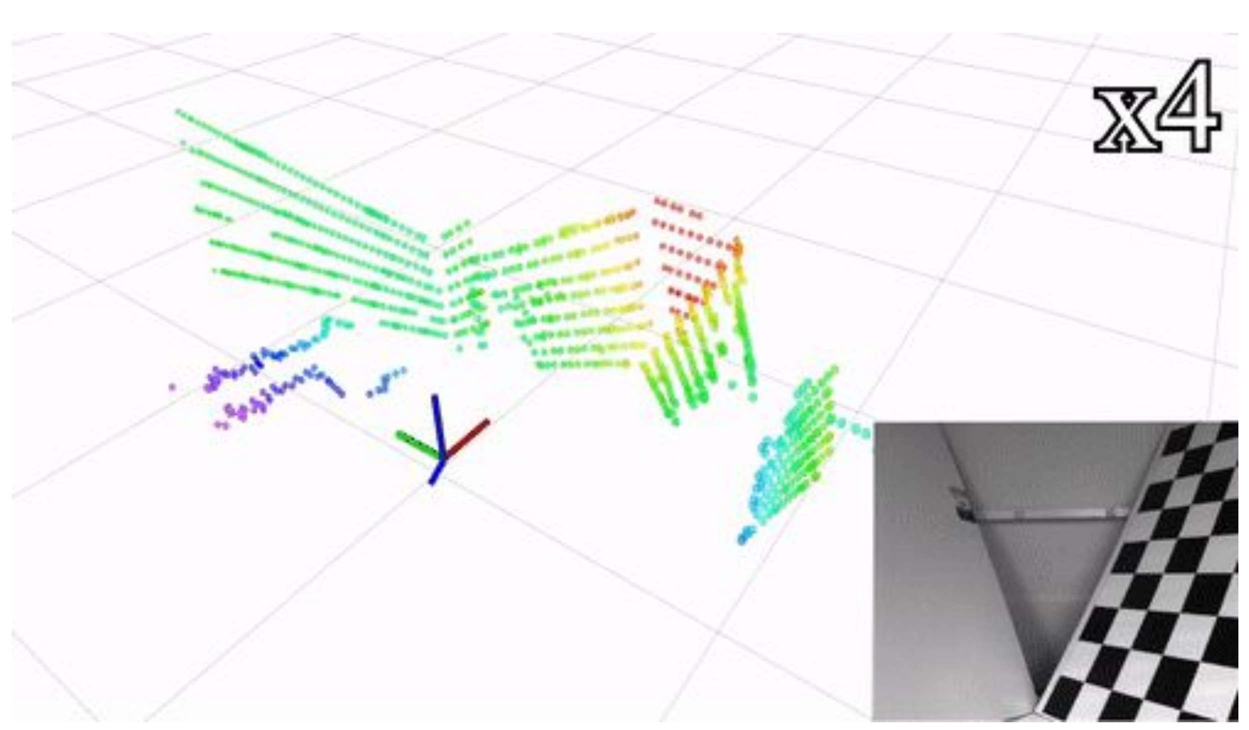






- Custom LiDAR inertial simulator was used to generate 180m long trajectory
- Open Sourced: https://github.com/rpng/lips
- Compared against quaternion plane representation [Kaess 2015]
- Analytical Jacobians for both representations were used for fair evaluation [see technical report]

Realworld Results



Conclusion

- Closest Point (CP) representation allows for minimal error states and improved performance
- Fused CP planes with IMU continuous preintegration in a graph-based setting
- Verifies LIPS with simulation and realworld experiments