Robust LiDAR-Inertial Localization with Prior Maps in GNSS-Challenged Environments

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Motivation

Autonomous robots require accurate localization in GPS-denied environments like indoors or urban canyons.GNSS-INS systems are prone to failure in these conditions, while real-time SLAM often drift without loop closures

Map-based localization offers a stable and accurate alternative, but it faces several key challenges:

- **Real-time performance and Scalability**: Handling high-resolution 3D maps and computing scan-to-map registration efficiently.
- **Drift correction**: Fusing local motion estimation with global map constraints while preserving consistency.
- **Dynamic environments**: Removing or mitigating the effect of moving objects during scan matching.
- Localization failures in feature-sparse or unmapped transition zones.

Contribution

This thesis presents a robust and real-time localization framework for GNSS-denied environments by fusing LiDAR-Inertial Odometry (FAST-LIO2) with multithreaded NDT-based map matching using a sliding-window factor graph. It introduces a scalable submap management strategy and integrates dynamic object removal via deep learning, enabling consistent pose estimation even in dynamic, degraded, or feature-sparse areas. The system achieves centimeter- to decimeter-level accuracy across diverse datasets, maintaining low-latency performance suitable for real-world autonomous navigation. Extensive evaluations show that the proposed method not only surpasses standalone odometry and SLAM baselines but also outperforms recent state-of-the-art map-based localization approaches in accuracy, robustness, and scalability.

Methodology

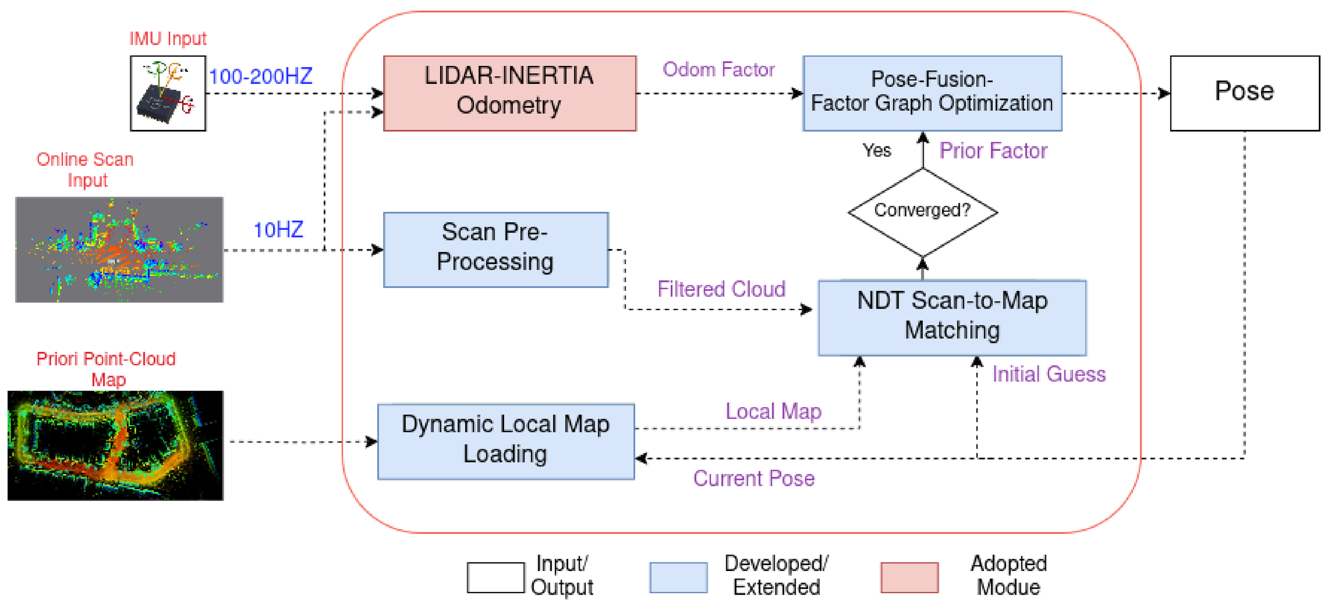
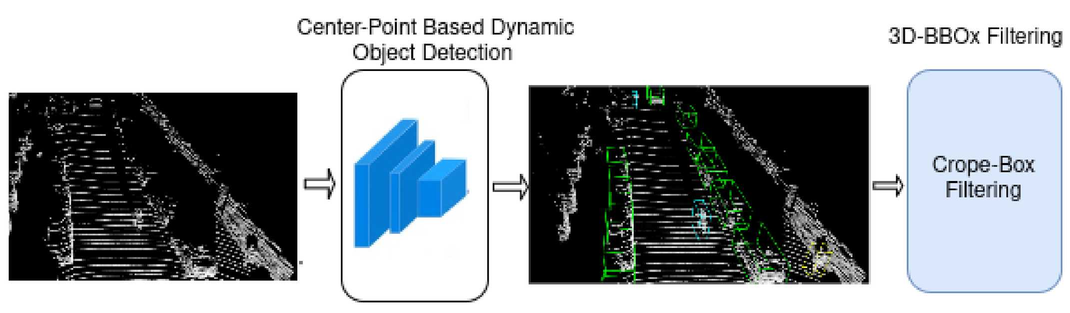


Figure 1: Complete Diagram of The Localization System

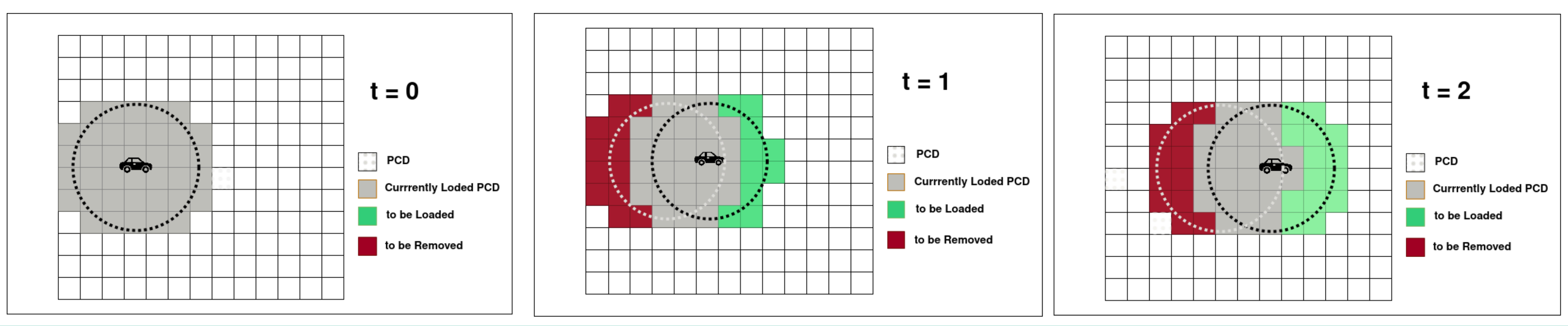
Scan Pre-Processing

Dynamic objects are removed from LiDAR scans using a deep learning-based 3D detector (CenterPoint) to improve scan-to-map alignment.



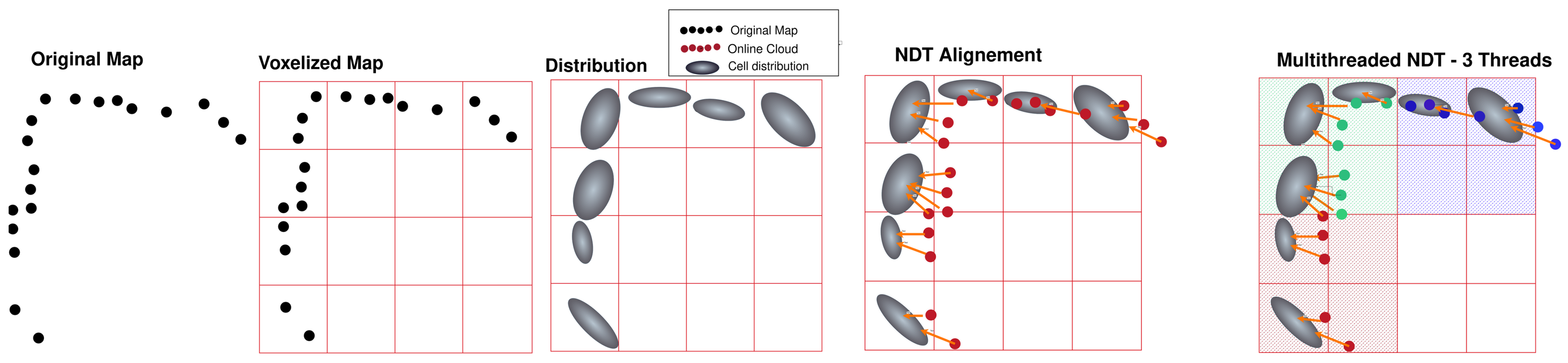
Local Map Loading

loads only relevant submaps based on the robot's estimated position



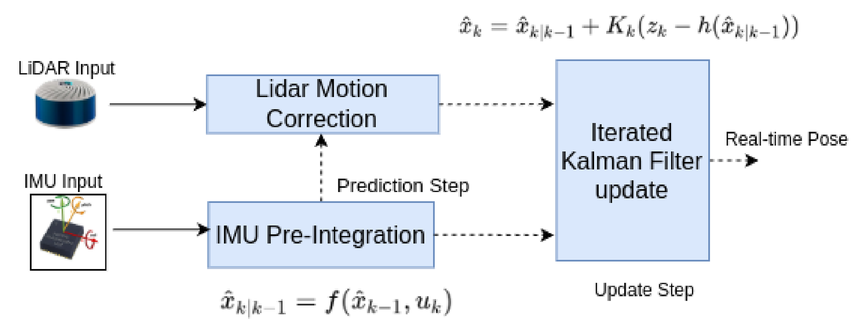
Scan-to-Map Matching

multithreaded implementation of the Normal Distributions Transform (NDT) used to accelerate scan-to-map matching



Local Motion Estimation

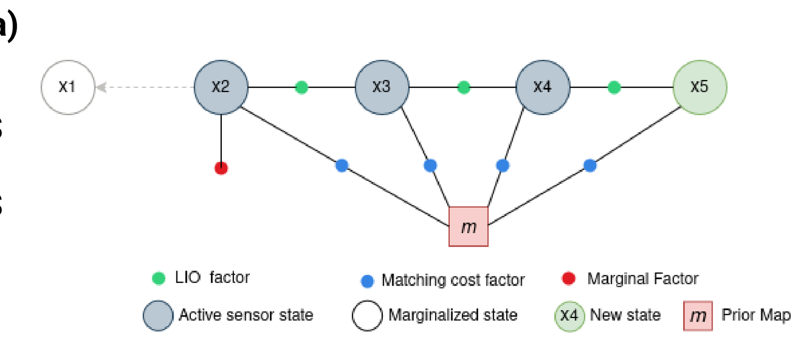
FAST-LIO2 based LiDAR-Inertial Odometry for real-time local pose estimation.



Sliding Window Pose-Graph Optimization

Odometry poses from FAST-LIO2 are added as relative motion and Scan-to-map corrections from inserted as absolute pose factors.

a)



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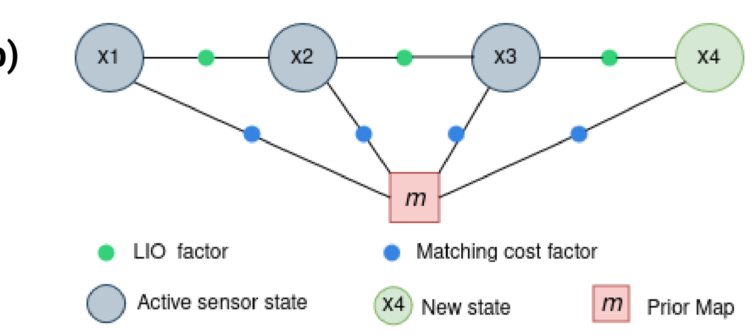

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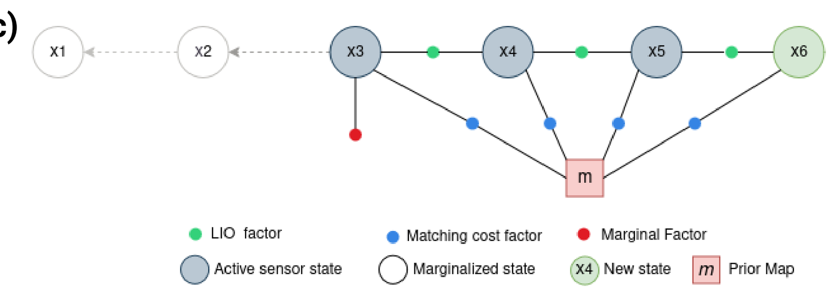


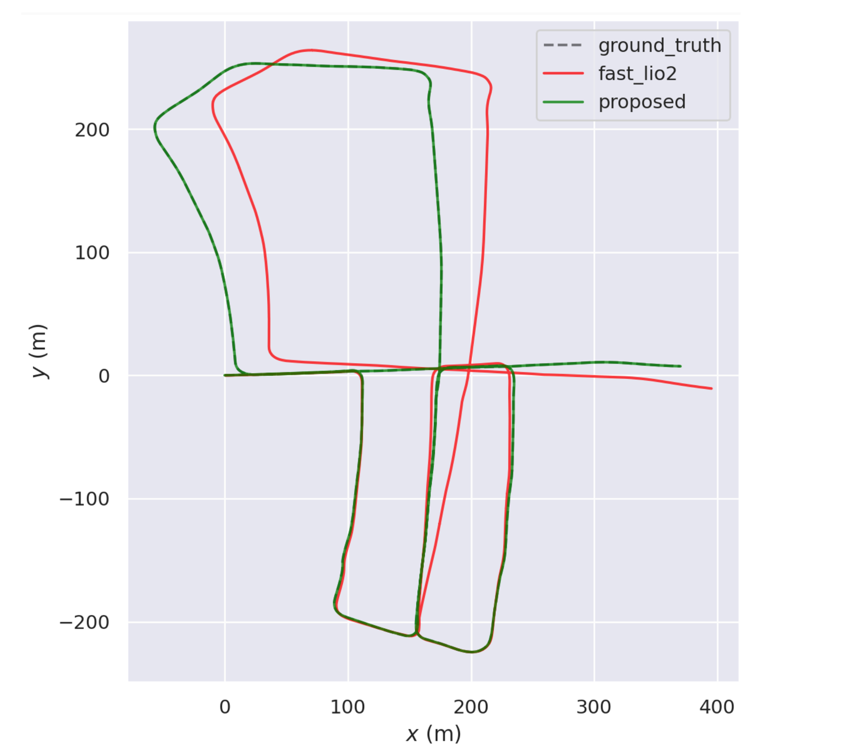
Experimental Results

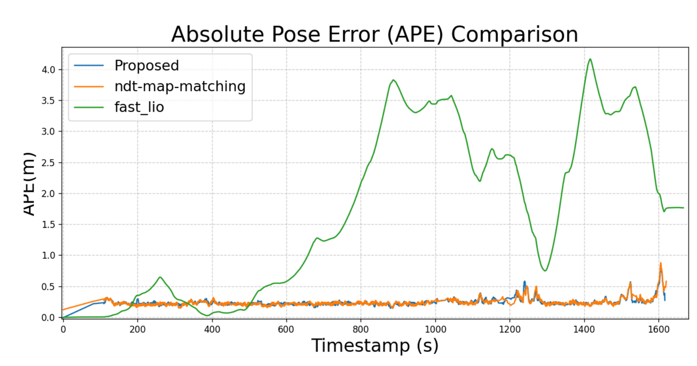
Comparison with baseline methods: LIO exhibits high drift over time while proposed method acheives both low localization error and high temporal consistency.

Method	Metric	Sequence 2 Max	Sequence 2 RMSE	Sequence 2 Mean ± Std	Sequence 3 Max	Sequence 3 RMSE	Sequence 3 Mean ± Std
Proposed	APE (m)	0.44	**0.11**	0.09 ± 0.06	0.82	**0.14**	0.10 ± 0.09
	Rot. (deg)	4.36	**1.05**	0.78 ± 0.70	2.02	**1.04**	0.73 ± 0.74
Map Matching	APE (m)	0.25	0.12	0.10 ± 0.06	0.30	**0.13**	0.11 ± 0.06
	Rot. (deg)	2.64	1.39	1.20 ± 0.72	3.24	1.65	1.37 ± 0.92
Fast-LIO2	APE (m)	6.99	3.88	3.56 ± 3.88	4.08	2.16	1.47 ± 1.15
	Rot. (deg)	5.49	2.68	2.25 ± 1.46	2.75	1.09	0.96 ± 0.52

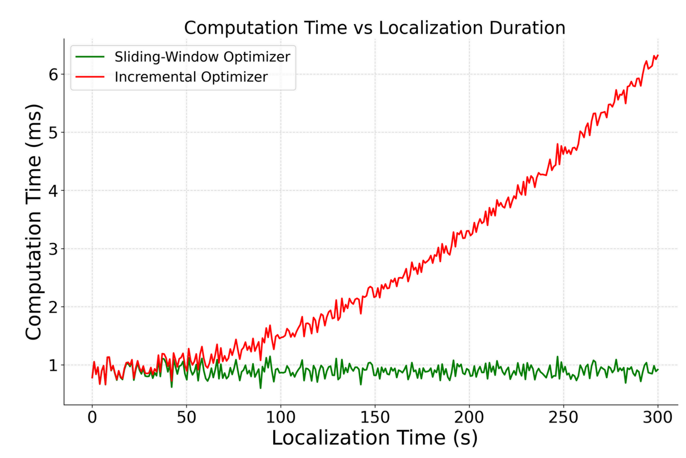
Benchmarking on Public Dataset: tested on kitti05

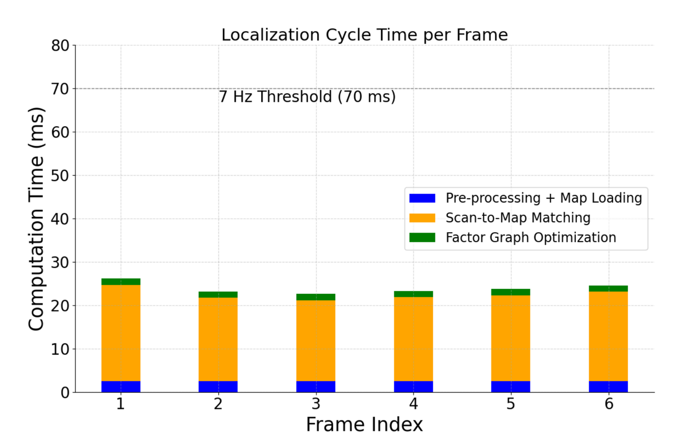
Method	Map Correction	Translation Error (m)	Rotation Error (°)
Proposed (Ours)	✓	**0.121 ± 0.077**	**0.30 ± 0.144**
Youngji Kim et al.	✓	0.15 ± 0.14	0.34 ± 0.40
D. Rozenberszki et al	✓	∼2.5 ± 2.0	–
Xiaohu Lin et al.	✓	3.18 ± 5.58	1.27 ± 1.97
FAST-LIO2	✖	9.18 ± 3.58	5.2 ± 1.7





Real-time performace: 23 ms (✓ 43 Hz real-time) per frame latency





Conclusions and Future Work

Accurate & Drift-Free
Achieves **centimeter-to-sub-decimeter** accuracy by fusing FAST-LIO2 and NDT with a sliding-window factor graph, effectively reducing drift without loop closures.

Real-Time & Scalable
Maintains **<23 ms** latency using multithreaded NDT and dynamic submap loading. Sliding window factor graph optimization remains bounded regardless of trajectory length.

Robust to Challenges
Dynamic object removal improves convergence, and fused graph keeps **localization stable** even when scan matching fails.

Limitations & Future Work
Assumes a known initial pose and a static map. Future directions include global re-localization, adaptive map updating, and integration of camera/radar for increased robustness.

References

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[4] Lin, X. et al. Autonomous Vehicle Localization with Prior Visual Point Cloud Map Constraints in GNSS-Challenged Environments. Remote Sensing, 2021