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A Ground-Aware LiDAR Intensity Filter for Reliable SLAM in Challenging Reflection Environments

***Federico Rollo**[1,2], Valentina Pericu[1], Marco Roveri[2], Arash Ajoudani[3] and Navvab Kashiri[1]*

[1] Robotics Laboratory, Innovation Hub & IP, Leonardo S.p.A., Genoa, Italy
[2] Industrial Innovation, DISI, Università di Trento, Trento, Italy
[3] HRII, Istituto Italiano di Tecnologia, Genoa, Italy

Contact: federico.rollo@leonardo.com

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IARIA

Personal Presentation

Federico Rollo, PhD*

Technical Coordinator of the Perceptive Navigation research area at Robotics Lab, Leonardo Spa

Professional Experience:
- Senior Researcher at Leonardo Spa, Genoa, Italy
- Affiliate Researcher at Istituto Italiano di Tecnologia (IIT), Genoa, Italy

Education:
- PhD in Mobile Robotics and AI at University of Trento
- MSc in Control Engineering at La Sapienza University of Rome
- BSc in Computer Science at Roma Tre University

Research Interests:
- Mobile Robots Navigation and SLAM
- Semantic Perception and Mapping
- AI applied to Mobile Robots

* almost

Robotics Laboratory

- Three Clusters:

INTELLIGENT ROBOTIC MANUFACTURING

SPACE ROBOTIC SERVICING

LAND EXPLORATION SOLUTIONS

- Three Competence Areas:

MANIPULATION CONTROL

MECHATRONICS

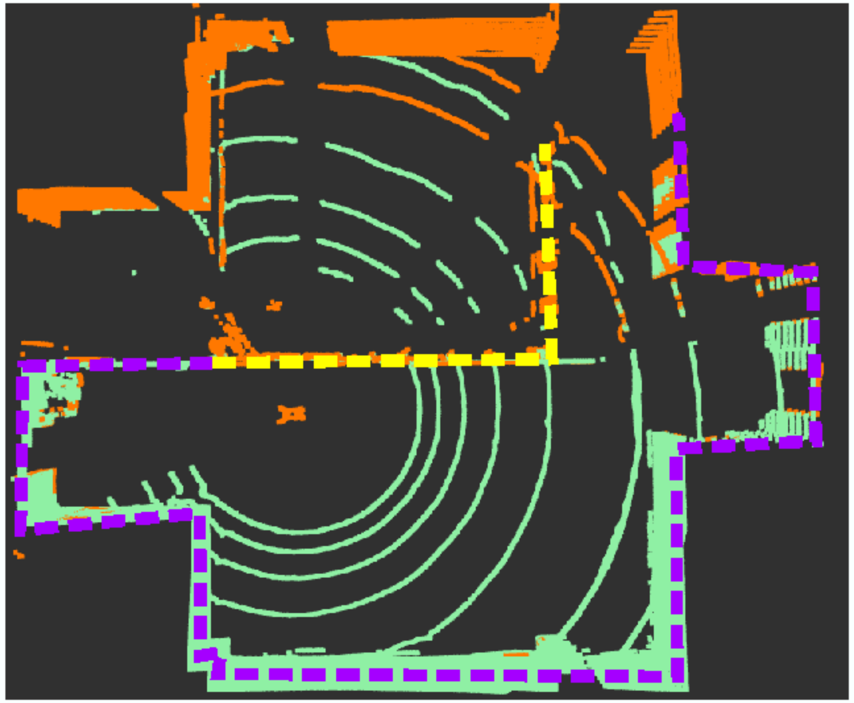
PERCEPTIVE NAVIGATION

- Projects
  - Autonomous handling of selected objects from conveyor belts.
  - Edge sealing operation of carbon fibre frame.
  - In-Orbit-Servicing (IOS) refueling tasks.
  - 3D Mapping, Localization and Navigation, and dynamic obstacle avoidance in unstructured environments
  - Autonomous mobile robot for maintenance activity of electronic panels, operating in synergy with human worker.

Why Point Cloud Intensity Filtering?

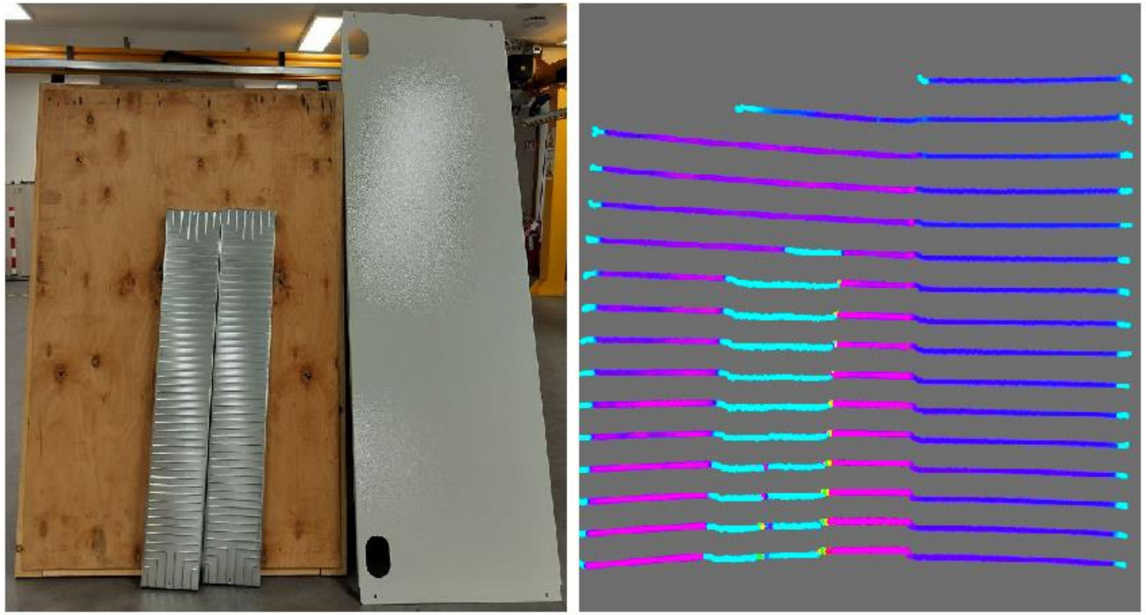
The Challenge: Reflective Environments

- Point clouds are highly susceptible to errors in environments with reflective surfaces (e.g., mirrors, polished metal, glass).



The Opportunity: Intensity Data

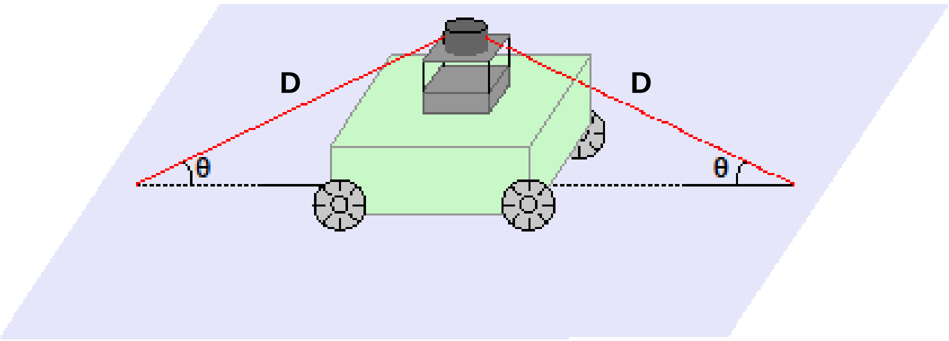
- Most LiDAR sensors provide an intensity value for every point.
- These intensity signatures can be used to distinguish between valid structural points and erroneous reflections.



Problems

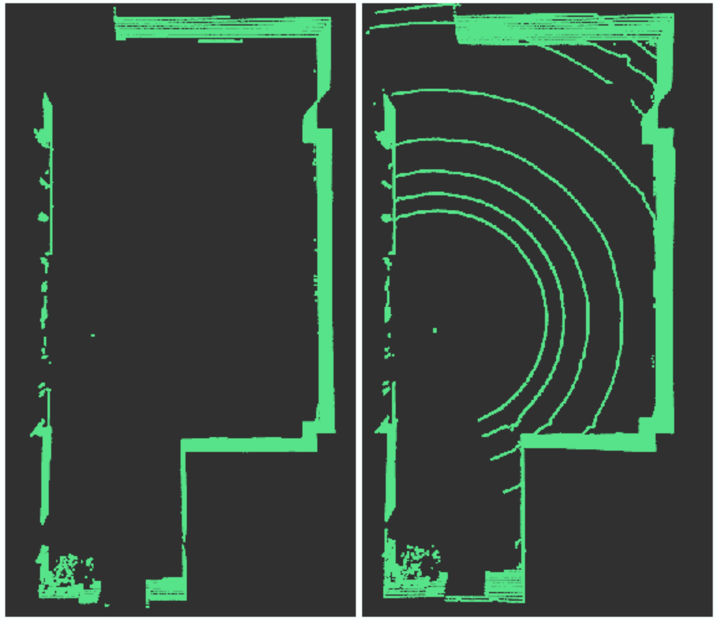
The Incidence Angle Problem

- **Variable Intensity:** Not only dependent on Material but they are heavily modulated by the incidence angle θ and distance D.
- **False Positives:** At low incidence angles even "safe" ground surfaces produce intensity signatures similar to reflection noise.



The "Over-Filtering" Trap

- **Ground Erosion:** Standard intensity filters often misclassify ground points as noise due to low-return intensities at distance.
- **Impact on SLAM & Odometry:**
  - **Loss of Constraints:** Removing ground points eliminates critical vertical constraints (z-axis stability).
  - **Feature Scarcity:** Modern SLAM algorithms rely on ground plane estimation for robust ego-motion tracking; filtering the ground leads to drift or system failure.



Our Solutions

Filtering Intesity using minimal and maximum boundaries

$$\psi_i \notin \psi^* \equiv (\psi_i < \psi^*_{min}) \ \& \ (\psi_i > \psi^*_{max})$$

We then proposed two solutions:

1) Naive Intensity Filter

retain all points located below the robot's footprint

$$^l\mathbf{P}^* = \{^l\mathbf{p}_i \in {}^l\mathbf{P} \mid (\psi_i \notin \psi^*) \ \& \ (^l z_{p_i} < {}^l z_f)\}$$

2) Normal Intensity Filter

Retain all point which have a norm parallel to the robot's footprint

The Normal Intensity Filter consists of two steps:

a) Compute the normal vectors $^l\boldsymbol{\eta}_i$ for each point $^l\mathbf{p}_i$.

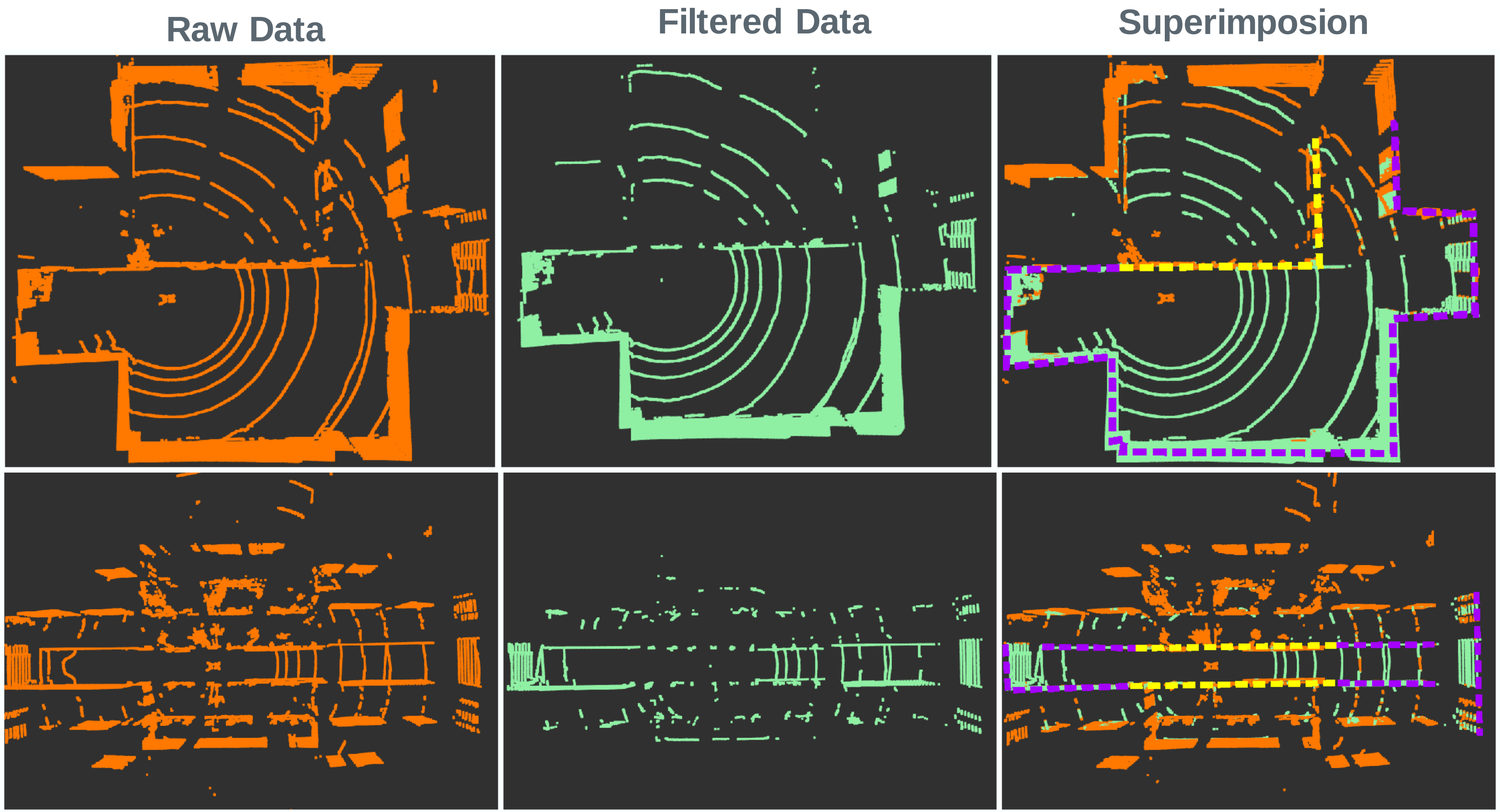
b) Check if the point's normal vector $^l\boldsymbol{\eta}_i$ is parallel to the z-axis of the robot's footprint frame *f*.

$$^f\boldsymbol{\eta}_i = {}^l\mathbf{H}_f * {}^l\boldsymbol{\eta}_i$$

$$\theta_{\eta_i} = \frac{^f\boldsymbol{\eta}_i \cdot {}^f\mathbf{z}}{\|^f\boldsymbol{\eta}_i\|\|^f\mathbf{z}\|}$$

$$^l\mathbf{P}^* = \{^l\mathbf{p}_i \in {}^l\mathbf{P} \mid \theta_{\eta_i} < \epsilon_\eta \}$$

Some examples



Results

Tested against two state-of-the-art LiDAR odometry frameworks: **KISS-ICP** [1] and **DLO** [2] (Direct LiDAR Odometry) using Translation and Orientation Errors (TE, OE) and Total Variation Error (TVE) metrics to highlight stability.

- **The "Intensity-Only" Failure:**
  - DLO: standard intensity filtering *increased* translation error (TE) compared to no filter at all. This confirms that removing the ground reduce odometry accuracy.
  - KISS-ICP: standard intensity filtering *improves* translation error (TE) because TVE improves along x and y axis.
- **Vertical Stability (z-axis):** Our **Ground + Intensity** approach achieved the lowest z-axis error in both frameworks.
- **Precision Recovery:** We successfully filtered noise without the "penalty" of losing the ground plane, resulting in the best overall accuracy across almost all metrics.

Framework	Filtering Mode	TE [m]	OE [rad]	TVE [m] (x y z)
Kiss-ICP [1]	No Filter	22.529	0.270	18.848 12.129 2.298
	Intensity	2.585	0.100	**0.278** 1.152 2.297
	Ground + Intensity	**1.112**	**0.075**	0.478 **0.986** **0.187**
DLO [2]	No Filter	**0.410**	0.068	0.164 **0.109** 0.359
	Intensity	2.395	0.098	0.179 0.408 1.979
	Ground + Intensity	0.428	**0.0637**	**0.156** 0.397 **0.031**

[1] Vizzo, Ignacio, et al. "Kiss-icp: In defense of point-to-point icp–simple, accurate, and robust registration if done the right way." IEEE Robotics and Automation Letters 8.2 (2023): 1029-1036.
[2] Chen, Kenny, et al. "Direct lidar odometry: Fast localization with dense point clouds." IEEE Robotics and Automation Letters 7.2 (2022): 2000-2007.

Conclusion

Robust LiDAR Filtering for Real-World Robotics

Summary of Contributions

- Developed a novel **ground-aware intensity filter** that effectively mitigates reflections without compromising critical environmental geometry.
- Demonstrated significant improvements in robustness and accuracy for state-of-the-art LiDAR odometry systems, particularly in maintaining vertical stability (z-axis).
- Successfully removed noise from reflective surfaces while preserving the crucial ground plane, which is vital for many robotic navigation tasks.

Key Takeaway

- Our approach offers a more intelligent and context-aware solution to LiDAR intensity filtering, directly benefiting applications in autonomous navigation and mapping within complex, reflective environments.

Thank you
for your attention

Federico Rollo
Technical Coordinator of Perceptive Navigation

Robotics Laboratory
Innovation Hub & IP, Leonardo Spa
Genova, Italy, 16151

federico.rollo@leonardo.com

LinkedIn

Website

leonardo.com

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