Formally Correct Deep Perception For Cyber-Physical Systems

LiDAR localization with guarantees

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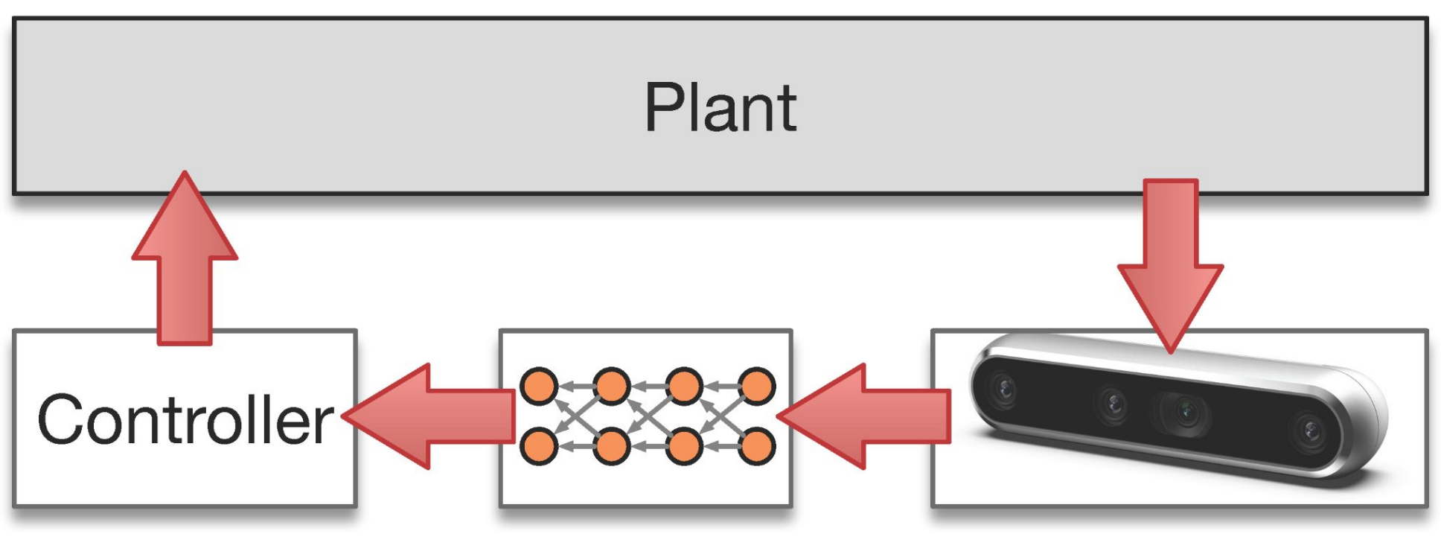
Context

- The **perception** pipeline of autonomous systems increasingly relies on deep learning methods, that provide **no formal guarantees** of correctness or performance.



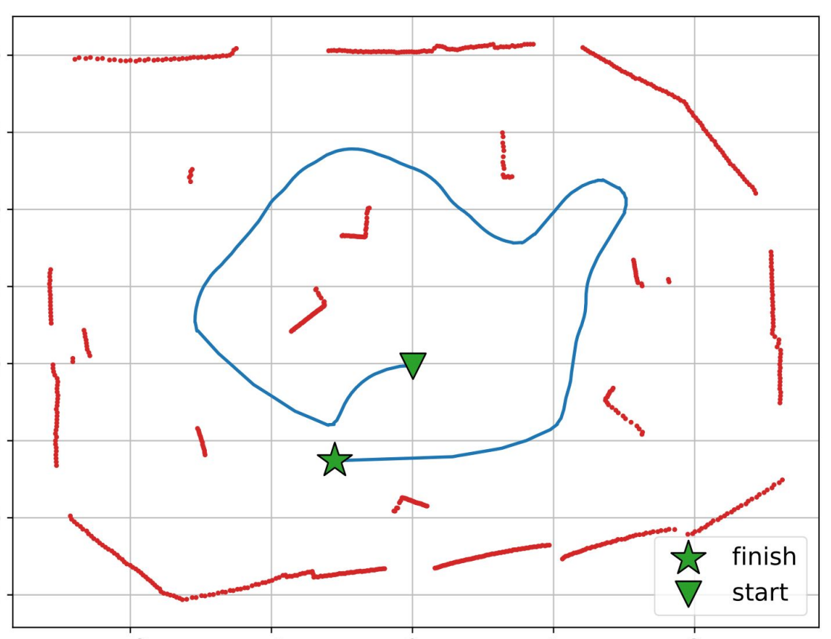
- We aim to provide such guarantees, in two possible ways:
  - proving **deterministic worst-case bounds** on learning models;
  - using a **supervisor** to correct the learning method when needed (this poster).
- Meeting our goals will have major impact by:
  - boosting the adoption of **provably safe** autonomous cars, UAVs, and other autonomous platforms..
  - **reducing risks** associated with existing autonomous vehicles
  - introducing new graduate courses and on the **intersection of learning and control**.

Problem

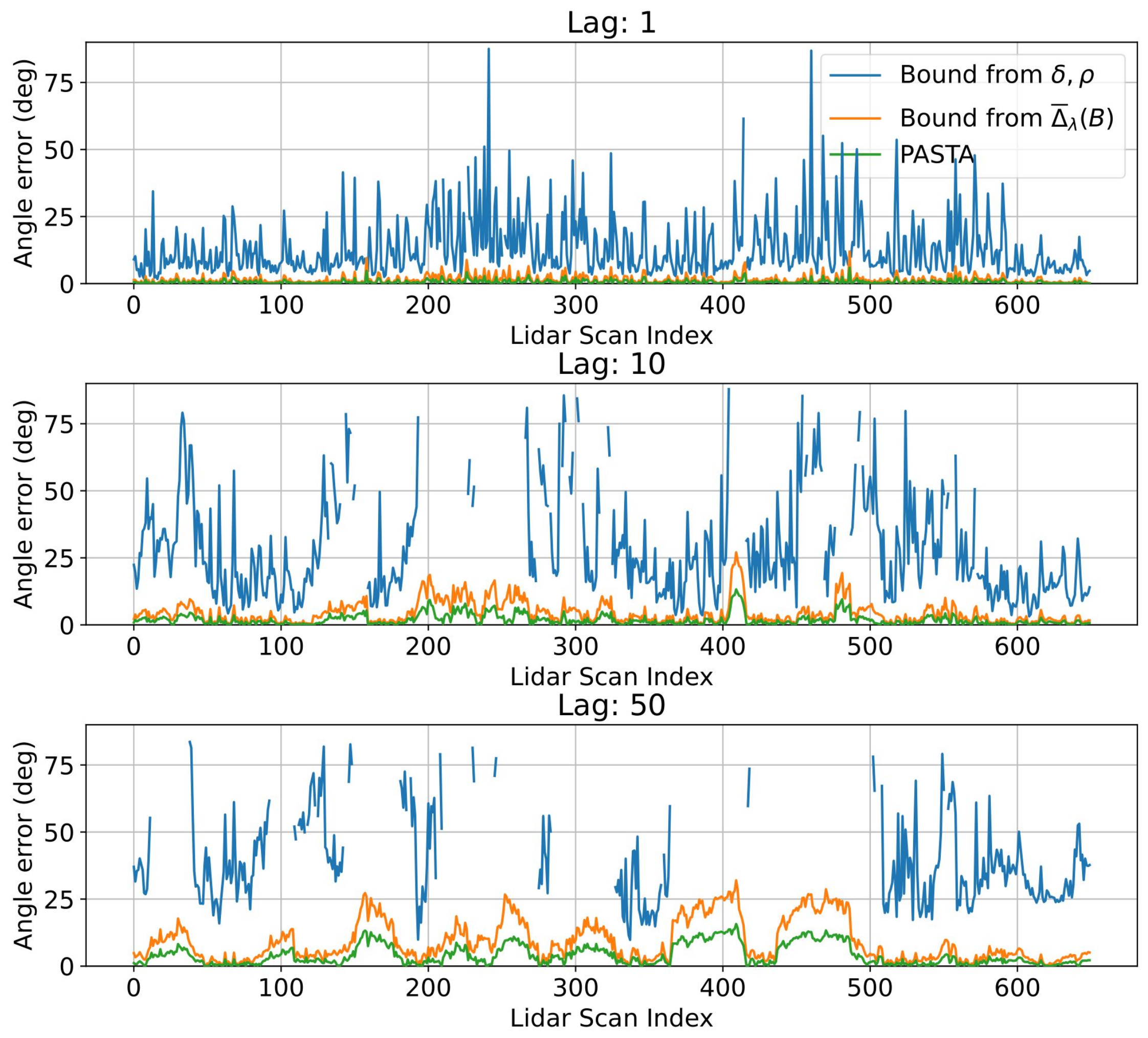
- **Point cloud registration** (relating two LiDAR scans from different poses) is a key step in localization/SLAM.
- We want a reliable way to perform ***global*** registration. I.e., no "good initialization" should be required for correctness.
- Existing algorithms are ***local*** and need point correspondences, which may not exist in LiDAR point cloud.

Error Bounds in Practice

- We verify our improved theoretical bounds experimentally.



- A robot moves in an environment with **multiple obstacles** while recording point clouds with a 2D LiDAR.



- We align pairs of point clouds collected a “**lag**” number of samples apart with PASTA, and calculate the resulting **error bound** for different lags.
- Greater lag means **lower overlap δ** between the point clouds. The bound **degrades gracefully** as lag increases.

Algorithm

- We previously developed a registration algorithm named **PASTA** [1] (Provably Accurate Simple Transformation Alignment).
- It is **fast** and comes with worst-case **guarantees**.

```
Algorithm 1 PASTA
Input: Point clouds $\{\mathbf{r}_1^{(i)}\}_{i=1}^{m_1}$, $\{\mathbf{r}_2^{(i)}\}_{i=1}^{m_2}$
Output: Transformation $\hat{\mathbf{R}}, \hat{\mathbf{p}}$
  for each point cloud $i$ do
    $H_i \leftarrow$ convex hull of $\{\mathbf{r}_i^{(j)}\}_{j=1}^{m_i}$
    $\mathbf{c}_i, \mathbf{\Sigma}_i \leftarrow$ first and second moments of $H_i$
  end for
  $\hat{\mathbf{R}} \leftarrow$ closed-form solution of $\mathbf{\Sigma_2} = \mathbf{R}\mathbf{\Sigma}_1\mathbf{R}^T$
  $\hat{\mathbf{p}} \leftarrow$ closed-form solution of $\mathbf{c}_2 = \mathbf{R}\mathbf{c}_1 + \mathbf{p}$
```

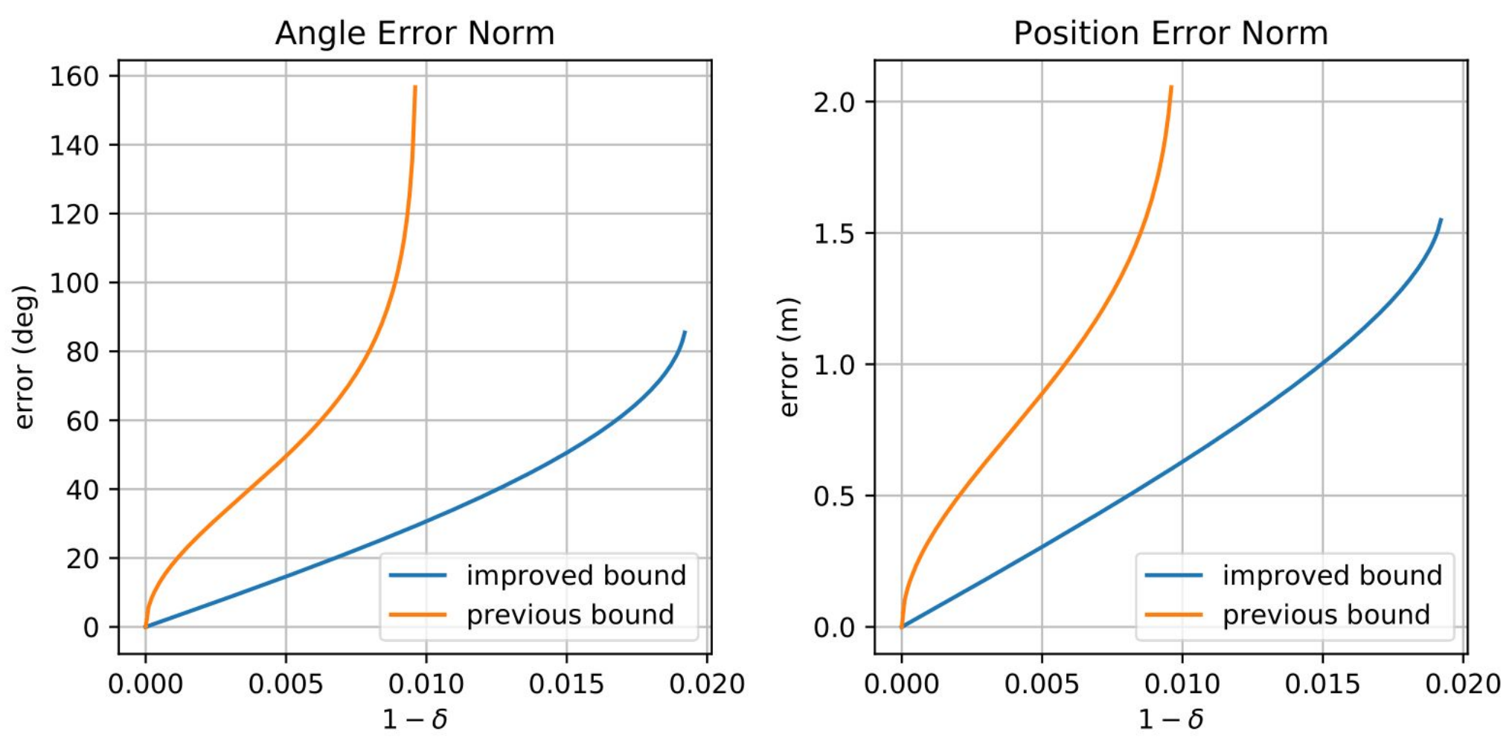
Formal Guarantees

- While we already proved that PASTA enjoys formal deterministic **error bounds**, any improvement in the tightness is very important in practice.
- In [2] we massively **tightened** the provable bound, resulting in the **theorem** to the right (**δ** describes the overlap of the two point clouds).
- The new bound **scales substantially better** with the overlap, especially in the regime of high **δ** (low 1-**δ** in the plot to the right).

Theorem: Given an environment size ***ρ*** and overlap **δ**, the error between PASTA’s estimate and the true transformation is bounded:

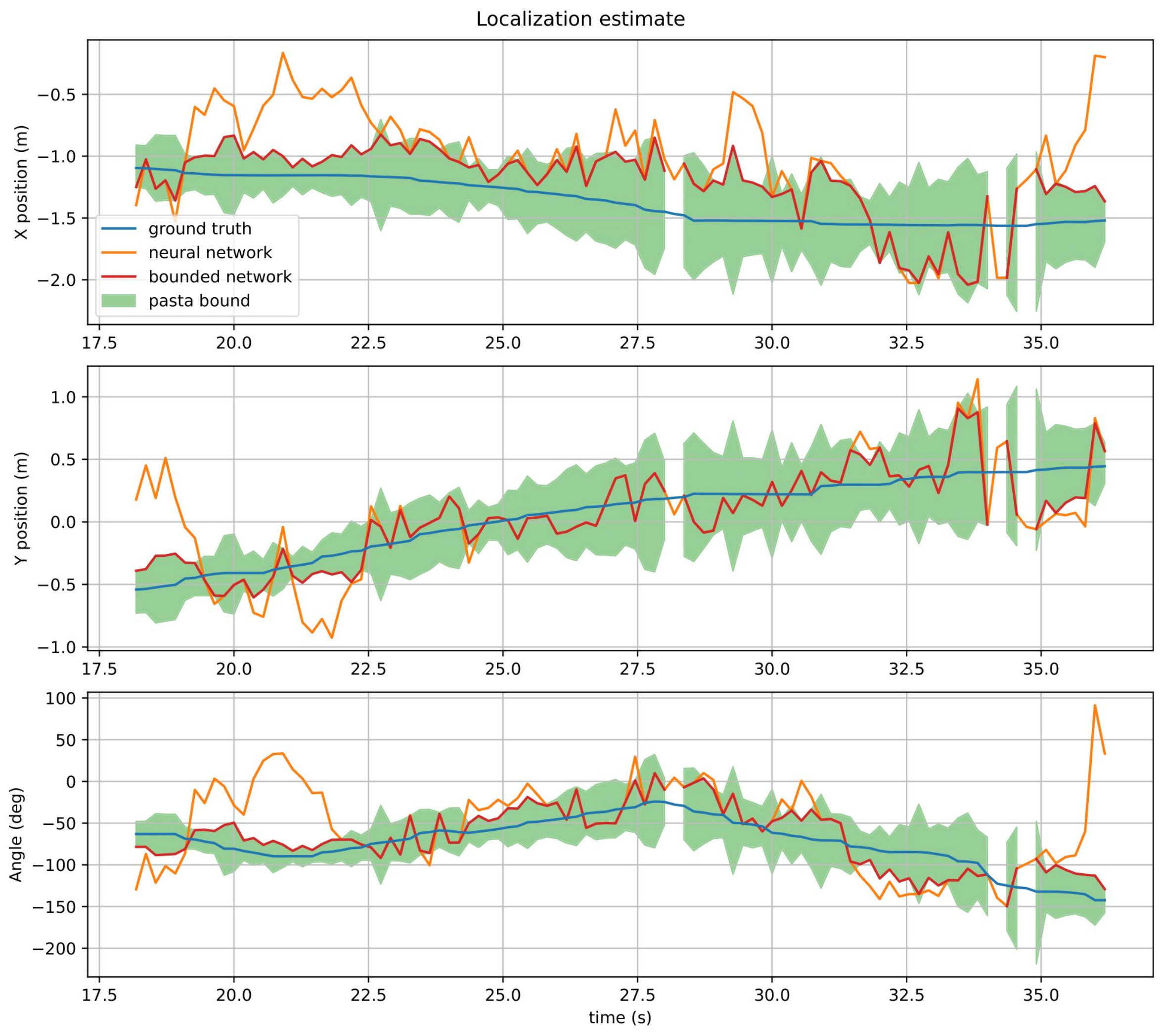
$$\|\hat{\mathbf{R}} - \mathbf{R}\| \leq \sqrt{n}\frac{e_\Sigma(\rho, \delta)}{\min_{i \neq j}|\lambda_i - \lambda_j|}$$

$$\|\hat{\mathbf{p}} - \mathbf{p}\| \leq \sqrt{n}\frac{e_\Sigma(\rho, \delta)}{\min_{i \neq j}|\lambda_i - \lambda_j|}\mathbf{c} + e_c(\rho, \delta).$$



PASTA Supervised Neural Network

- We train a **neural network** to perform localization using point clouds as input, and test it on the trajectory data we collected.



- PASTA and its bound act as a **supervisor** for the neural network.
- The neural network has good average performance, but sometimes behaves poorly. The **PASTA supervisor bounds the network’s output**, maintaining a limited worst-case error.

[1] M. Marchi, J. Bunton, B. Gharesifard, P. Tabuada. "LiDAR Point Cloud Registration with Formal Guarantees." IEEE 61st Conference on Decision and Control. 2022.

[2] M. Marchi, J. Bunton, Y. Gas, B. Gharesifard, P. Tabuada. “Sharp Performance Bounds for Pasta”. IEEE Control Systems Letters. 2023.

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