Linear Four-Point LiDAR SLAM for Manhattan World Environments

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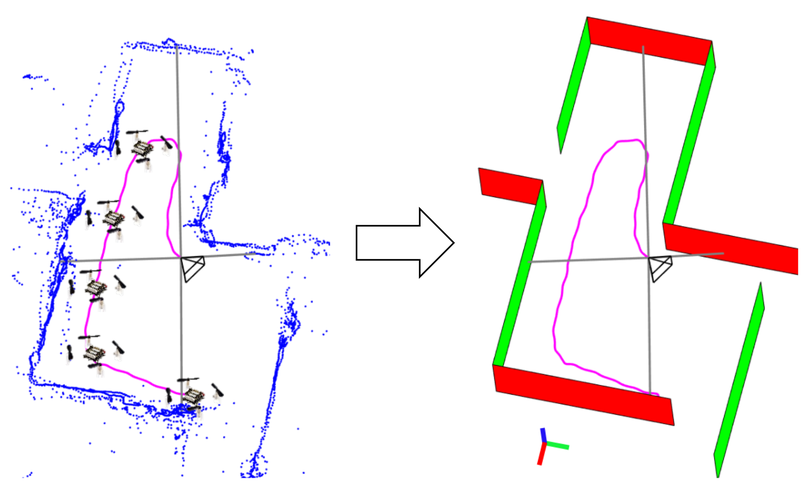
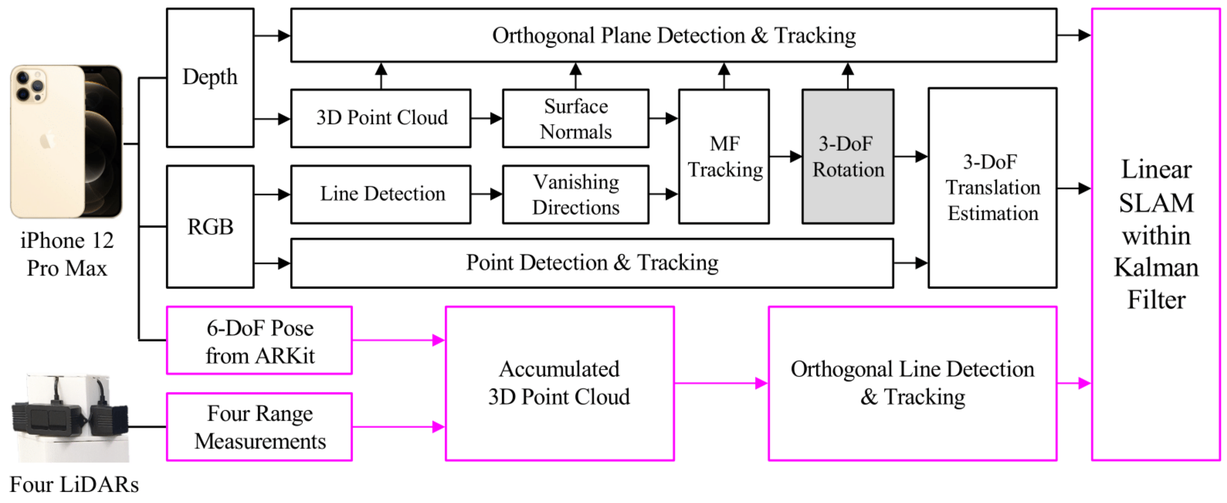
Motivation

- **Short Effective Range** (up to 5 m) of **Depth Cameras**
- **Very Fragile** for RGB-D SLAM in **Wide and Open Spaces**
- **Too Heavy/Expensive** Commercial LiDAR for **Nano Drones**

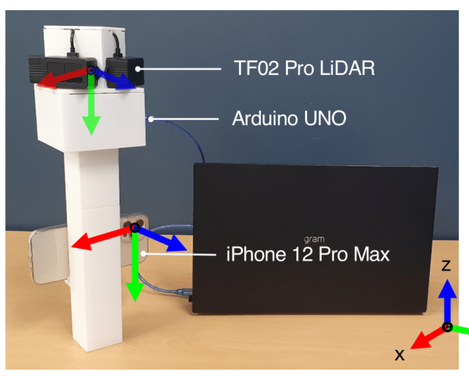


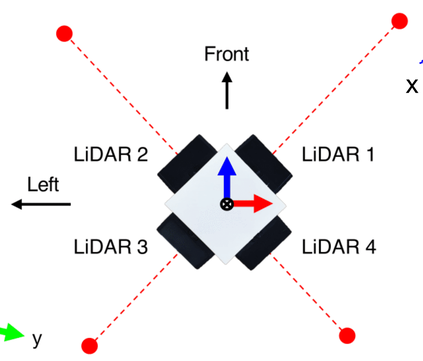
Contributions

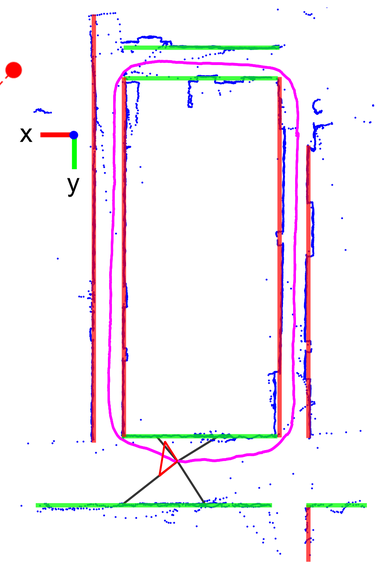
- Structure Map with **Sparse Sensing of Four-Point LiDARs**
- Accurate Localization and Mapping with **MW Structures**
- Seamless Integration with VO Methods for Open Spaces



Sensor Configuration



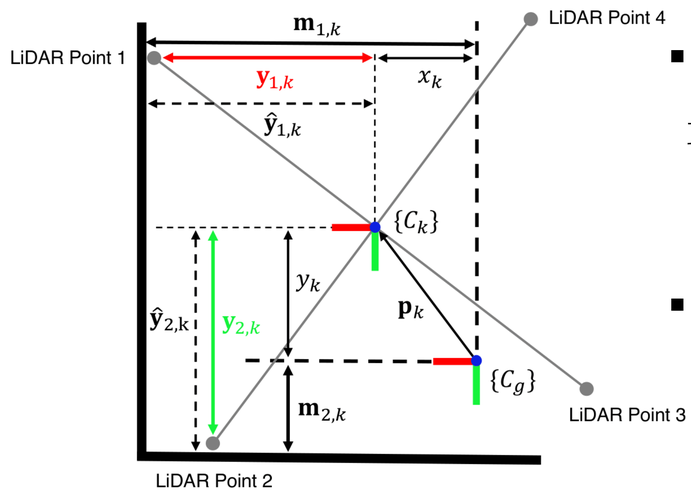




- **Four Radially-Spaced, Single-Point LiDARs** at 15 Hz
- **Commercial VIO (Apple ARKit)** for the SLAM Front-End
- Depth Measurement Capabilities:

  TF02 Pro LiDAR: Depth Measurement Range up to 40m
  Apple ARKit: Depth Measurement Range up to 5m

Linear Four-Point LiDAR SLAM



- **State Vector**

$$\mathbf{X}_k = \begin{bmatrix} \mathbf{p}_k^\top & \mathbf{m}_{1,k} & \cdots & \mathbf{m}_{n,k} \end{bmatrix}^\top \in \mathbb{R}^{3+n}$$

where $\mathbf{p}_k = \begin{bmatrix} x_k & y_k & z_k \end{bmatrix}^\top \in \mathbb{R}^3$

$\mathbf{m}_{i,k} = \begin{bmatrix} o_{i,k} & (alignment) \end{bmatrix} \in \mathbb{R}^1$

- **Process Model**

$$\mathbf{X}_k = \mathbf{F}\mathbf{X}_{k-1} + \boxed{\triangle \mathbf{p}_{k,k-1}} + \mathbf{w}_{k-1}$$

where $\mathbf{F} = \mathbf{I}, \mathbf{w}_{k-1} \sim N(0, \mathbf{Q}_{k-1})$

- **Measurement Model**

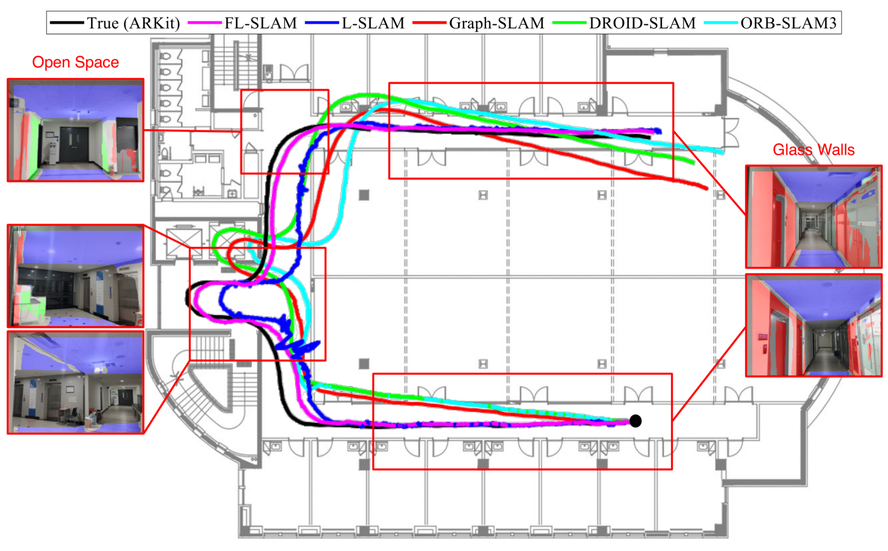
$$\mathbf{y}_k = \begin{bmatrix} \mathbf{m}_{1,k} - x_k \\ \mathbf{m}_{2,k} - y_k \\ \mathbf{m}_{3,k} - z_k \\ \vdots \end{bmatrix} = \mathbf{H}_k \mathbf{X}_k + \mathbf{v}_k \quad \text{where} \quad \mathbf{H}_k = \begin{bmatrix} -1 & 0 & 0 & 1 & 0 & 0 & \cdots \\ 0 & -1 & 0 & 0 & 1 & 0 & \cdots \\ 0 & 0 & -1 & 0 & 0 & 1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

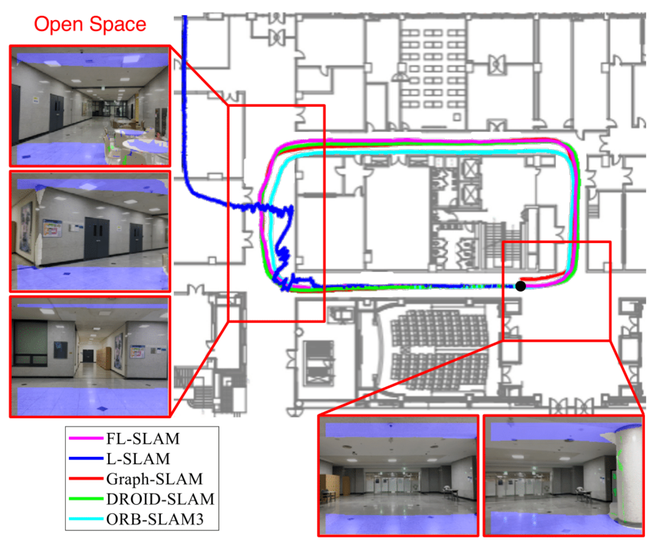
$\mathbf{v}_k \sim N(0, \mathbf{R}_k)$

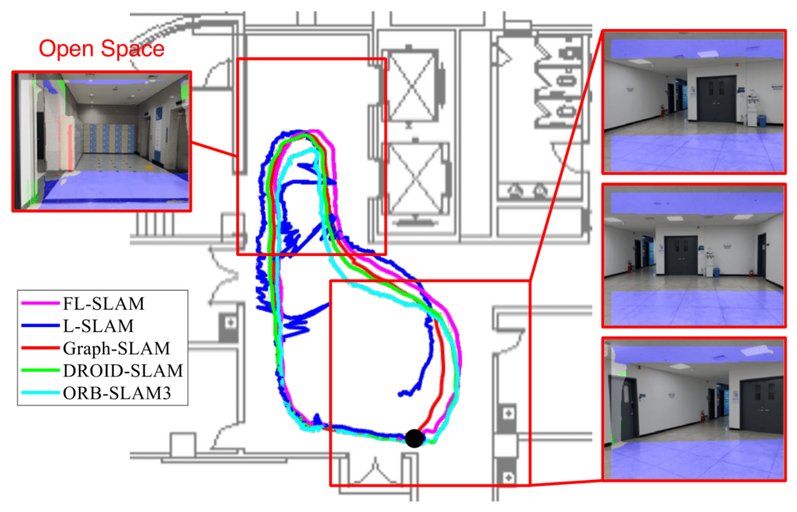
- Detect **orthogonal walls** by fitting the lines to 2D points.
- Update **2-DoF translation** and **1-D map** within a linear Kalman filter.

Evaluations

Experiment	FL-SLAM (Ours)	L-SLAM	Graph-SLAM	DROID-SLAM	ORB-SLAM3	Length (m)
L-shaped Corridor	**0.660**	1.990	29.373	<u>0.845</u>	1.510	52.032
U-shaped Corridor	**0.738**	<u>1.476</u>	3.177	2.657	3.846	64.361
Open Hallway 3	<u>0.390</u>	7.164	0.406	**0.326**	0.699	34.564







- FL-SLAM achieves **comparable performance** using only the sparse sensing of inexpensive four-point LiDARs.
- FL-SLAM constructs reliable global MW maps, resulting in **more accurate translation updates in open spaces**.