The Reflectance Field Map: Mapping Glass and Specular Surfaces in Dynamic Environments

Paul Foster[1], Collin Johnson[2], and Benjamin Kuipers[3]

[1]Cruise Automation, San Francisco, CA, USA [2]May Mobility, Ann Arbor, MI, USA [3]CSE, University of Michigan, Ann Arbor, MI, USA

Overview

- Modern man-made environments present significant difficulties for safe navigation of mobile robots that rely on lidar:
  - Specular surfaces (glass, metal, mirrors) are nearly invisible.
  - Dynamic objects present the same sensor signature as specular surfaces.
- Our method for mapping specular environments, the Reflectance Field Map (RFM), is:
  - A new approach for lidar-based robotic mapping that allows for robust mapping in the presence of specular surfaces.
  - An algorithm for distinguishing specular surfaces from dynamic obstacles in the Reflectance Field Map to support real-time operation in both highly dynamic and highly specular environments.

The RFM Represents the Environment Appearance from Every Viewing Direction

- Every material surface can be characterized by a function $f(w_i, w_o)$ expressing how much light is emitted in any direction w_o for a given direction of incoming light w_i.
  - This function is called the Bidirectional Scattering Distribution Function [1].
  - The transmitted and absorbed parts are often ignored, giving the Bidirectional Reflectance Distribution Function (BRDF).
- The *reflectance field, R,* is the set of BRDFs throughout space [2]:

$$R = R(x, y, z, w_i, w_o) = R(x, y, z, \theta_i, \phi_i, \theta_o, \phi_o)$$

- Assuming a 2D planar environment, we can approximate the full 7D function using a simpler 3D reflectance field:

$$\hat{R} = R(x, y, \theta_i)$$

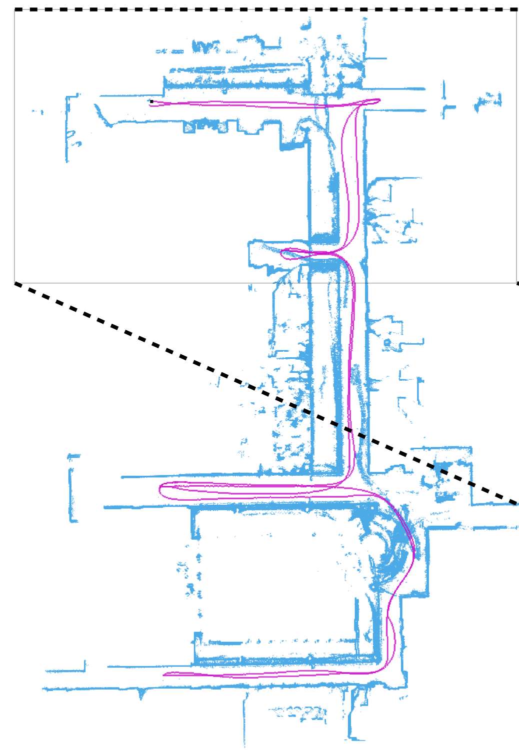
- The *reflectance field map (RFM)* is an approximation of continuous field as a 3D discretized grid:

$$\hat{\mathbf{R}}_i = \{\hat{R}_i\}$$

  - Uniform cells of size Δ_{xy} in the *x-y* plane and Δ_θ in the range θ=(0,2π].
  - Each cell, estimates “Is there any detectable reflectance at all?” as a binary random variable.

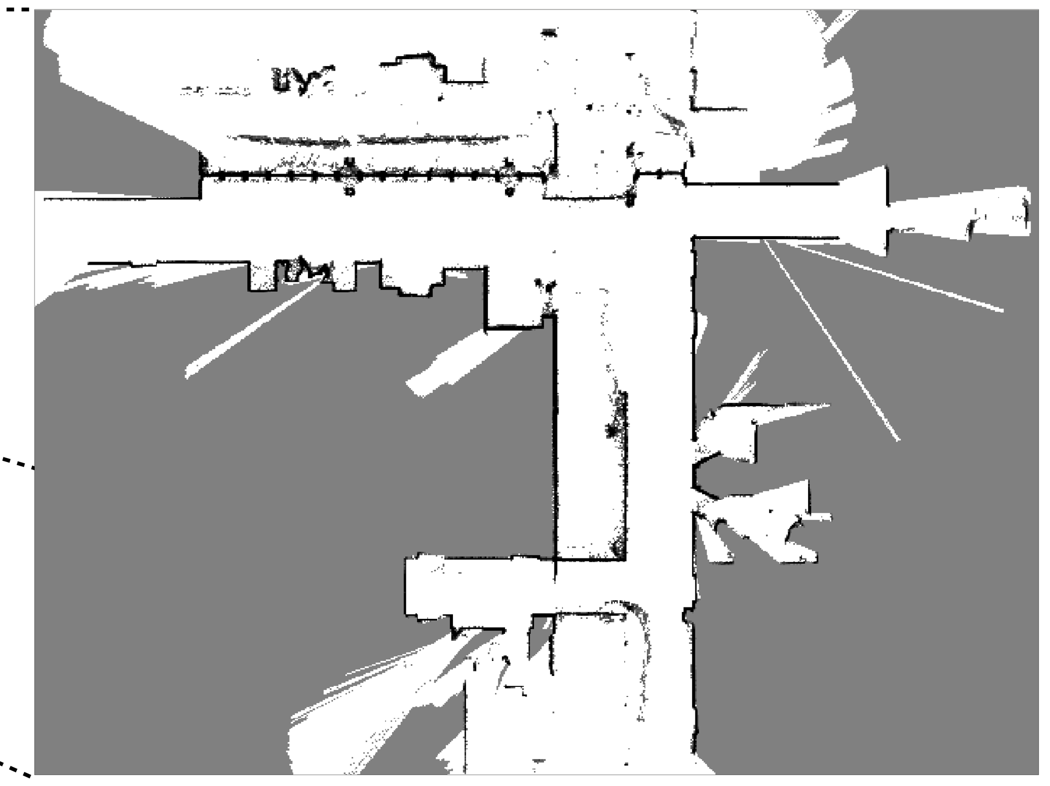
The Reflectance Field Map Discards Dynamic Agents and Reflections While Preserving Glass

Step 1: Acquire Data and Localize Robot



- Raw sensor data is acquired by onboard lidar(s).
- The robot is localized in the map.

Step 2: Add Scan to RFM Using Ray Casting

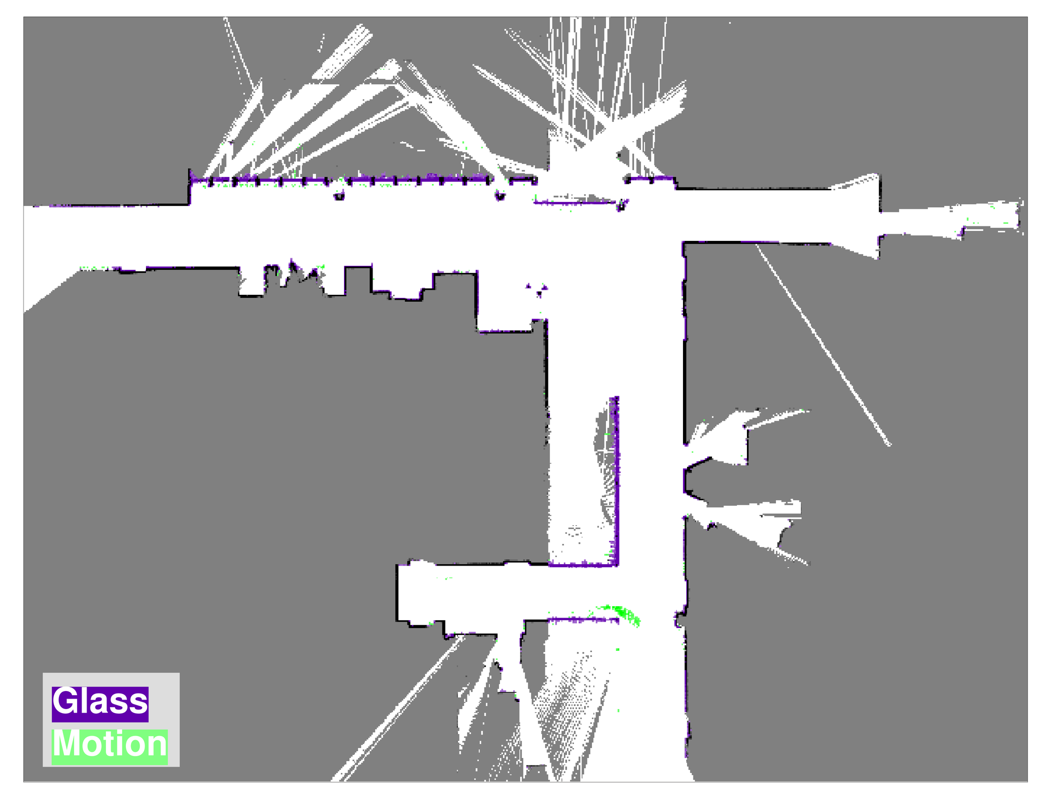


- Each ray in the lidar scan is added to the map using ray casting.

Step 3: Filter Motion by Finding Connected Components Containing Highly Visible Cells

- *Highly visible cells* are those visible from a wide range of angles, like the vertical lines in the H structure for glass.
- Dynamic obstacles are filtered by eliminating connected components that do not contain a highly visible cell.

Step 4: Remove Reflections by Periodically Reprocessing Scans

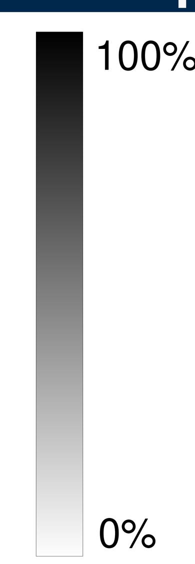


- Reflections are filtered by creating a new RFM based on the existing RFM.
- If a ray passes through glass, discard the evidence beyond the glass.

The RFM Substantially Improves Mapping of Specular Surfaces

Confusion Matrix for Occupancy Grid Classification of Laser Rays

		Predicted	
	Total	Kept (%)	Removed (%)
Diffuse	2253828	98.3	1.7
Glass	176619	51.6	48.4
Metal	13470	96.8	3.2
Motion	22439	0	100
Reflection	2102216	24.6	75.4



Confusion Matrix for RFM Classification of Laser Rays

		Predicted	
	Total	Kept (%)	Removed (%)
Diffuse	1705612	98.5	1.5
Glass	104478	98.7	1.3
Metal	7049	99.4	0.6
Motion	22439	0.3	99.7
Reflection	2102216	1.8	98.2

Cells With Sufficient Probability of Reflectance Are Treated As Obstacles

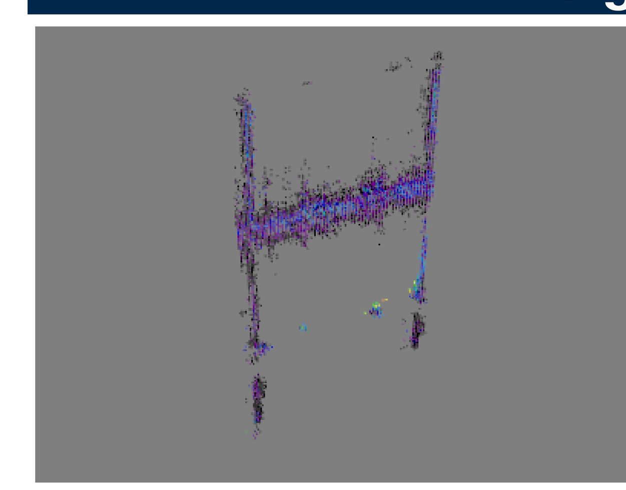
$$f_{\hat{R}}(x, y) = \sum_{\Theta=0}^{2\pi} [\Theta \in p(\hat{R}(x, y, \Theta) | \mathbf{Z^T}, \mathbf{X^T}) > \mathbf{0.5}] \mathbf{\Delta}_\theta > \alpha$$

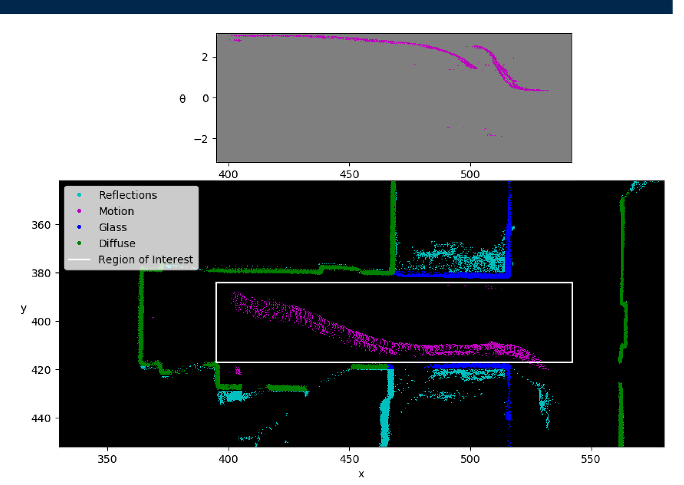
- An occupancy grid can be constructed from the RFM by marking cells with sufficient probability of reflectance as obstacles.

Dynamic Obstacles Create Ambiguities

- When a lidar sensor passes a point in a straight line:
  - It will only observe that point from any given angle once.
  - The intensity may also be similar to a diffuse wall.
- Consequently, there is no robust way to tell if a brief set of observations at that point are due to a moving object.
- We call this issue the *local ambiguity problem.*
- Our solution to the local ambiguity problem finds a non-local feature that is:
  - Highly discriminative between motion and glass,
  - Robust to varying levels of curvature and transparency, and
  - Robust to out-of-plane tilt caused by bumps or suspension loading.

Specular Surfaces in the RFM Have a Distinctive Signature





- If we plot the reflective cells from an RFM taken near a pane of glass in 3D (x,y,θ), we see a distinctive H shape.
  - The side of the H are aligned to the θ-axis.
- In contrast, a moving object appears as a single relatively thin stroke in 3D. The stroke:
  - Has no intersections with other strokes.
  - Does not travel parallel to the θ-axis unless the object temporarily stops.

References

[1] F. O. Bartell, E. L. Dereniak, and W. L. Wolfe, “The theory and measurement of bidirectional reflectance distribution function BRDF and bidirectional transmittance distribution function BTDF,” in *Radiation scattering in optical systems*, vol. 257. SPIE, 1981, pp.154–160.

[2] P. Debevec, T. Hawkins, C. Tchou, H.-P. Duiker, W. Sarokin, and M. Sagar, “Acquiring the reflectance field of a human face,” in *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, 2000, pp. 145–156.