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

Eliyas Kidanemariam Abraha

Supervisors: Prof.Zoltan Istenes & Prof.Mohammad Aldibaja

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Thesis Presentation Outline

Motivation

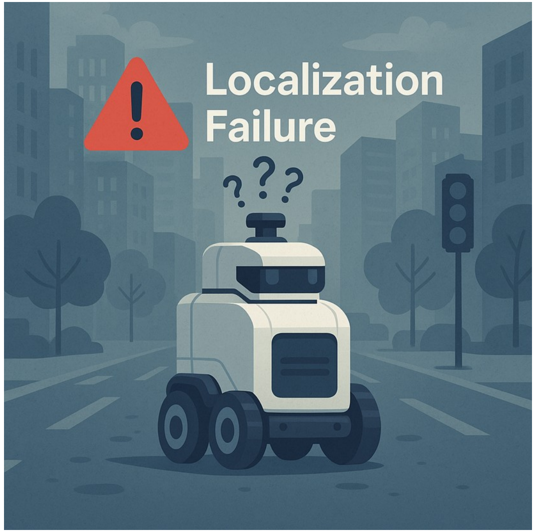
Accurate localization is crucial for autonomous robots to enable reliable path planning, obstacle avoidance, and other repetitive missions.

Typically, positioning relies on:

1. **GNSS-INS Methods**
   Unreliable in urban/indoor environments.

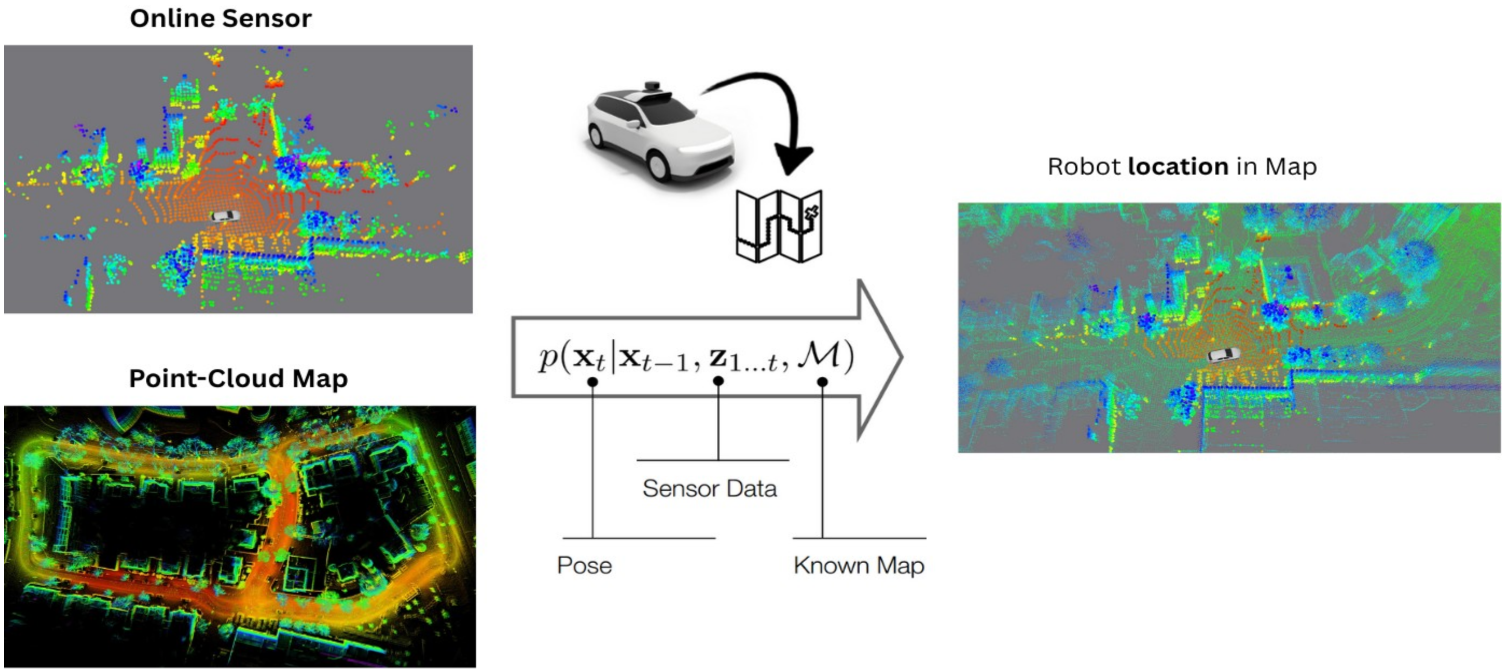
2. **LIDAR/VISUAL Inertial Odometry**
   Drifts over time without correction.

3. **Real-Time SLAM**
   Drift if loop closures are infrequent. Which may be sparse, delayed, or absent.



Map Based Localization

Uses prior maps as a global reference to improve accuracy and stability. The robot's current LiDAR scan is matched against the map to estimate its precise position.



Challenges

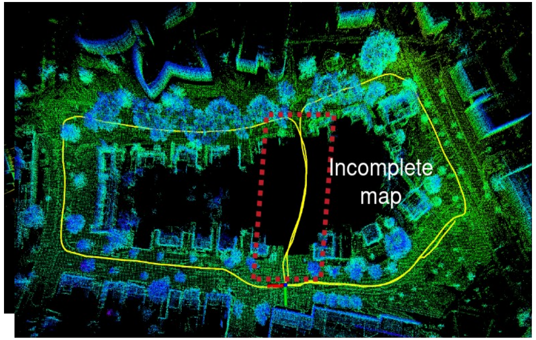
Map-based localization offers a stable and accurate alternative, but it faces several key challenges:

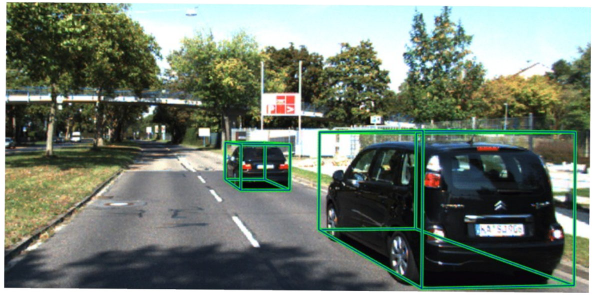
1. **Large Scale High Resolution 3D Map**
   Failure in scan-to-map matching

2. **Dynamic Objects**
   Cars , pedestrians decrease the accuracy of registration

3. **Feature Sparse Environments**
   localization failure in incomplete , boundary or transition zone of the map

4. **Adverse Environmental Conditions**





Research Questions

1. How can LiDAR-Inertial odometry and map observation be **effectively fused** to enhance real-time localization accuracy and robustness?To what extend improve the localization?

2. How can the proposed system maintain **real-time performance** and **scalability** in large-scale settings?

3. Does the method ensure accurate localization in **feature-sparse** and **noisy environments**?

Objectives

Accuracy and Robustness

Centimeter to Decimeter level accuracy. High available with out large errors .

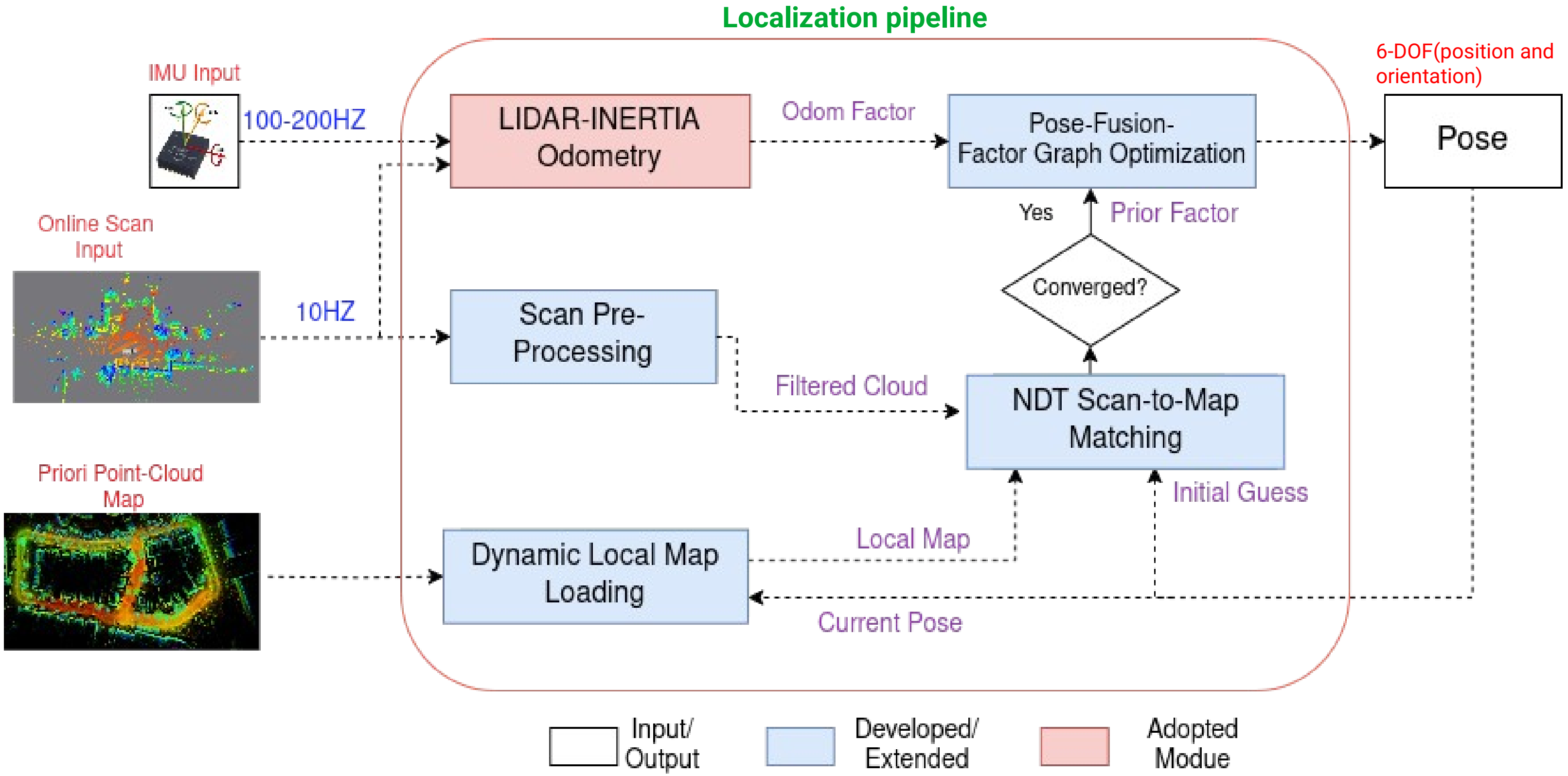
Real-time and Computational efficiency

low processing time and minimal computational resources.

Scalability

Working in large scale environment.

Methodology



System architecture of the proposed map-based localization pipeline

Scan Pre-Processing

LiDAR scan vary in density across the range of the sensor.

1 **Crop-Box Filter**

Eliminates distant or irrelevant points.

2 **Outlier Removal**

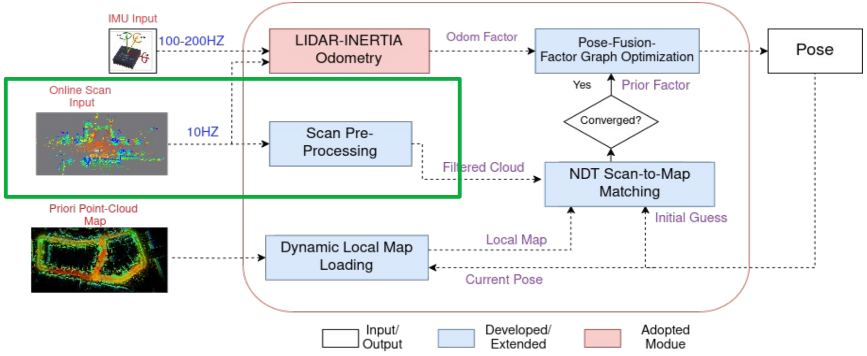
Statistical filter that removes isolated points.

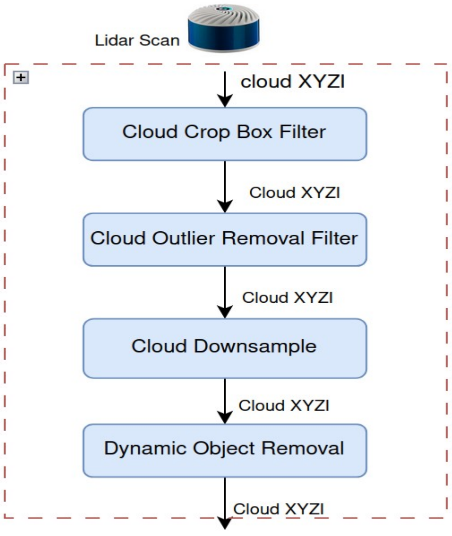
3 **Down-sample**

Reduce data size while preserving geometric structure.

4 **Dynamic Object Removal**

Remove moving objects.



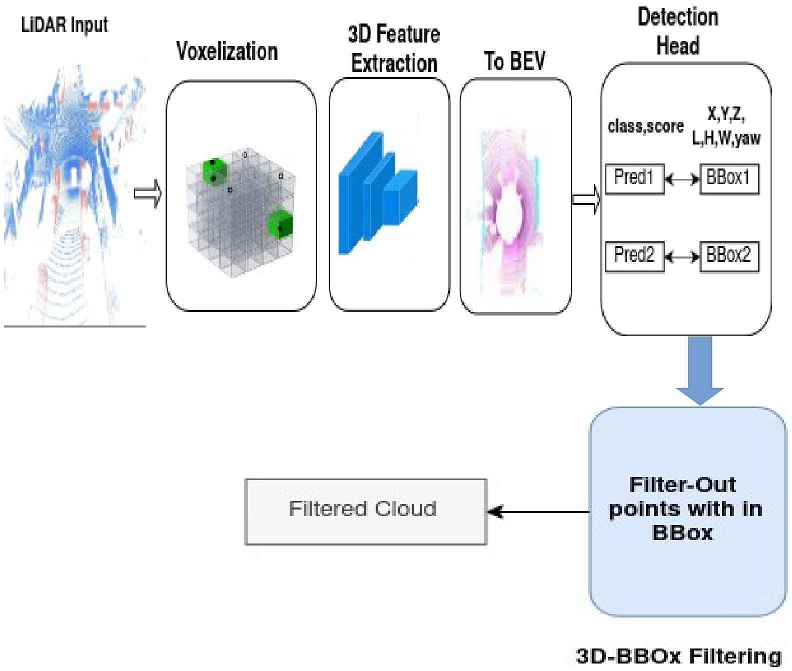


Filtered Cloud

Dynamic Object Removal

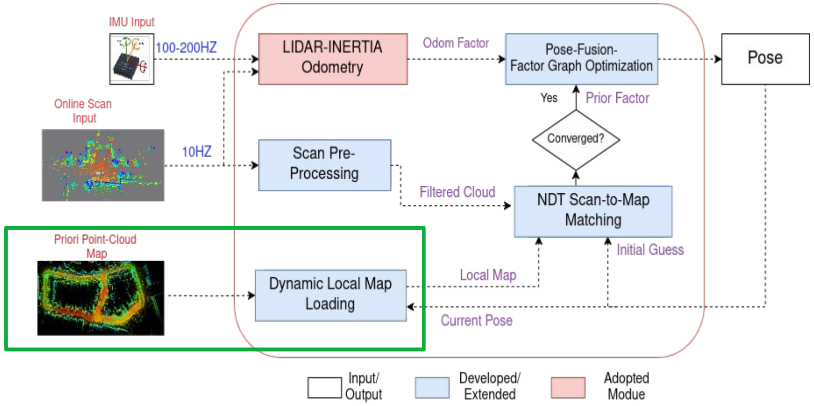
To reduce alignment errors caused by moving objects, we remove dynamic points from LiDAR scans before map matching.

- Deep learning-based 3D object detection based on CenterPoint.
- Detects objects by predicting their center points and 3D bounding boxes.
- Filter to **remove all LiDAR points** inside those bounding boxes.
- Pre-trained model with five object classes: **Car**, **Truck**, **Bus**, **Bicycle**, and **Pedestrian**.

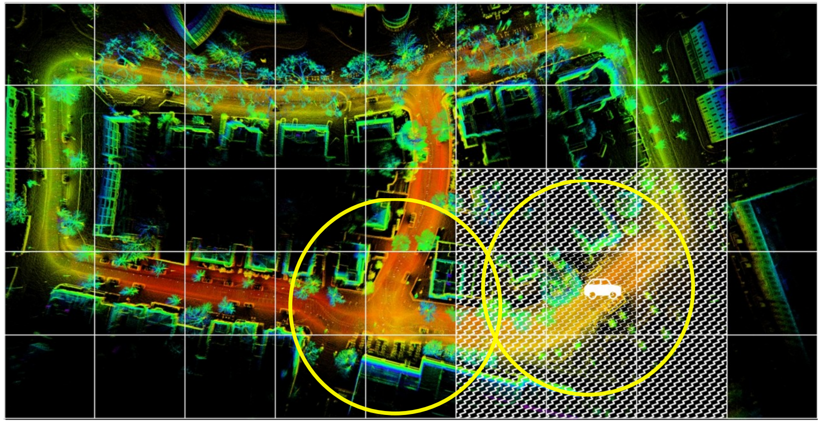


Local Map Loading

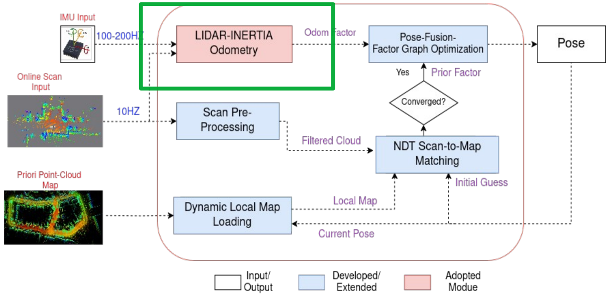
To ensure that scan-to-map matching always operates on the most relevant portion of the prior map.



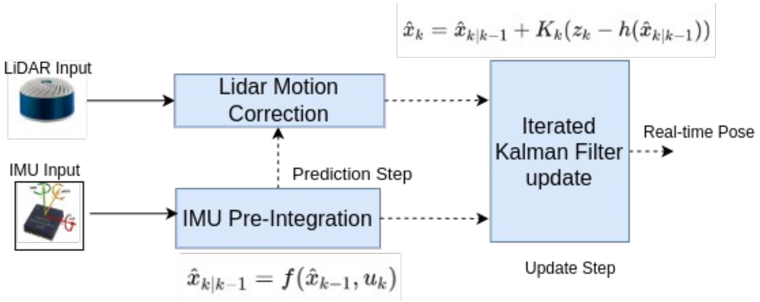
1. Divide Global Map into grid area
2. Determine The Local sub Map radius
3. Select and Load areas within radius
4. Remove out of range gride



Local Motion Estimation with LIO



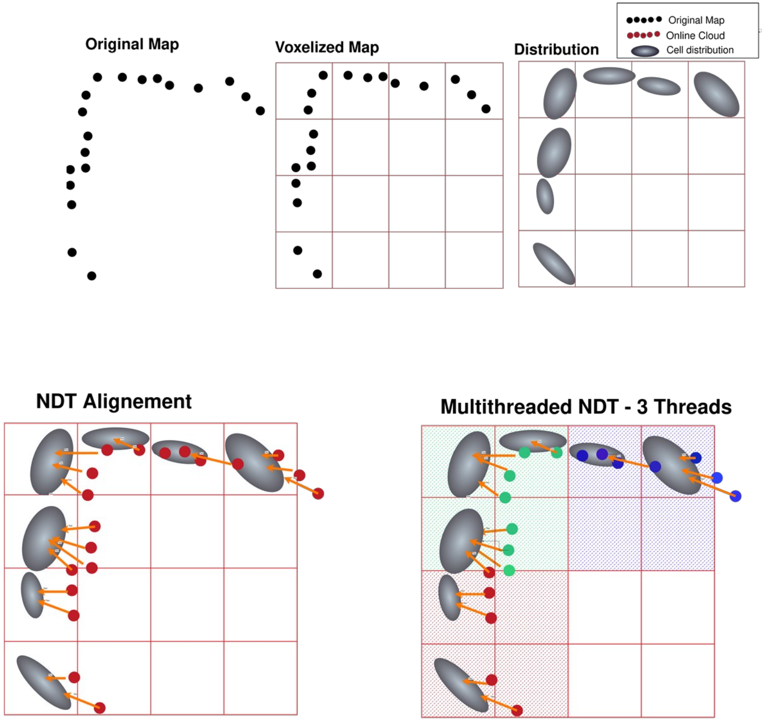
- FAST-LIO2 is used as the local motion estimation module in our system.
- Tightly couples LiDAR and IMU using an iterated Kalman filter.
- The IMU provides high-rate motion prediction, while LiDAR updates correct the drift.
- **High local accuracy** , **lightweight** and **computationally efficient** designed for challenging environments.



Multithreaded NDT Registration

To **accelerate** scan-to-map matching, we use a multithreaded implementation of the Normal Distributions Transform (NDT)

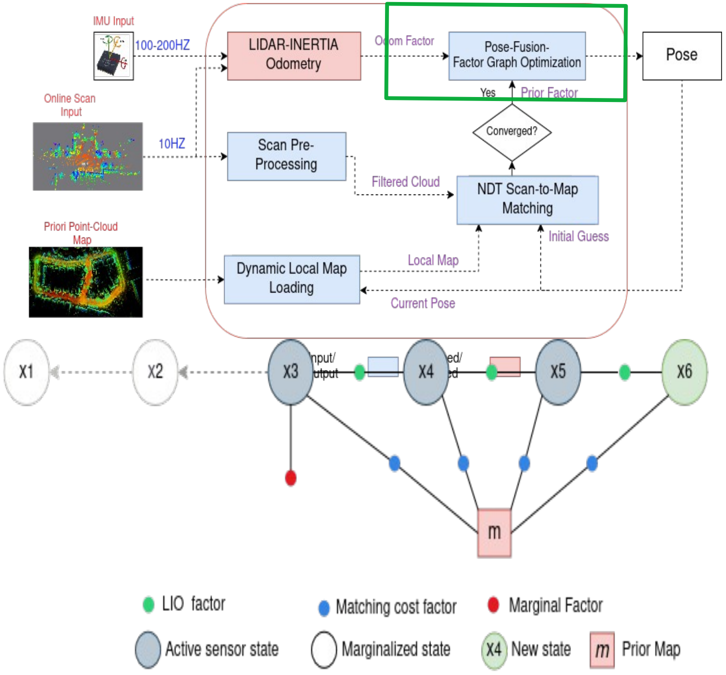
- Incoming scan is aligned by maximizing likelihood of point fit
- Multithreaded NDT distributes the registration workload across multiple CPU cores.
- The input point cloud is split into chunks, each processed independently.
- Once computed, all thread results are merged to produce the final pose estimate.



Factor Graph Optimization

To combine local odometry with global map corrections, we use a real-time factor graph optimization framework.

- A factor graph models the robot's trajectory as a set of pose variables linked by constraints (factors).
- Odometry poses from FAST-LIO2 are added **relative** motion.
- Scan-to-map corrections from NDT are inserted as **absolute** pose factors.
- To optimize only limited and affected poses Incremental Optimizer with sliding window approach is used.



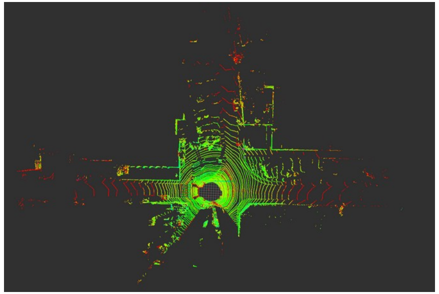
Environmental Noise Simulation

Test localization robustness under foggy conditions using simulated LiDAR degradation.

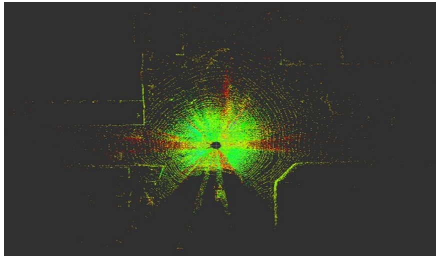
Introduces three major effects based **visibility-range(V),** the maximum distance at which an object can be reliably seen under foggy conditions:

1. **Deletion of Real Points**
   Far points are randomly removed
2. **Backscatter Modification**
   Some points shift closer to the sensor
3. **Intensity Attenuation**
   Reduce the intensity value of the remaining points

Original Point-Cloud



Noisy Point-Cloud



Experimental Setup

Dataset Overview

Evaluated on combination of **public benchmark** datasets and **custom recorded** sequence.

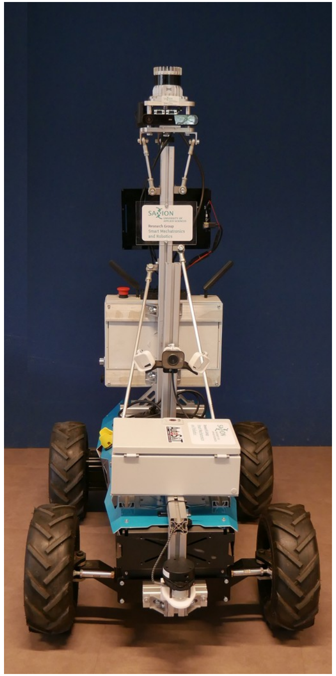
With different :

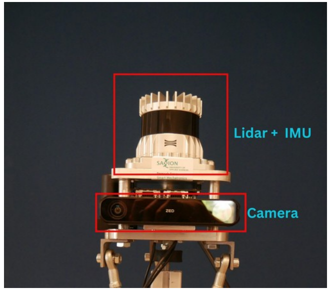
- Scene Environment
- Sensor Type
- Trajectory Length
- Structural Complexity

Dataset	Environment Description	Trajectory
Saxion-seq1	**Outdoor campus** area with moderate pedestrian and smooth motion.	~0.9 km/12 min
Saxion-seq2	**Outdoor campus** area with dynamic objects , sharp turns	~1.2 km/16 min
Saxion-seq3	**Long sub-urban** path with dynamic objects . apartment blocks	~1.8 km/27 min
Saxion-seq4	**Indoor area** characterized by long glass-walled corridors and repetitive office	~0.4 km/11 min
KITTI-seq05	**Outdoor Residential environment** with urban roads, parked vehicles,	~2.2 km/5 min
Mulran-KAiST-03	**Outdoor campus** area and multiple distinguishable structures.	~6.2 km/14 min

Hardware Setup

Hunter Mobile Robot





- Ouster OS1-128 - 128 beams
- 6-axis IMU
- camera for visual reference

Kitti Benchmark Dataset

Source: KITTI Vision Benchmark Suite

- Velodyne HDL-64E S2 – 64 beams
- 6-axis IMU
- Camera for visual reference

Evaluation Metrics and Methodology

Absolute Pose Error (APE)

- Measures **Euclidean distance** between estimated and ground-truth poses
- Computes RMSE, mean, median, and standard deviation of APE translational and rotational parts

Real-Time Performance Metrics

- Per-frame **execution time (**preprocessing, scan matching, optimization)
- **Convergence rate** and **iteration count** of registration

Comparisons

- **Component baselines:** Fast-LIO2, Scan-to-map matching
- **External methods**: Other map-based localization algorithms

Experimental Results

Comparison of translational and rotational error statistics with **baseline methods.**

Translation and Rotation Error

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

- **Fast_LIO2**: exhibits high drift over time,
- **Map-Matching**: low update frequency and pose jumps
- **Proposed**: both low localization error and high temporal consistency.

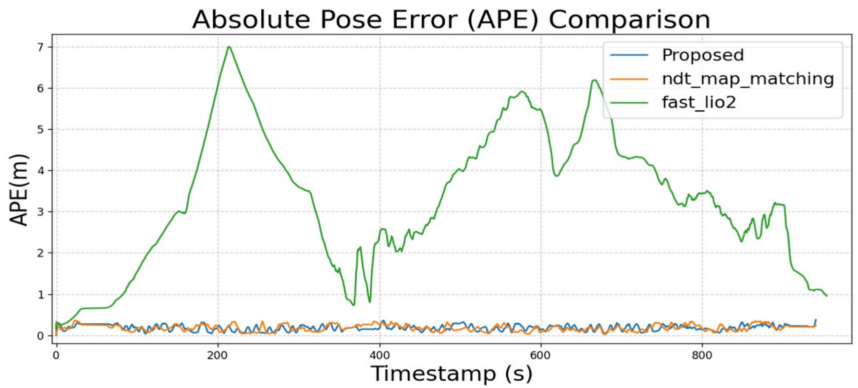


Fig:APE translation - Saxion Sequence 2

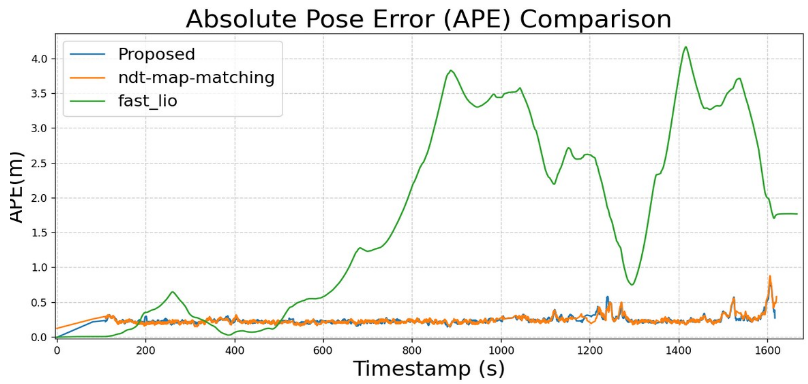
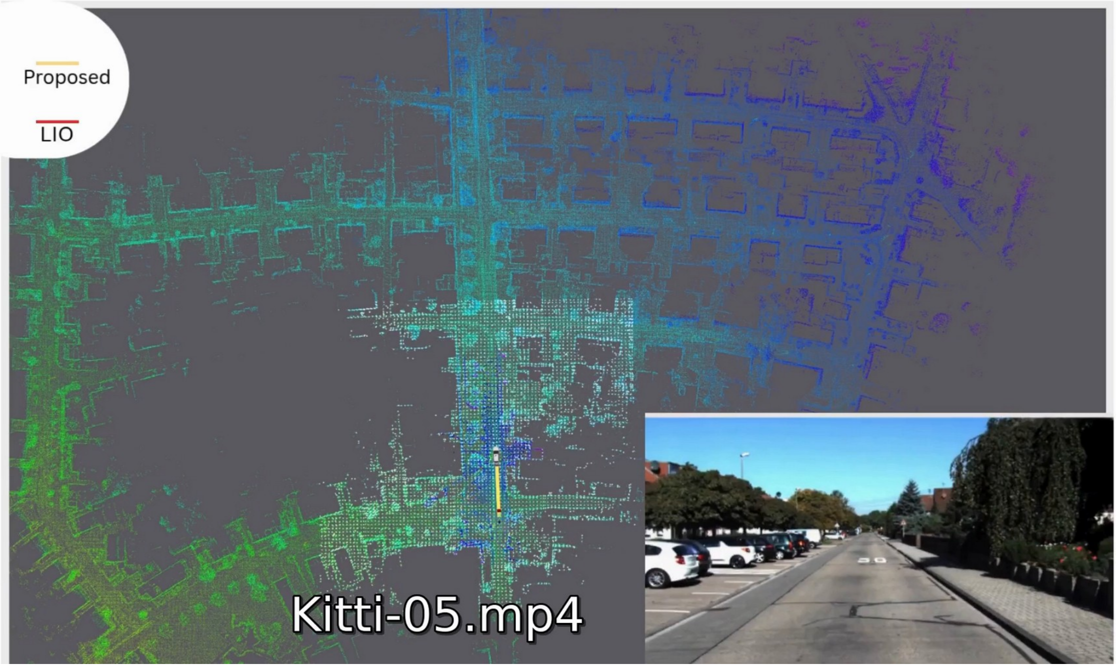
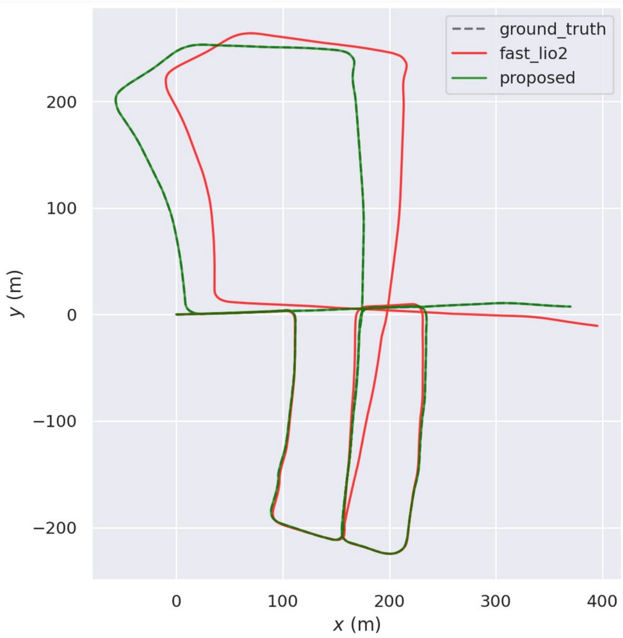


Fig: APE translation- Saxion Sequence 3

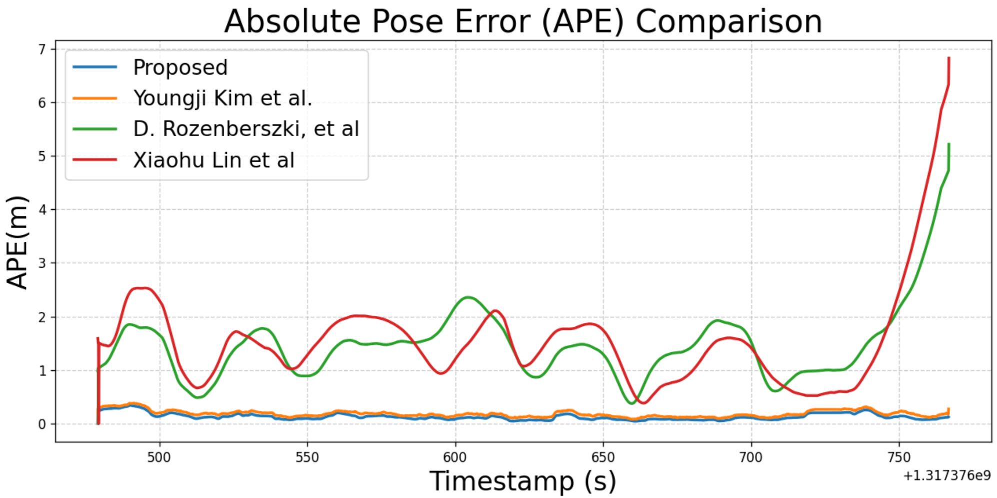
Benchmark Comparison on KITTI Sequence 05

The proposed method maintains **accurate alignment** with the map, while FAST-LIO2 **drifts over** time due to cumulative error.





Benchmark Comparison on KITTI Sequence 05



Method	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

- Achieves **lowest** translation and rotation error.
- **Outperforming recent map-based localization** techniques in both accuracy and consistency over time.

Real-Time Performance

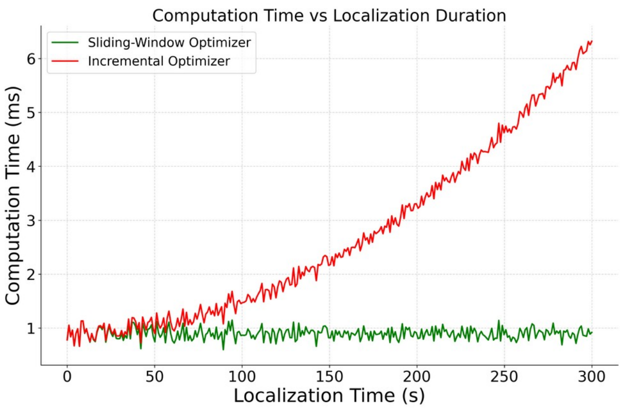


Fig:Computation time trend of sliding-window vs full-batch optimizer.

- The use **multithreaded NDT** with local map based registration reduces computation time without compromising robustness.
- The **sliding-window incremental** optimizer maintains near-constant solve time (~1 ms),while the full incremental solver grows in complexity over time.
- **Total latency**: 23 ms (✓ 43 Hz real-time), well below the 100 ms (10 Hz) requirement.

Map Radius(m)	Method	Mean Time(ms)	Converged(%)	Remarks
100	NDT	90	90	
	ICP	>100	90	
	NDT-OMP(8 thread)	15	99	
200	NDT	>100	<50	failures
	ICP	>100	<50	failures
	NDT-OMP(8 thread)	20	97	
350	NDT	>100	<50	failures
	ICP	>100	<50	failures
	NDT-OMP(8 thread)	25	90	some failures

Table : Scan-Matching Performance vs. Local Map Radius

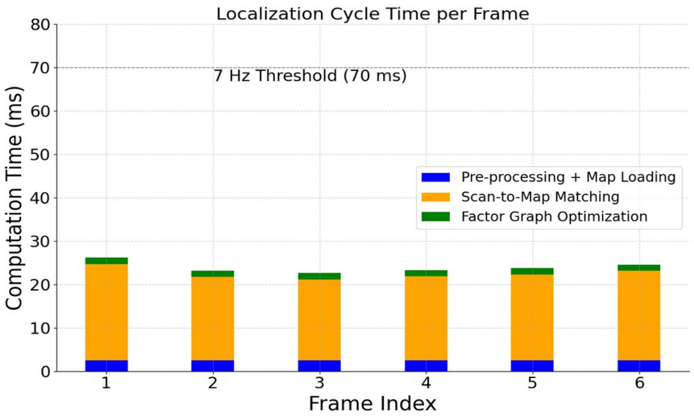
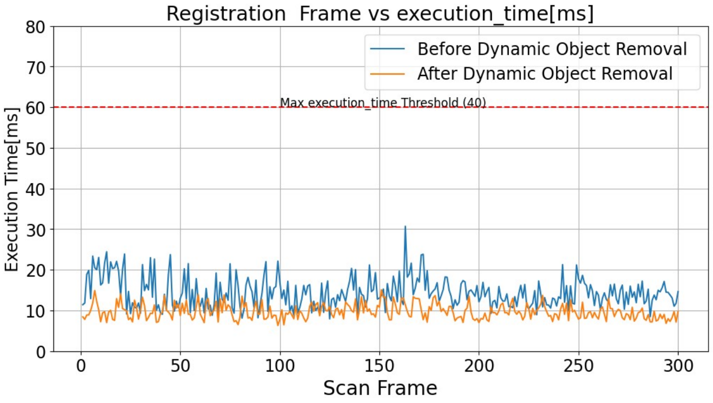


Fig: Computation time breakdown per frame

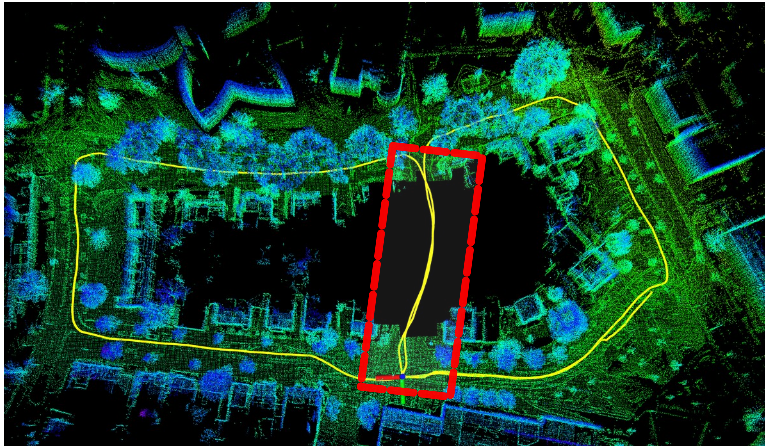
Dynamic Object Removal

Metric	Without Removal	With Removal	Improvement
Avg. Registration Iterations	19	12	↓ 7
Avg. Execution Time (ms)	14.41	9.73	↓ 4.68
Registration Failures	7	2	↓ 5

Reduction in average registration iterations, execution time , convergence failure



Localization In unmapped zone



- NDT-based map matching exhibited two prominent **error spikes** corresponding to the robot's entry into the unmapped region during both passes
- The proposed fusion system achieves **stable** localization by relying on high-frequency local estimates from LIO.

Method	Max APE (m)	Mean APE (m)	RMSE (m)	Std Dev (m)
Proposed Fusion	**0.455**	**0.078**	**0.095**	**0.054**
NDT Map Matching	1.278	0.131	0.295	0.264
FAST-LIO2	7.59	1.456	2.197	1.645

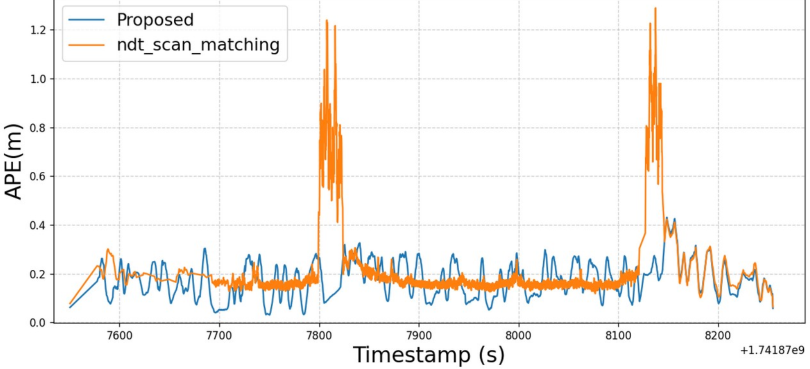
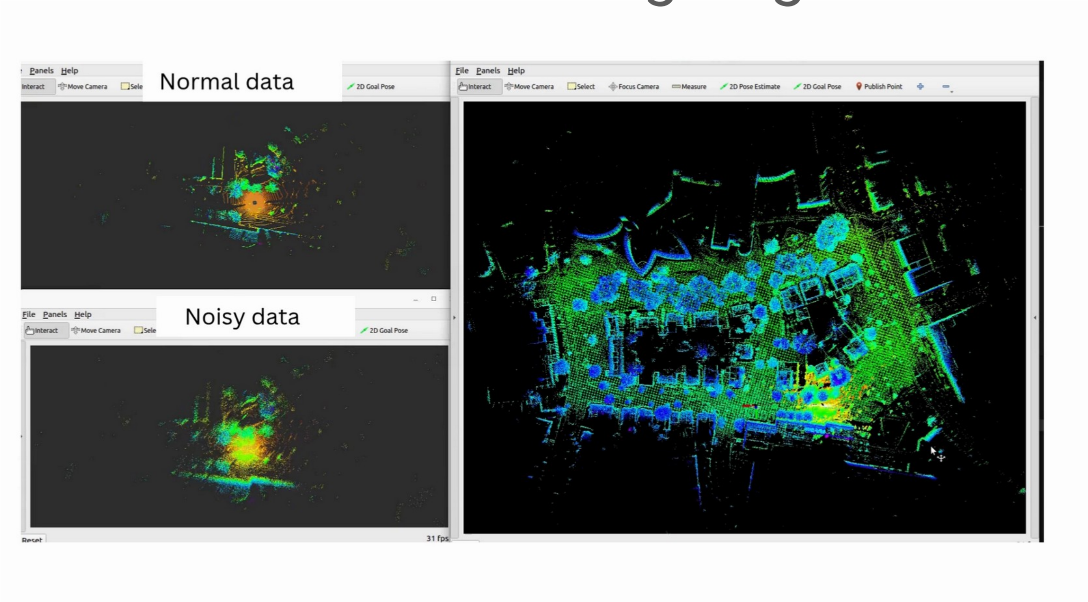
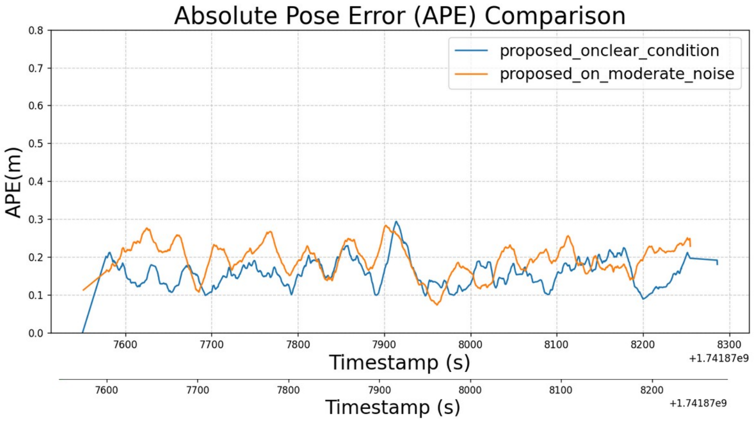


Fig: ATE Saxion Sequence 1

Localization Under Fog Degradation with a Recent Map





Fog Level	Visibility V (m)
Mild	100
Moderate	60
Severe	30

Translation error (APE) under fog visibility

Condition	Method	Max	Mean	Min	RMSE	Std Dev
Mild	Proposed	**0.3682**	**0.1238**	**0.0250**	**0.1356**	**0.0583**
	NDT Map Matching	0.4089	0.1474	0.0164	0.1585	0.0581
	Fast-LIO2	12.0253	4.2643	0.581	5.7521	3.2145
Moderate	Proposed	**0.3792**	**0.1326**	**0.0092**	**0.1452**	**0.0593**
	NDT Map Matching	1.3442	0.1712	0.0193	0.2178	0.1346
	Fast-LIO2	17.7823	6.2.3521	0.0610	12.9345	5.3614

Result Summary

RMSE below 20 cm

Low standard deviation

Sequence	Mean APE (m)	RMSE (m)	Std. Dev (m)
Saxion Sequence 1	0.052	0.067	0.042
Saxion Sequence 2	0.090	0.107	0.058
Saxion Sequence 3	0.097	0.135	0.094
Saxion Sequence 4	0.04	0.05	0.033
KITTI Sequence 05	0.121	0.143	0.077
MulRan KAIST 03	0.160	0.190	0.100

Discussion

Accuracy and Robustness

- Fusion of LIO and map correction reduces drift
- Maintained <0.20 m RMSE across all test sequences

Real-Time Performance

- Multithreaded NDT and sliding-window optimization enable fast, bounded computation
- Submap loading supports real-time localization at large scale
- Achieves 48 Hz (23 ms/frame) real-time operation

Environmental Adaptability

- Maintains stable localization in sparse map and transition zones using LIO
- NDT matching remains stable under moderate fog conditions

Dynamic Object Removal

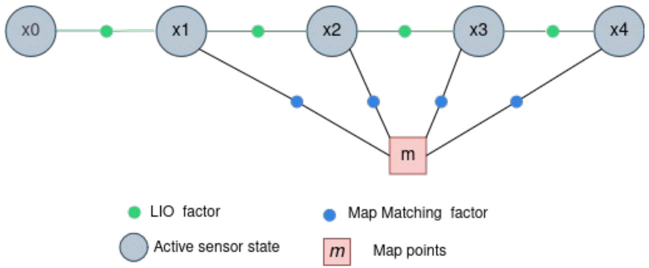
- Improves scan registration accuracy and speed
- Reduces convergence failures during matching

Limitation and Future Work

Limitations

- Requires a known or **approximated initial pose**
- No online map adaptation
- Fails under **severe LiDAR degradation**, such as dense fog , and lacks sufficient geometric richness.

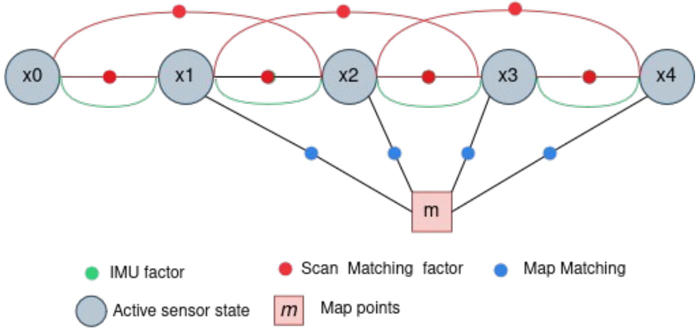
Current sensor fusion architecture



Future Work

- Integrate global localization and recovery
- Adaptive mapping using online map update or hybrid SLAM fusion
- Modify the graph architecture for **modular multi-sensor fusion**

Future sensor fusion architecture



Conclusion

- Developed a **real-time localization** system for **GNSS-denied** environments by fusing LiDAR-inertial odometry with map-based scan matching.
- Achieved globally consistent and **drift-resilient** localization through **sliding window factor graph optimization** of odometry and NDT constraints.
- Achieved **centimeter-to-decimeter-leve**l accuracy and real-time performance across benchmark and real-world datasets.
- Addressed real-world conditions like **dynamic agents**, **sparse features**, and **noisy environment**.

References

1. Xu, W. et al. "FAST-LIO2: Lightweight LiDAR-Inertial Odometry", IROS 2022

2. Rozenberszki, D. et al., LOL: LiDAR-only Odometry and Localization, ICRA 2020

3. Kim, Y. et al. "Stereo Camera Localization in 3D LiDAR Maps", IROS 2018

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

QUESTIONS

THANK YOU !

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

Methodology

You need to show all of the following within your methods:

Phase 1

- This is a sample text.
- You simply add your own text and description here.
- This text is fully editable.

Phase 2

- This is a sample text.
- You simply add your own text and description here.
- This text is fully editable.

Phase 3

- This is a sample text.
- You simply add your own text and description here.
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Phase 4

- This is a sample text.
- You simply add your own text and description here.
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Evaluation Metrics and Methodology

The Problem We Solve

Problem And Who Has It?

Explore the current situation

Paint a picture in words by including the "presenting problem," the impact it is having, the consequences of not solving the problem, and the emotions the problem is creating for those involved.

Explain

Once you have examined and clearly explained the situation, draft a simple problem statement by filling in the blank: The problem that we are trying to solve is: _____. Distill the problem to its simplest form possible.

Ask yourself

Ask yourself. "Why is that a problem?" If the answer is another problem, then congratulate yourself for moving from the "presenting problem" to a deeper problem.

Research Objectives

Research Objectives

Objective #1

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Objective #2

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Objective #3

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Objective #4

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The Type Of Study

The type of study you have conducted: qualitative, quantitative, or mixed

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Hypothesis

Provide information regarding how you have analyzed the data that you have collected

01

Hypothesis#1

This is a sample text. You simply add your own text and description here. This text is fully editable.

02

Hypothesis#2

This is a sample text. You simply add your own text and description here. This text is fully editable.

03

Hypothesis#3

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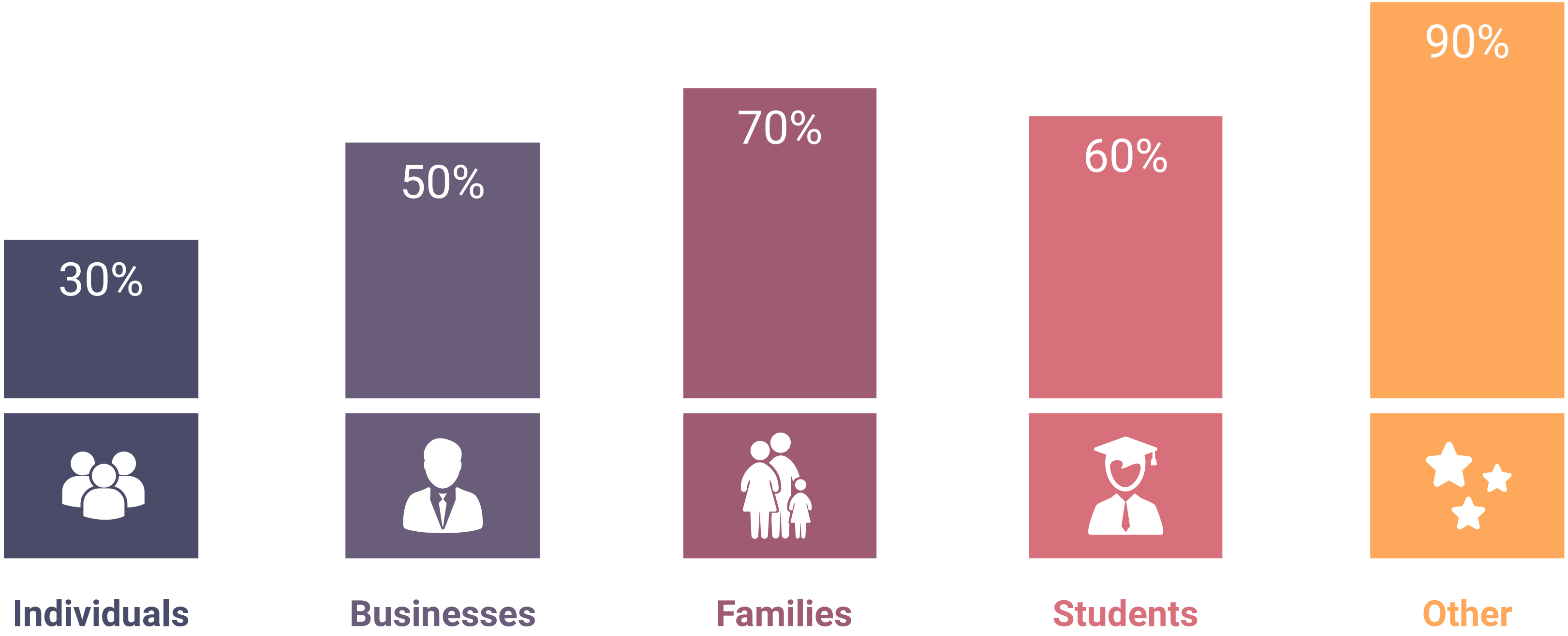
04

Hypothesis#4

This is a sample text. You simply add your own text and description here. This text is fully editable.

Define The Group of Study

Details of the population, sampling methods, and other information



Research Process

Provide information regarding how you have analyzed the data that you have collected

Step 01

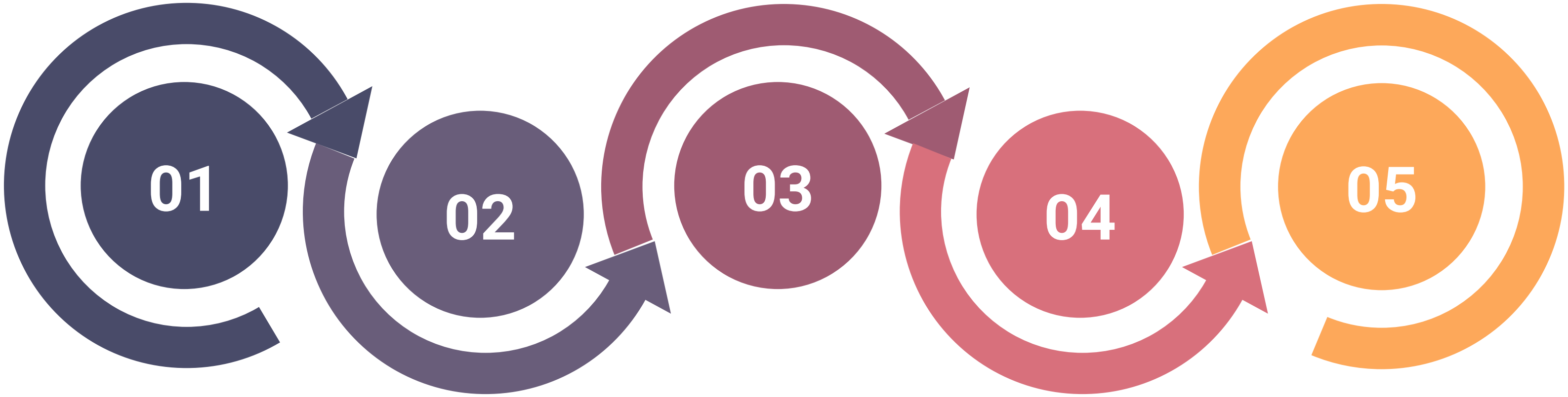
This is a sample text. You simply add your own text and description here.

Step 03

This is a sample text. You simply add your own text and description here.

Step 05

This is a sample text. You simply add your own text and description here.



Step 02

This is a sample text. You simply add your own text and description here.

Step 04

This is a sample text. You simply add your own text and description here.

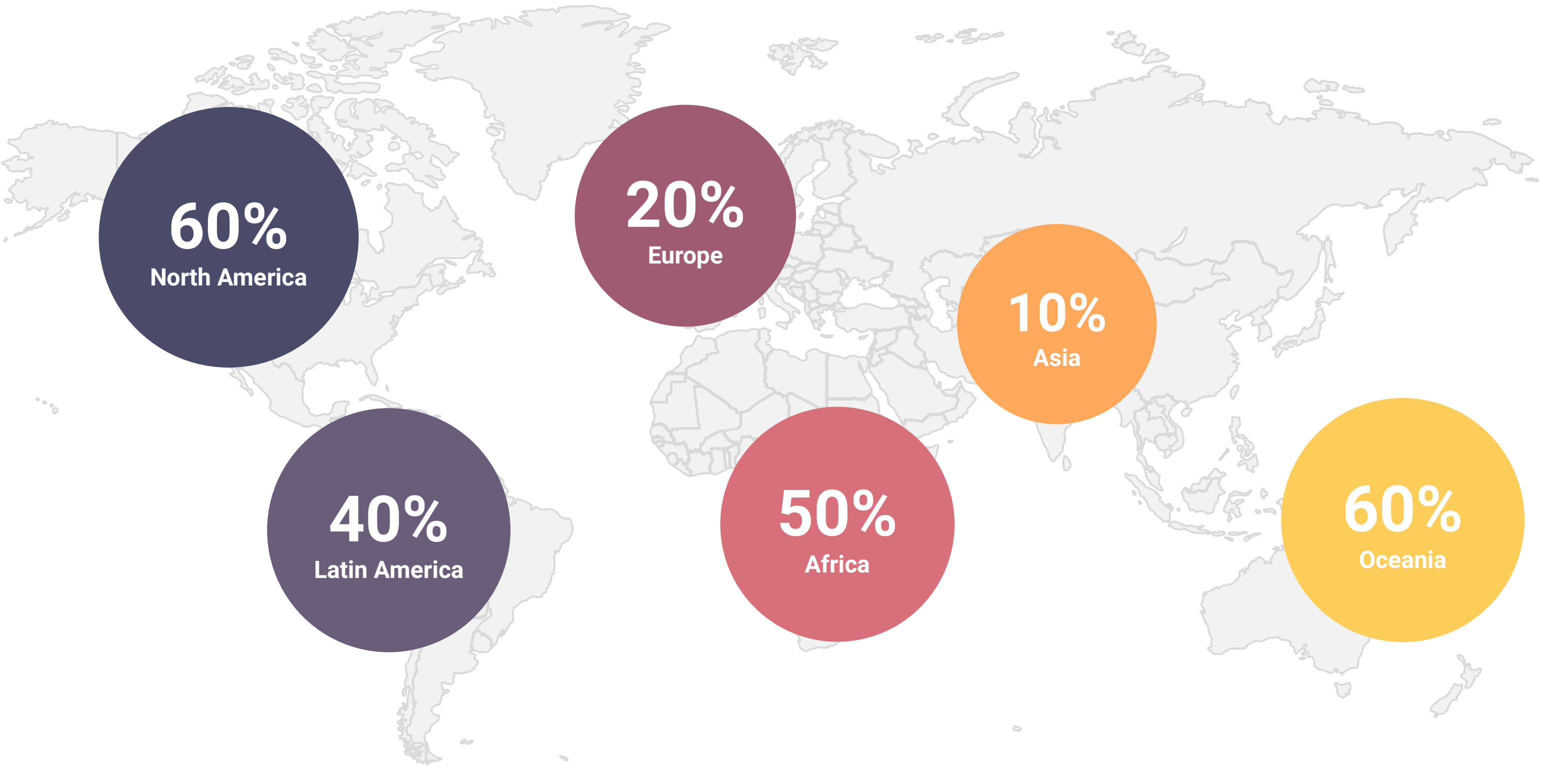
Statistical Analysis

Provide information regarding how you have analyzed the data that you have collected

Dataset	Element Title	Element Title	Element Title	Element Title	Element Title	Element Title
Element Title 01	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text
	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text
	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text
Element Title 04	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text
Element Title 04	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text	This is a sample text

Statistical Analysis

Provide information regarding how you have analyzed the data that you have collected



Research Results

What you actually found during your research

1. **Result #1**

   This slide should provide the reader with a good understanding of what you actually found during your research.

2. **Result #2**

   An overall description of the data that you collected during your research.

3. **Result #3**

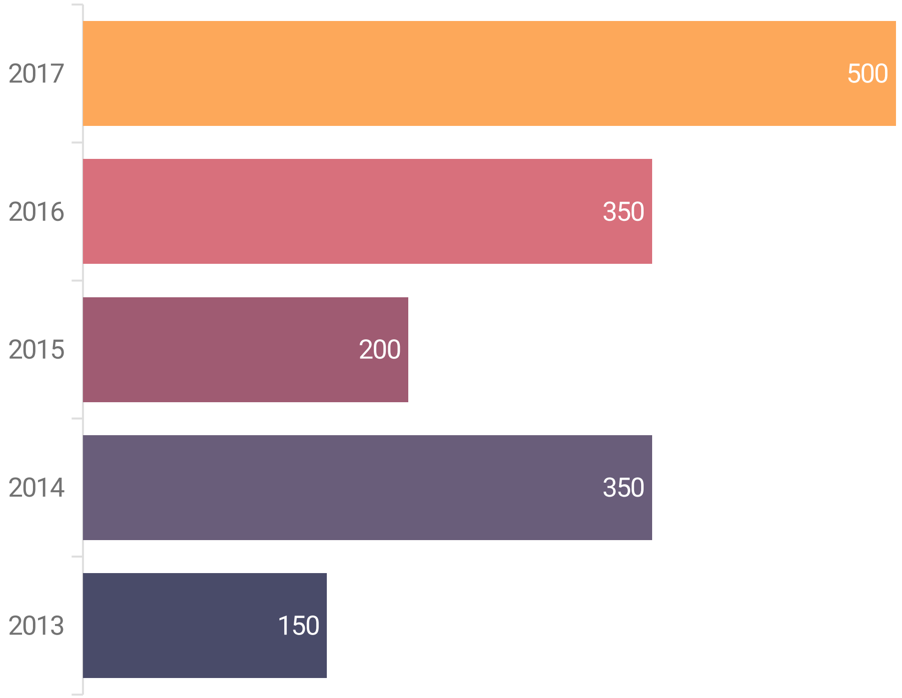
   The results of the analysis that you have done on that data.

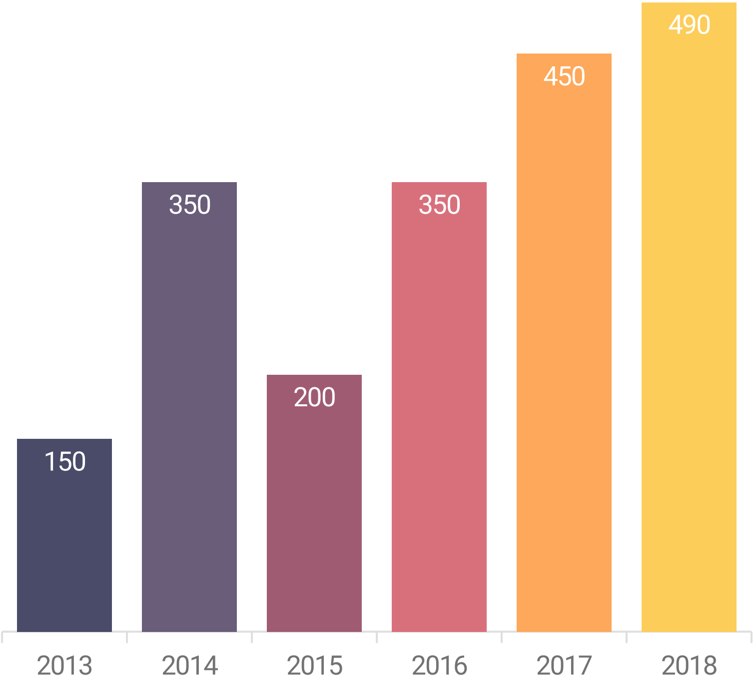
4. **Result #4**

   What were the most significant findings from your data.

Research Results

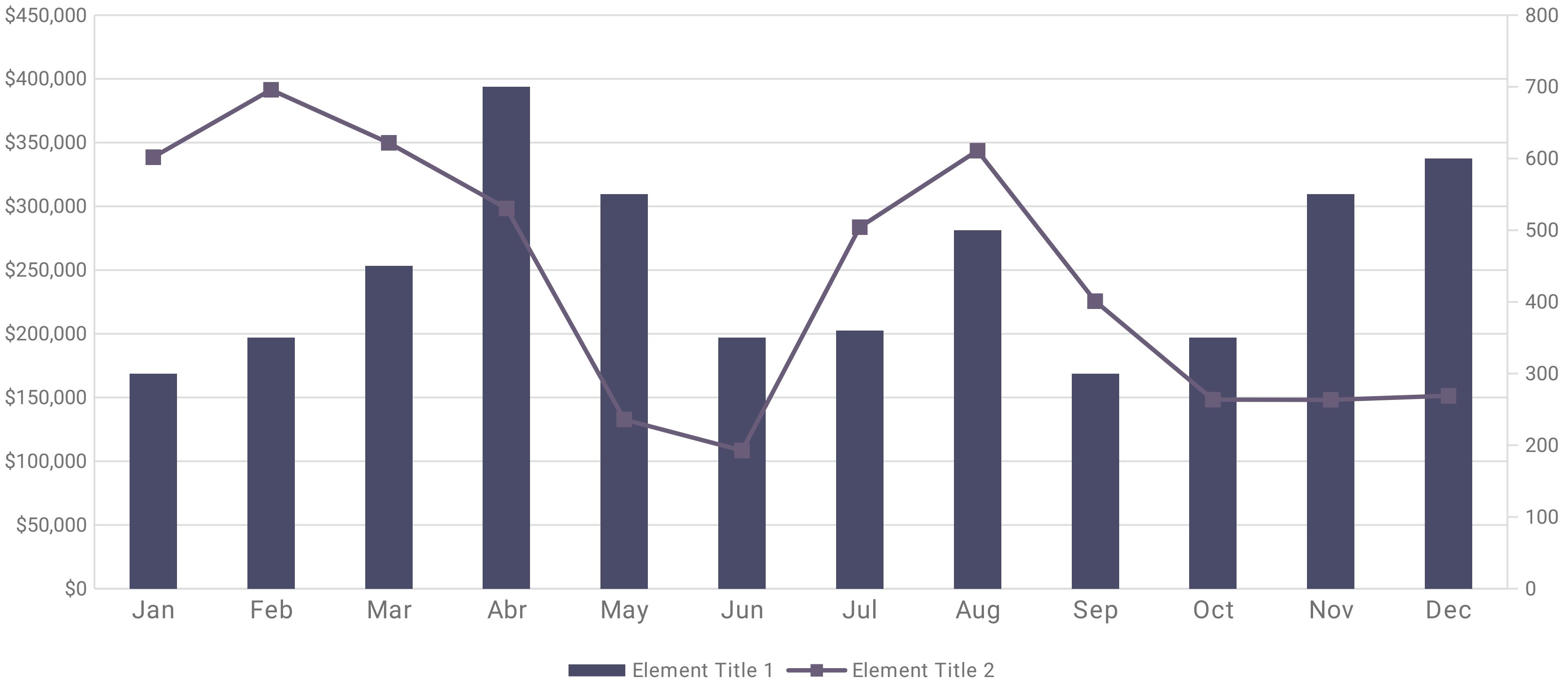
What you actually found during your research





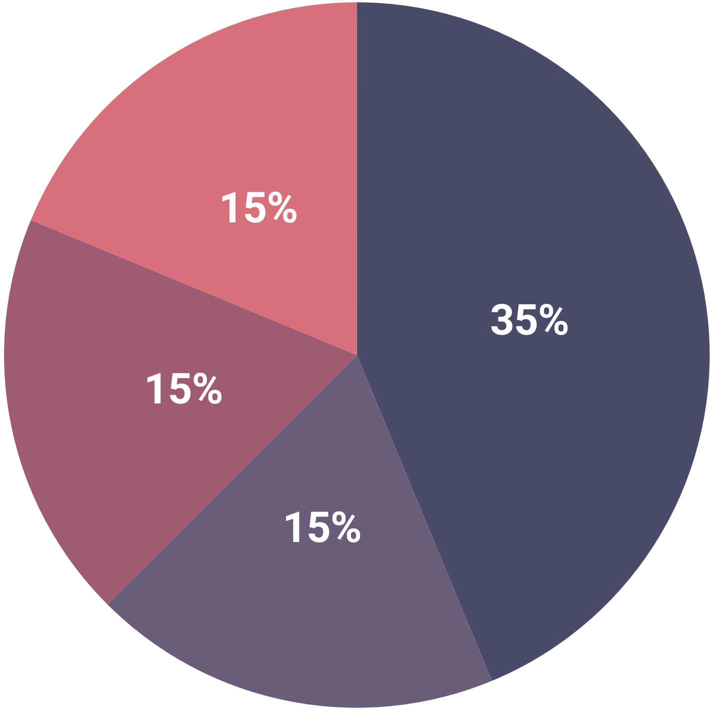
Research Results

What you actually found during your research



Research Results

What you actually found during your research



Key Figure Title	Key Figure Title
20% Key Number Title	**3+** Key Number Title

Key Figure Title	Key Figure Title
80% Key Number Title	**5x** Key Number Title

Discussion

Highlight what your results actually mean in relation to your field and the research that you have done

Discussion Tip #1

This is where you will highlight what your results actually mean in relation to your field and the research that you have done

Discussion Tip #2

What are the major findings and what do they mean in relation to your research

Discussion Tip #3

How do those findings relate to what others have found in the past

Discussion Tip #4

How can you explain any unusual or surprising results

QUESTIONS

Conclusions / Findings

This is where you summarize and tie up all that you have found within your research

Restate Your Research Questions

Show How Your Results Answer These Questions

Show What Contribution You Have Made

State Any Limitations To The Work You Have Done

Suggest Future Research

Make Any Recommendations

Conclusions / Findings

This is where you summarize and tie up all that you have found within your research

This is where you summarize and tie up all that you have found within your research

Suggestions

Suggest Future Research

Suggestion #1

This is a sample text. You simply add your own text and description here. This text is fully editable.

Suggestion #2

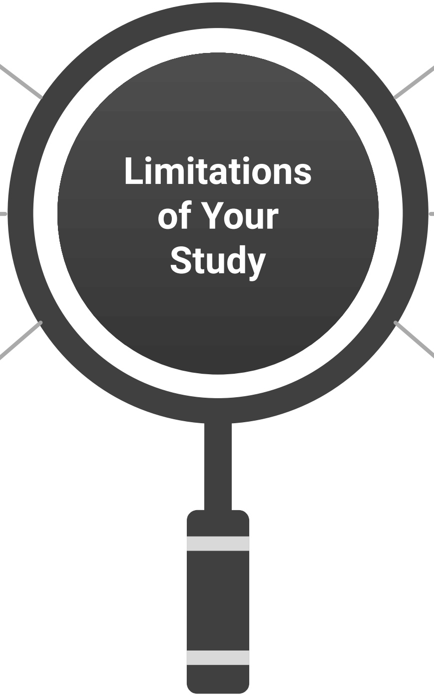
This is a sample text. You simply add your own text and description here. This text is fully editable.

Suggestion #3

This is a sample text. You simply add your own text and description here. This text is fully editable.

Limitations of Your Study

Limitations of Your Study



01

Assume Known initial pose

This is a sample text. You simply add your own text and description here.

02

Limitation 2

This is a sample text. You simply add your own text and description here.

03

Limitation 3

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04

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05

Limitation 5

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06

Limitation 6

This is a sample text. You simply add your own text and description here.

Recommendations

Make Any Recommendations

Recommendation 1

This is a sample text. You simply add your own text and description here. This text is fully editable.

Recommendation 1

This is a sample text. You simply add your own text and description here. This text is fully editable.

References

1. Xu, W. et al. "FAST-LIO2: Lightweight LiDAR-Inertial Odometry", IROS 2022
2. Rozenberszki, D. et al., LOL: LiDAR-only Odometry and Localization, ICRA 2020
3. Kim, Y. et al. "Stereo Camera Localization in 3D LiDAR Maps", IROS 2018
4. Lin, X. et al. Autonomous Vehicle Localization with Prior Visual Point Cloud Map Constraints in GNSS-Challenged Environments. Remote Sensing, 2021

THANK YOU !

THE TITLE OF YOUR

RESEARCH PAPER / THESIS

Your Name

University Name

Program Title

Name Of Advisor

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