Autonomous Reconstruction of Unknown Indoor Scenes Guided by Time-varying Tensor Fields

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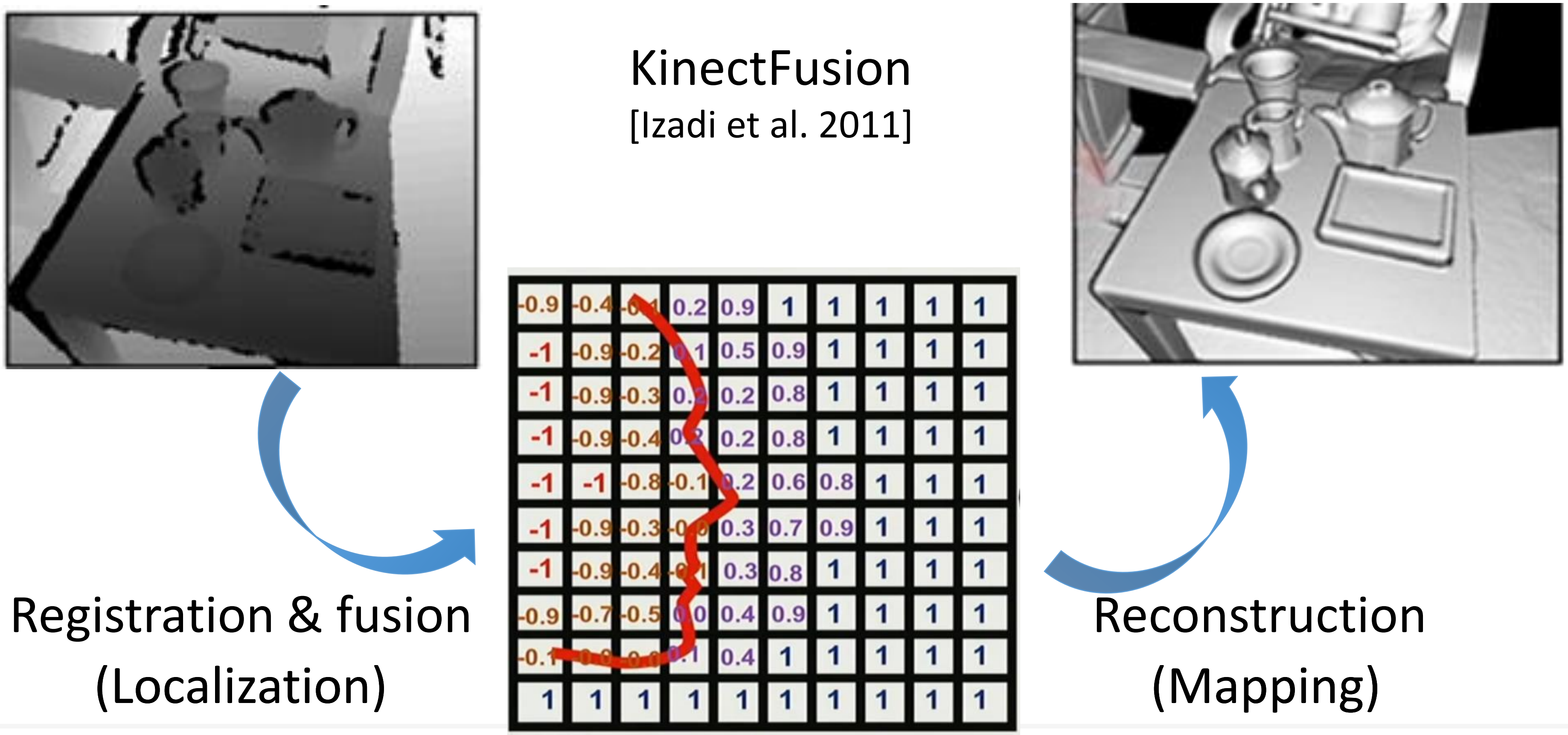
Shenzhen University
Oregon State University
Stanford University
National University of Defense Technology
University of Konstanz
Tel-Aviv University

Background

- Commodity RGBD sensors & real-time reconstruction



Background

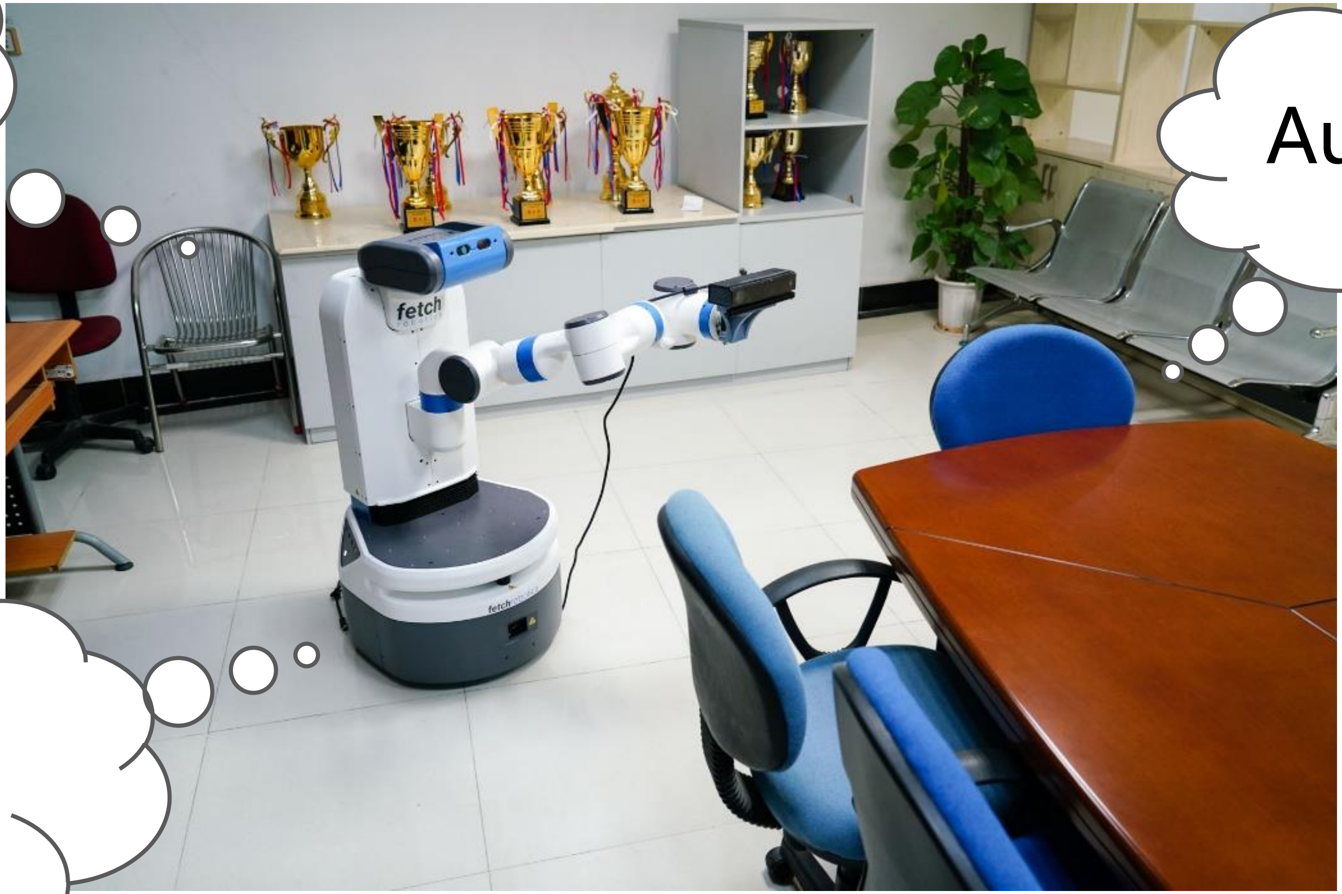
- Human scanning is a laborious task

Huge human effort

Inaccurate scanning

Motivation

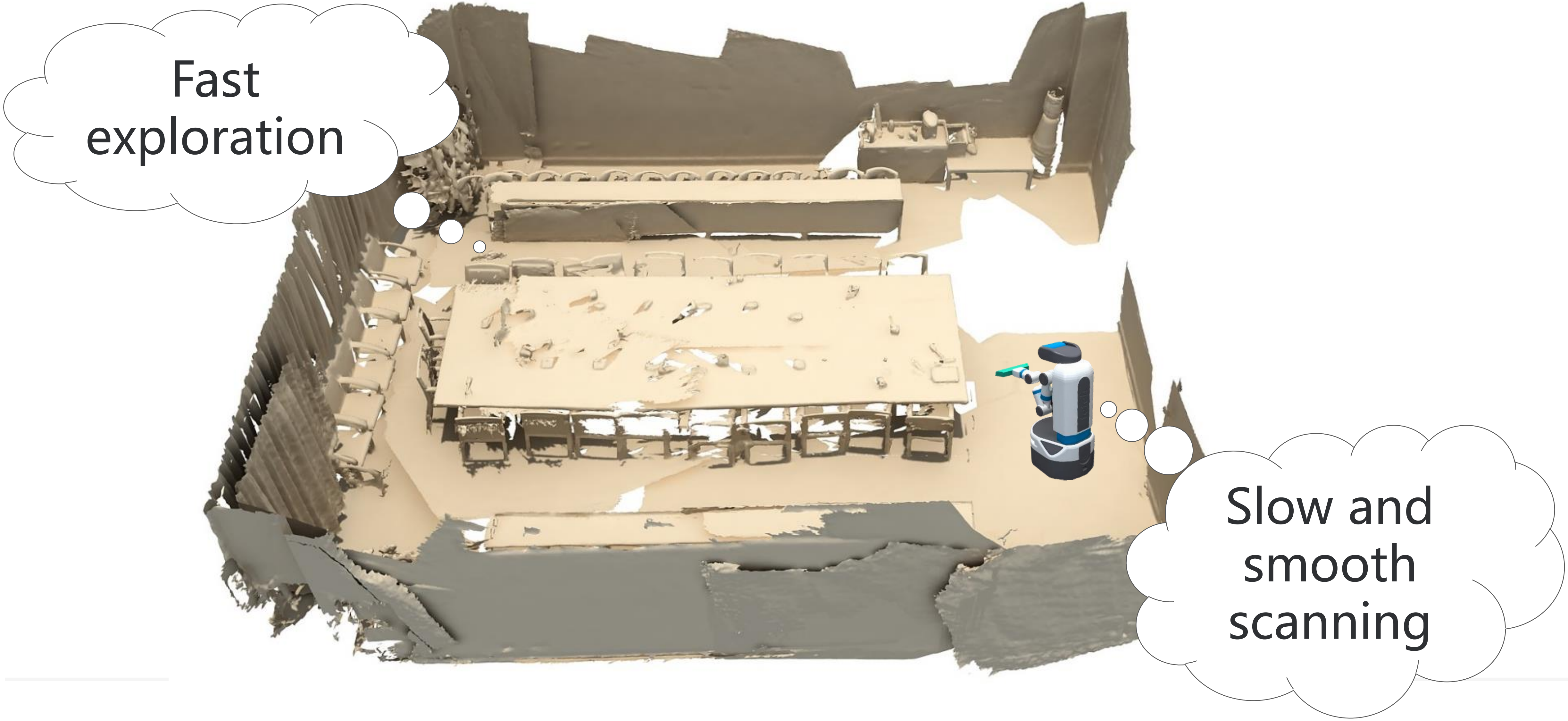
Never feel tired

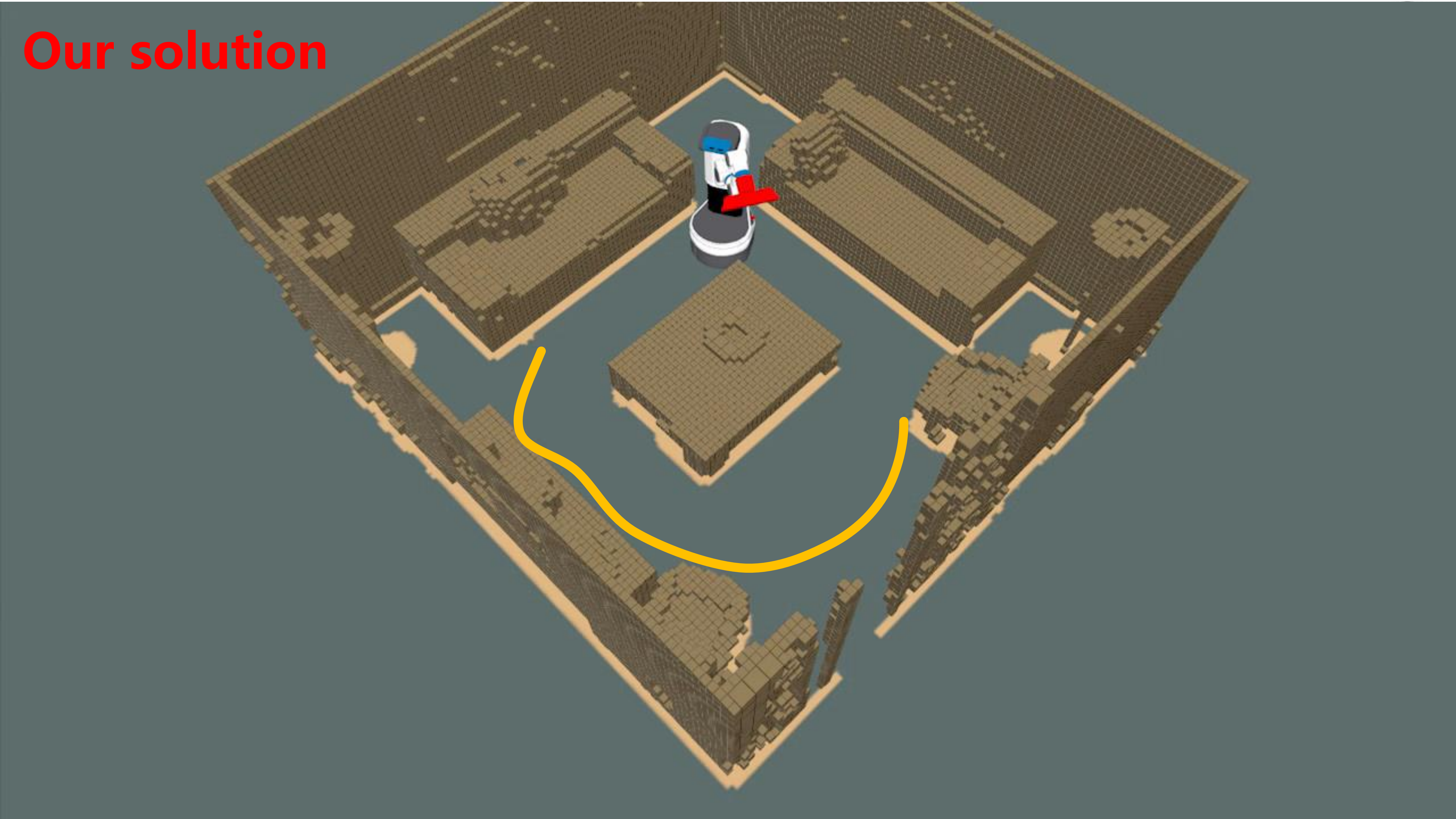


Automatic

Stable and accurate movement

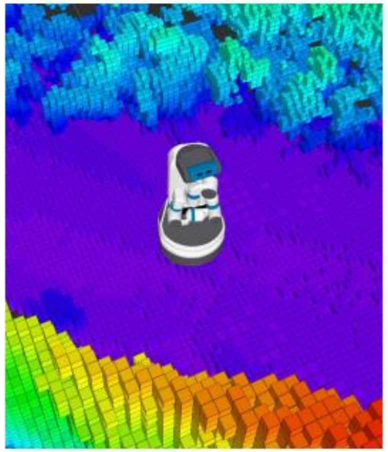
Difficulty of auto-scanning in *unknown* scenes



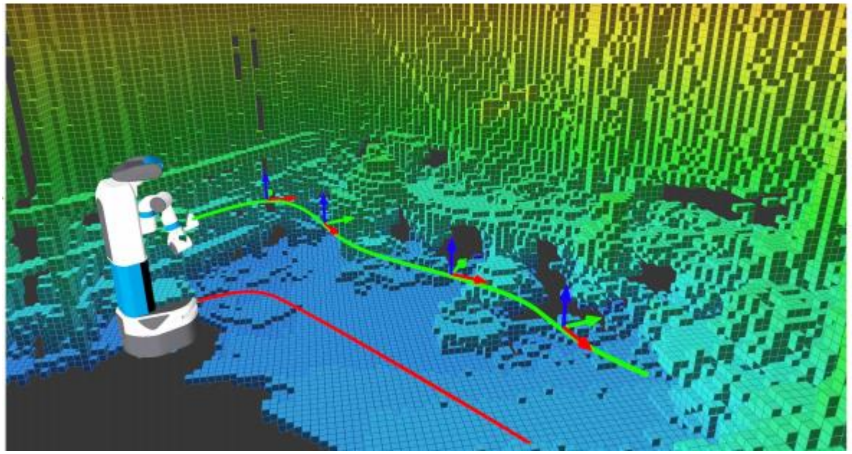

Our solution

Pipeline

Scanning and online reconstruction

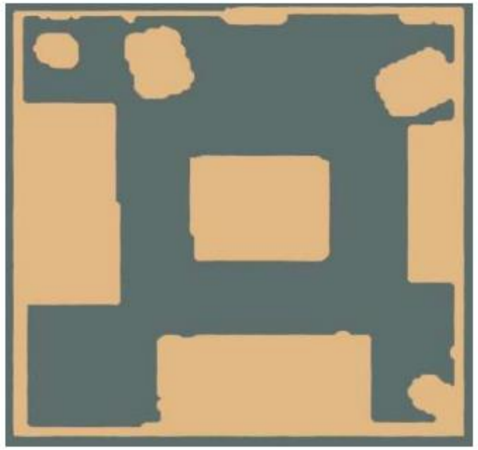


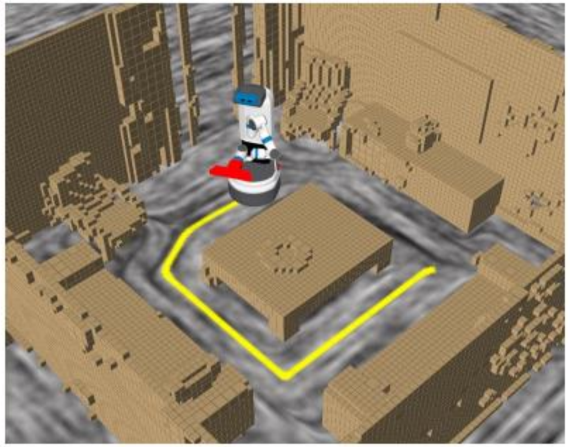
Estimating camera trajectory

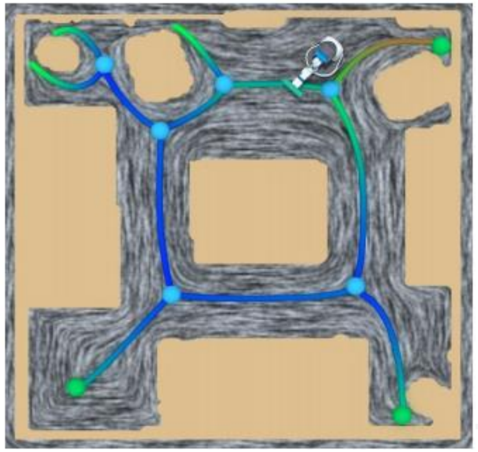


Local path advection

Global path routing







Field updating and field-guided path finding

Key techniques

- Tensor field update
  - 2D tensor field
  - Time-varying tensor fields update
- Field guided path planning
  - Local path generation by particle advection
  - Global path finding by field topology
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- Path-constrained camera trajectory estimation

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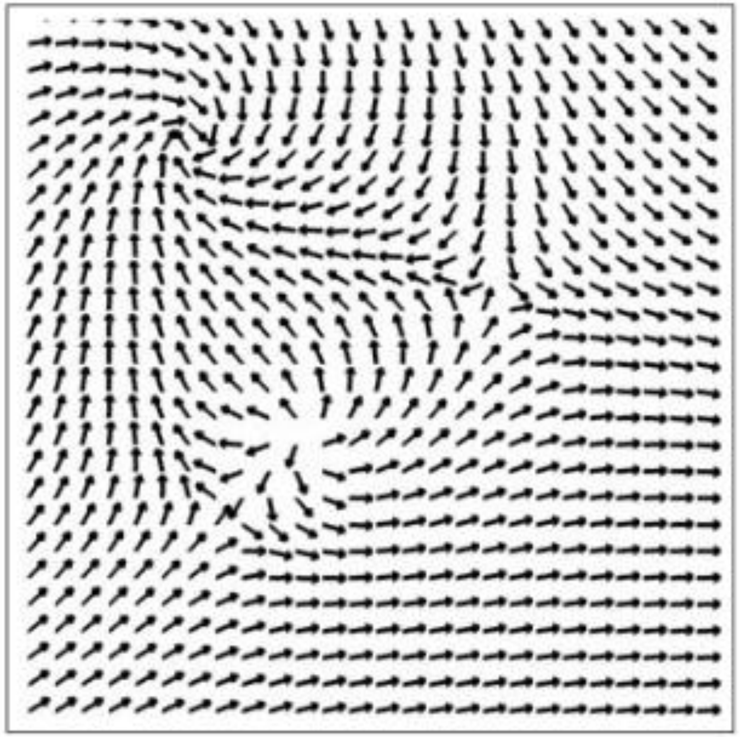
2D Tensor Field

In a 2D domain, assign every point a direction, but **NOT** orientation

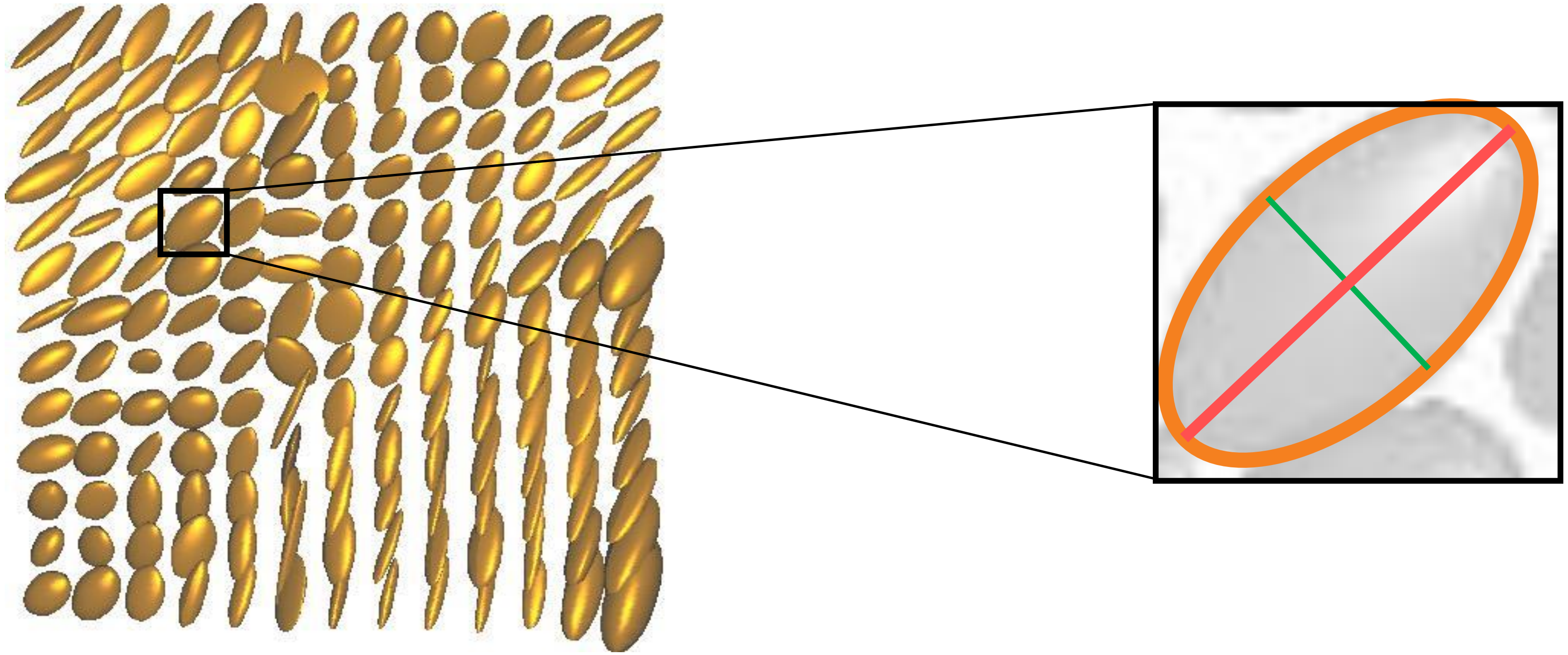


Vector field

Tensor field

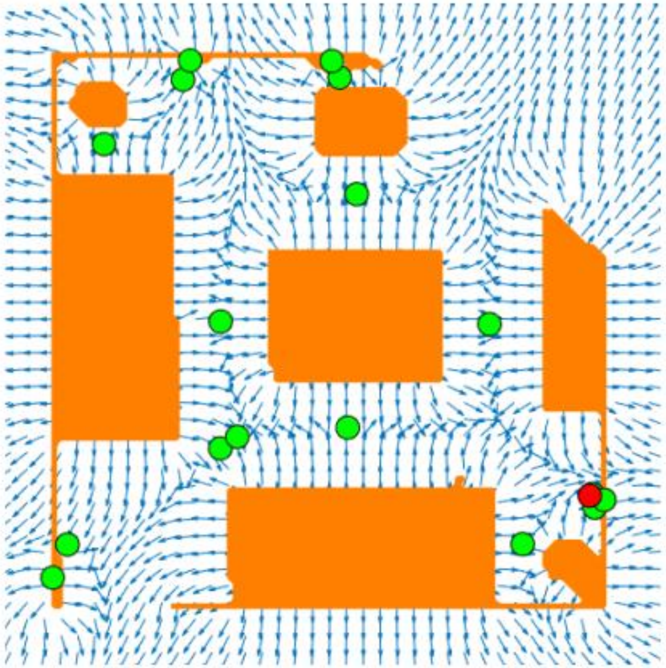
2D Tensor Field

- Assign every point a tensor: $T(p) = \begin{pmatrix} \tau_{11}(p) & \tau_{12}(p) \\ \tau_{21}(p) & \tau_{22}(p) \end{pmatrix}$



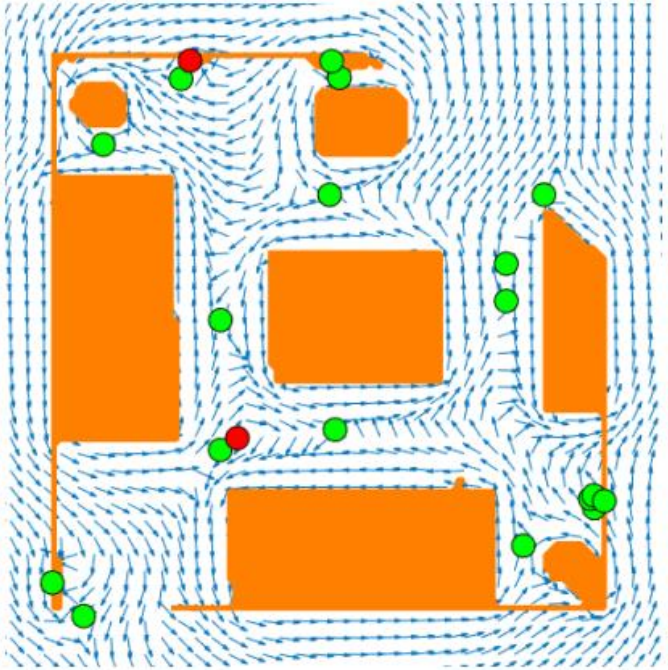
Why Tensor field?

- Fewer singularities



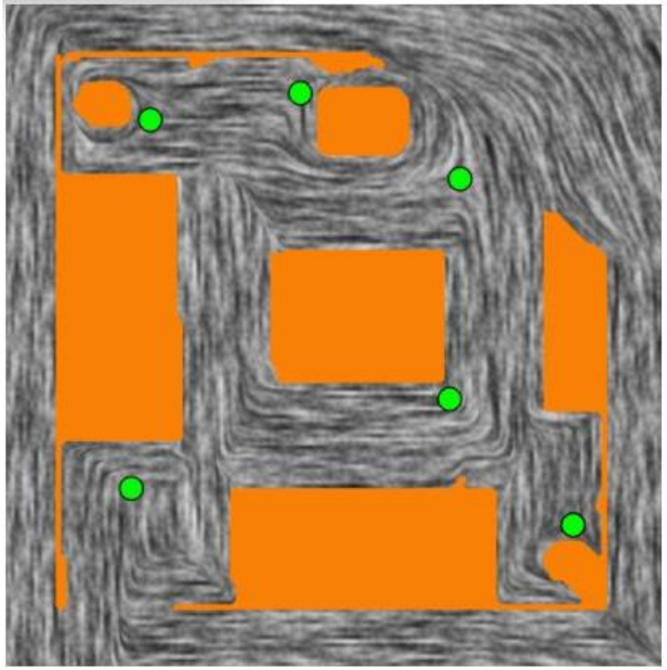
Potential field

[Khatib et al. 1986]



Gradient field

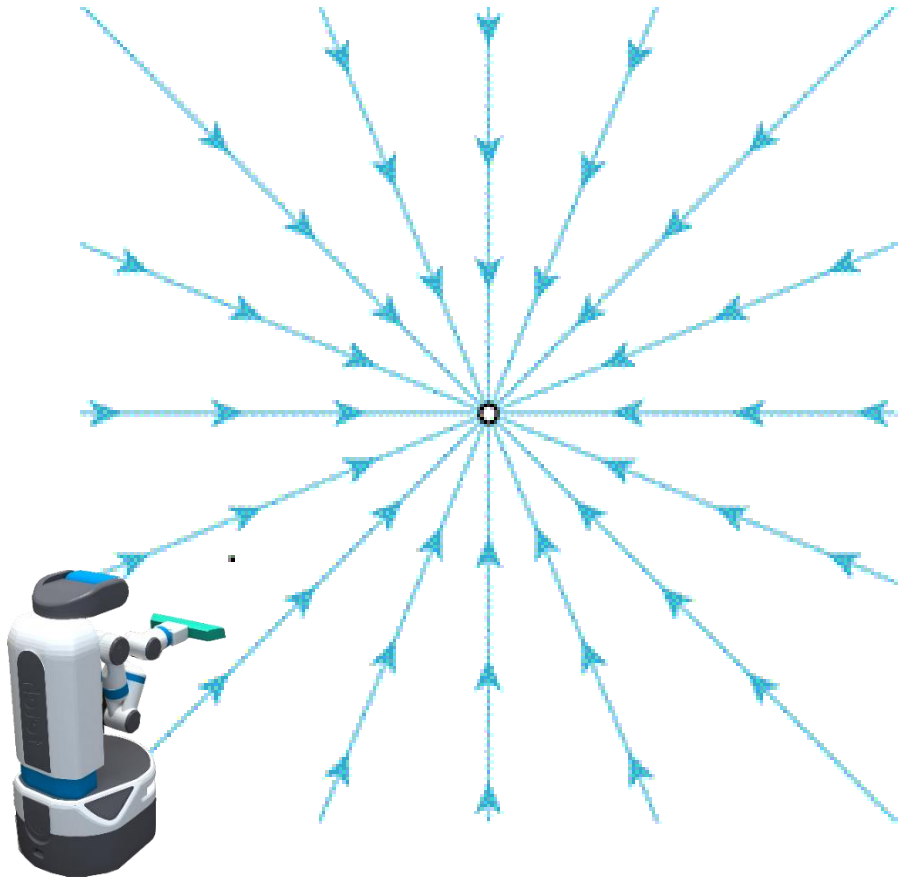
[Shade and Newman 2011]



Tensor field

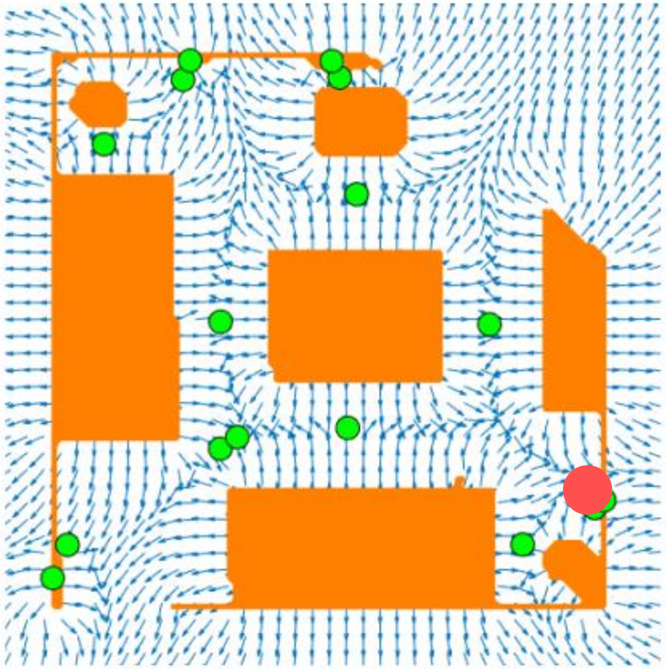
Why Tensor field?

- Sink-free



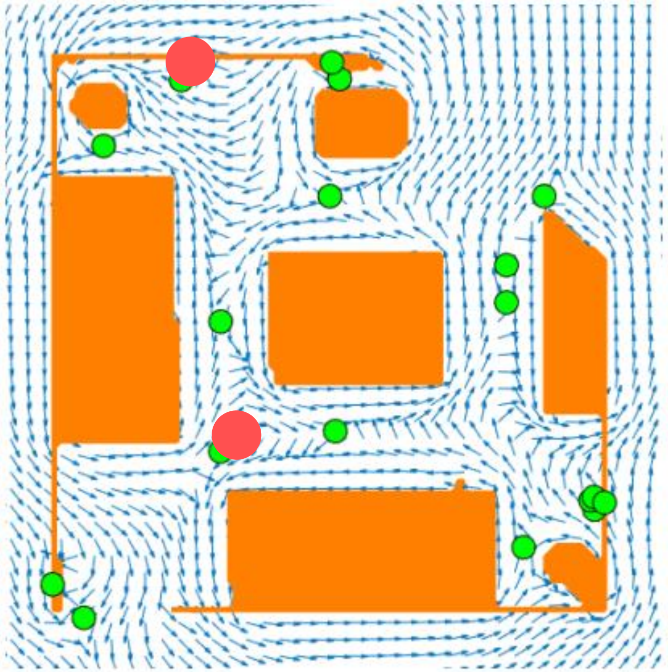
Why Tensor field?

- Sink-free



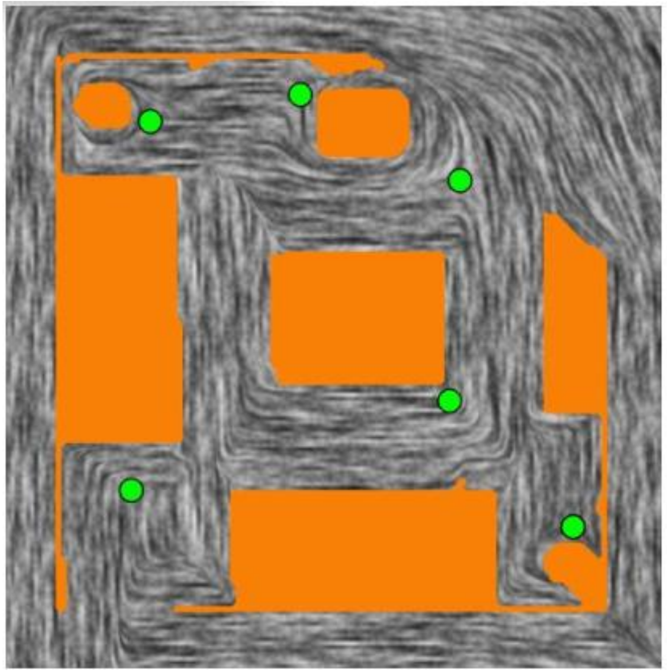
Potential field

[Khatib et al. 1986]



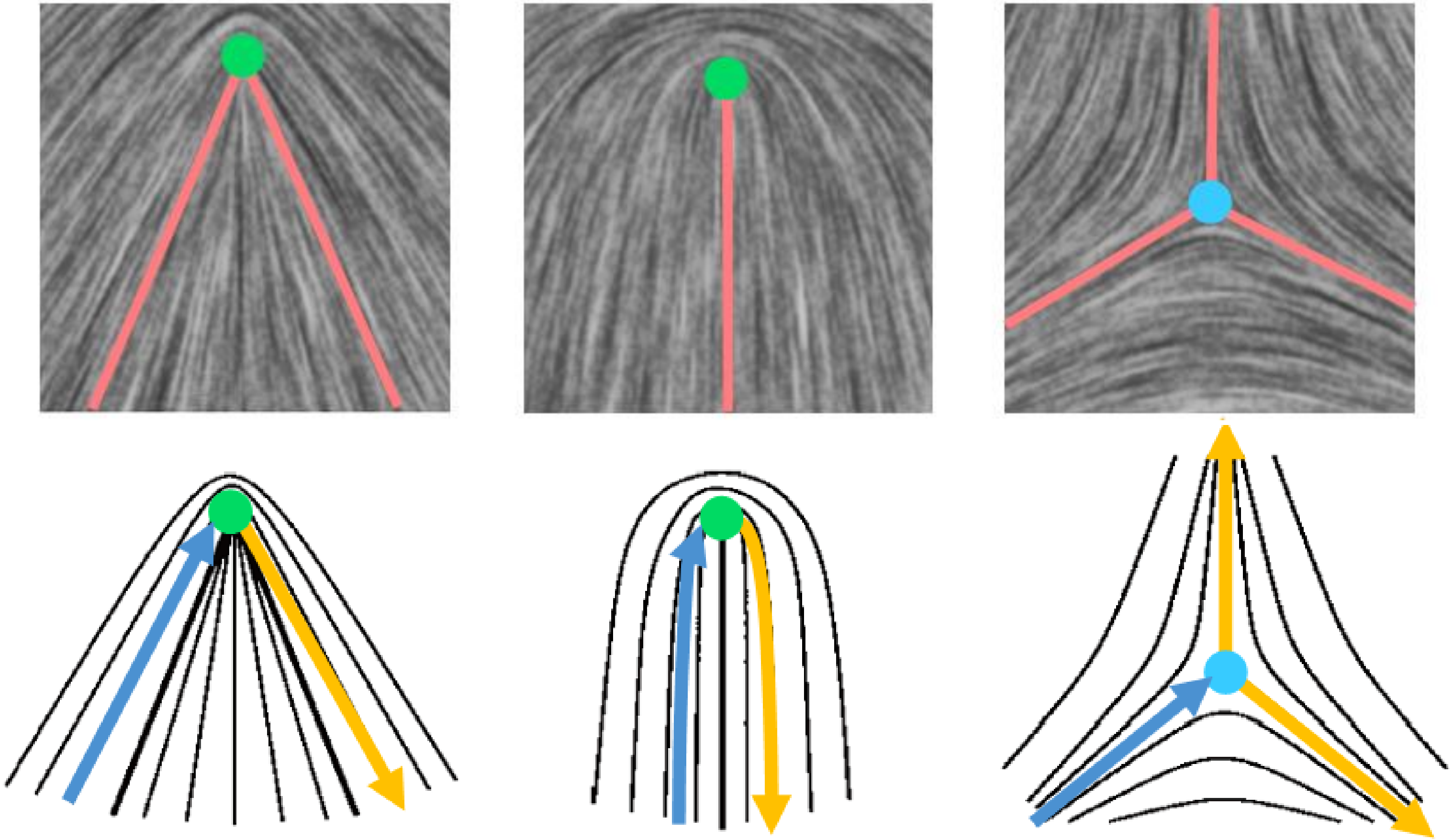
Gradient field

[Shade and Newman]



Tensor field

Why Tensor field?

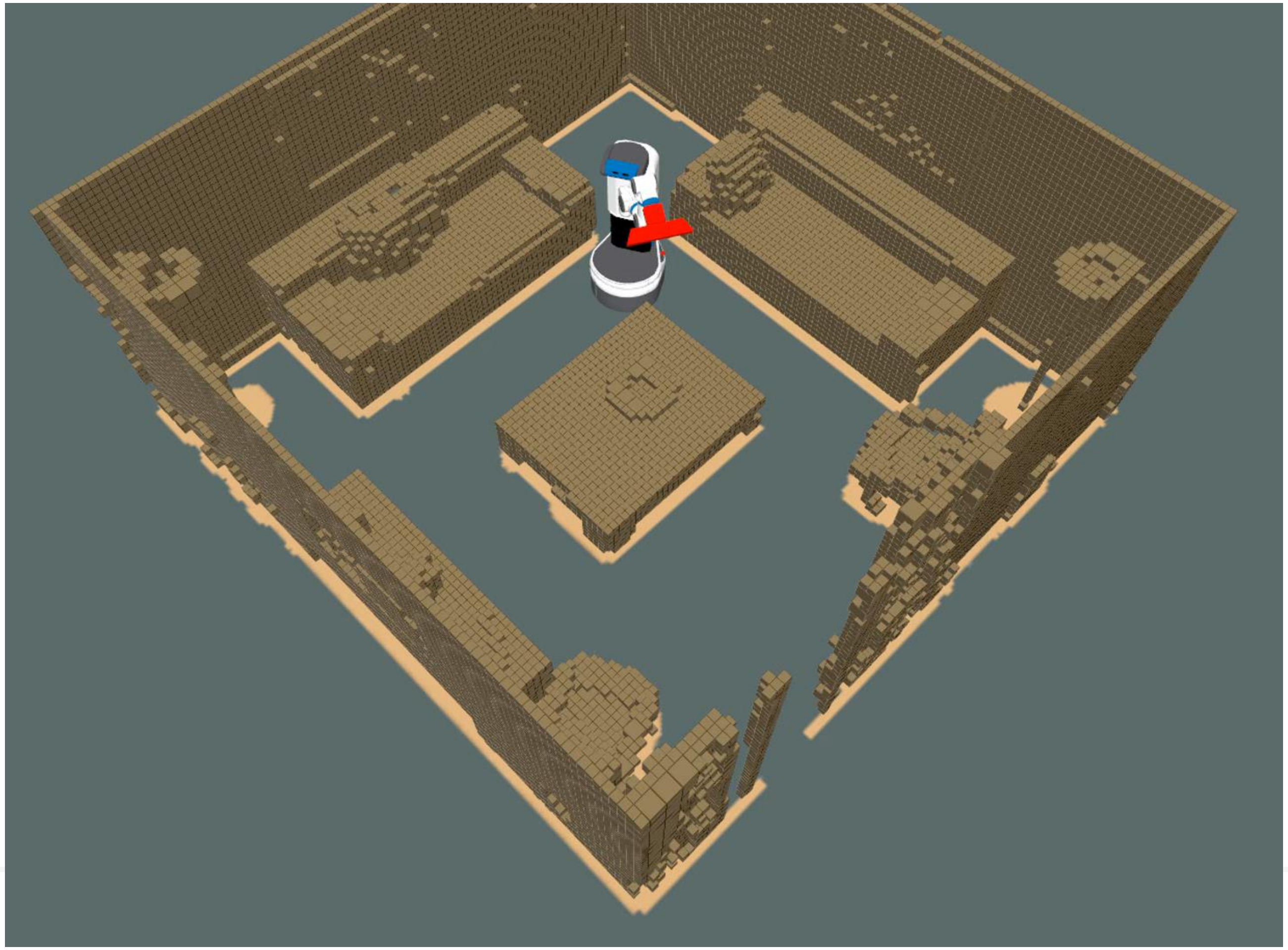


(a) Wedge-I (b) Wedge-II (c) Trisector

Tensor fields do have degenerate points

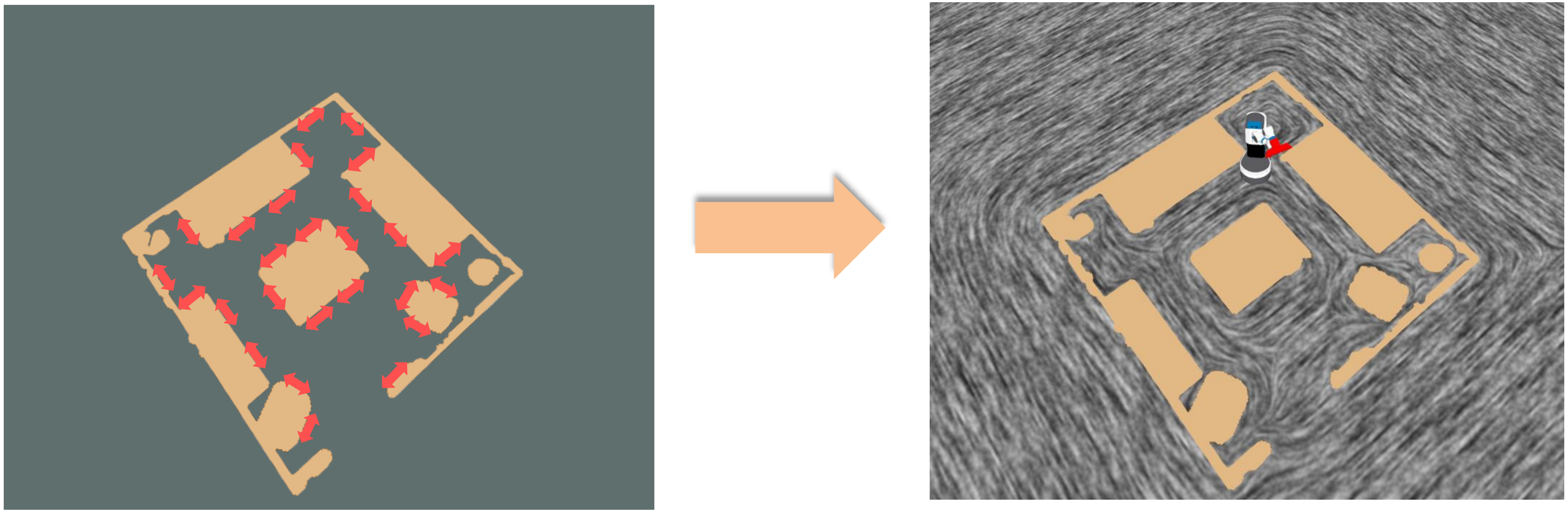
Tensor field update

- The currently scanned scene is projected onto the floor plane

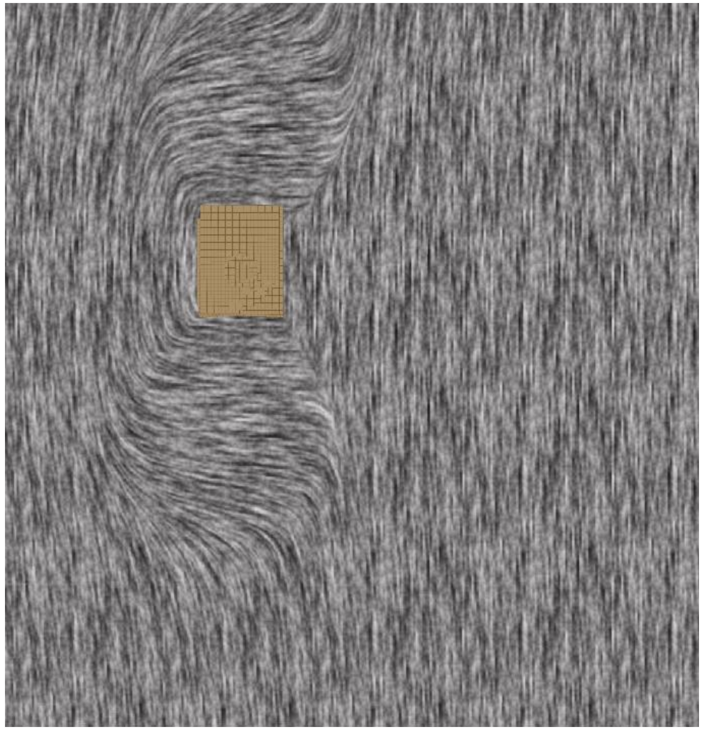


Tensor field update

- Based on the tangential constraint of the 2D projection, a 2D tensor field is computed

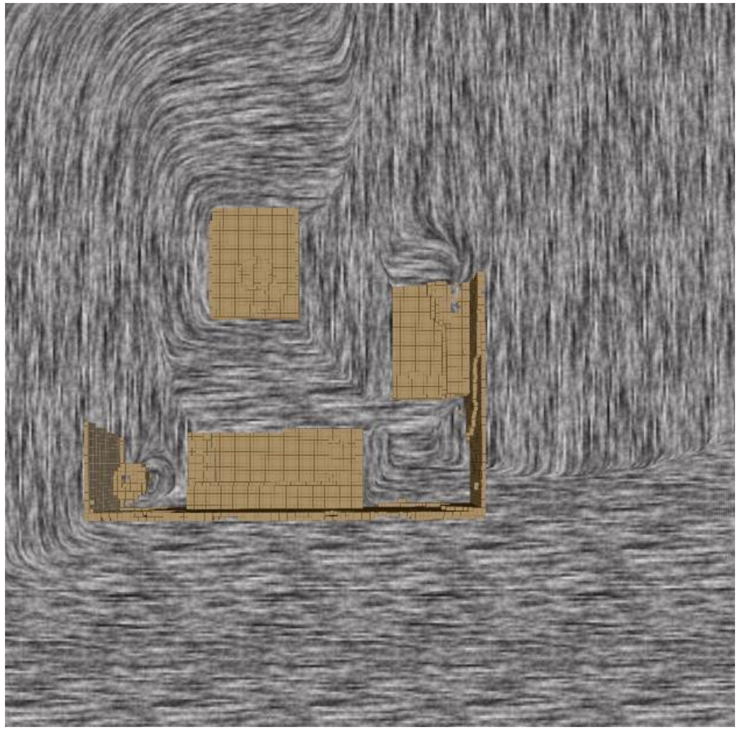


Tensor field update



T^{t-1}

A smooth transition from T^{t-1} to T^t ?

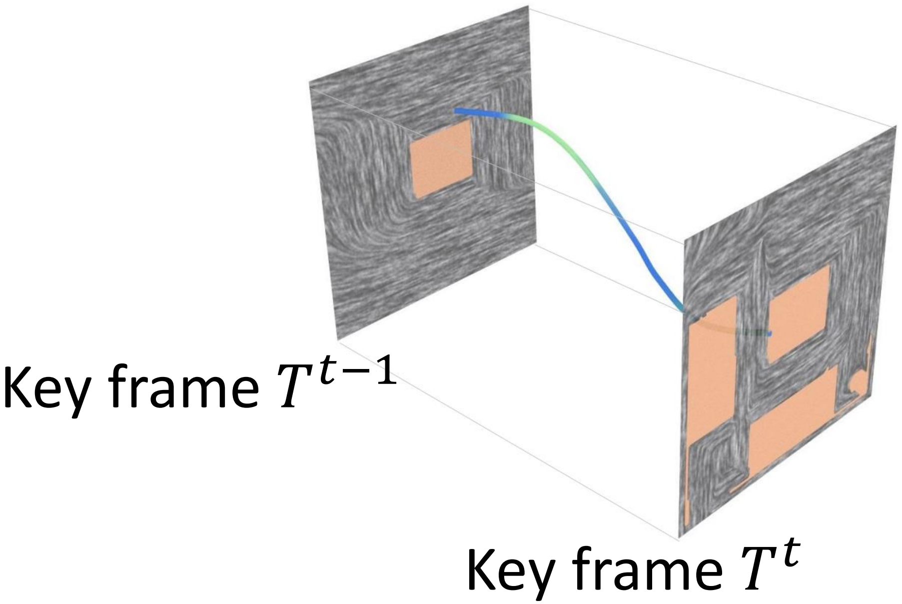


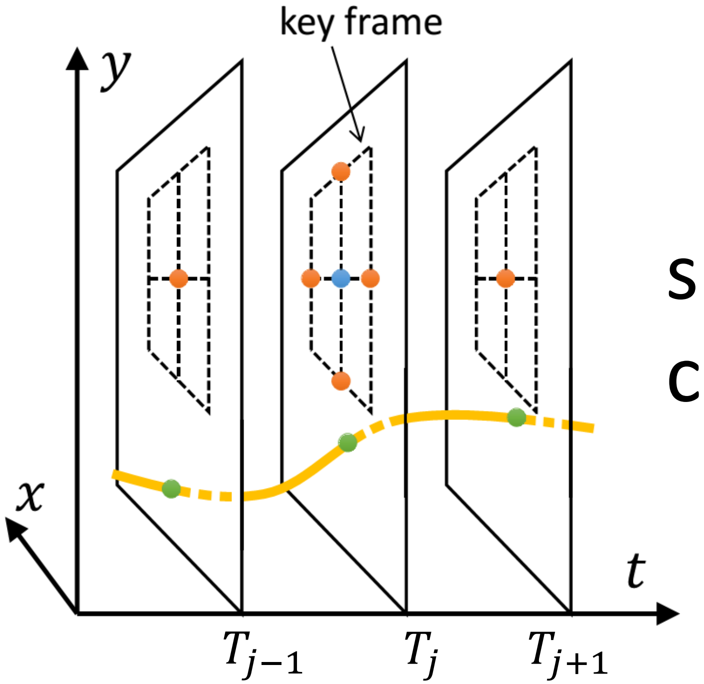
T^t

Time-varying tensor fields

Tensor field update

- Time-varying tensor fields update





spatial-temporal constraint

Solve a spatial-temporal Laplacian system

Key techniques

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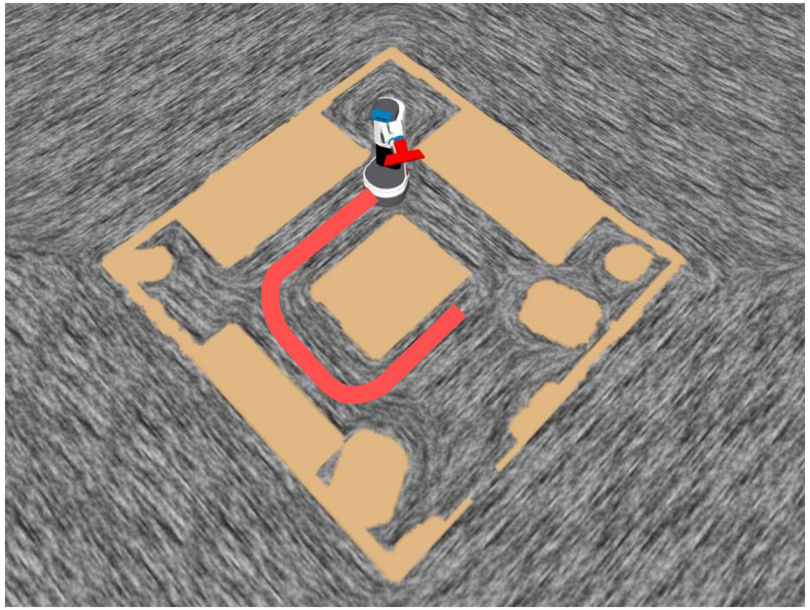
Local Path Generation

- Particle advection over tensor field



$$p(t) = p_0 + \int_0^t V(p(s); t_0 + t)\mathrm{d}s$$

Key Points

- Geometry-aware tensor field update
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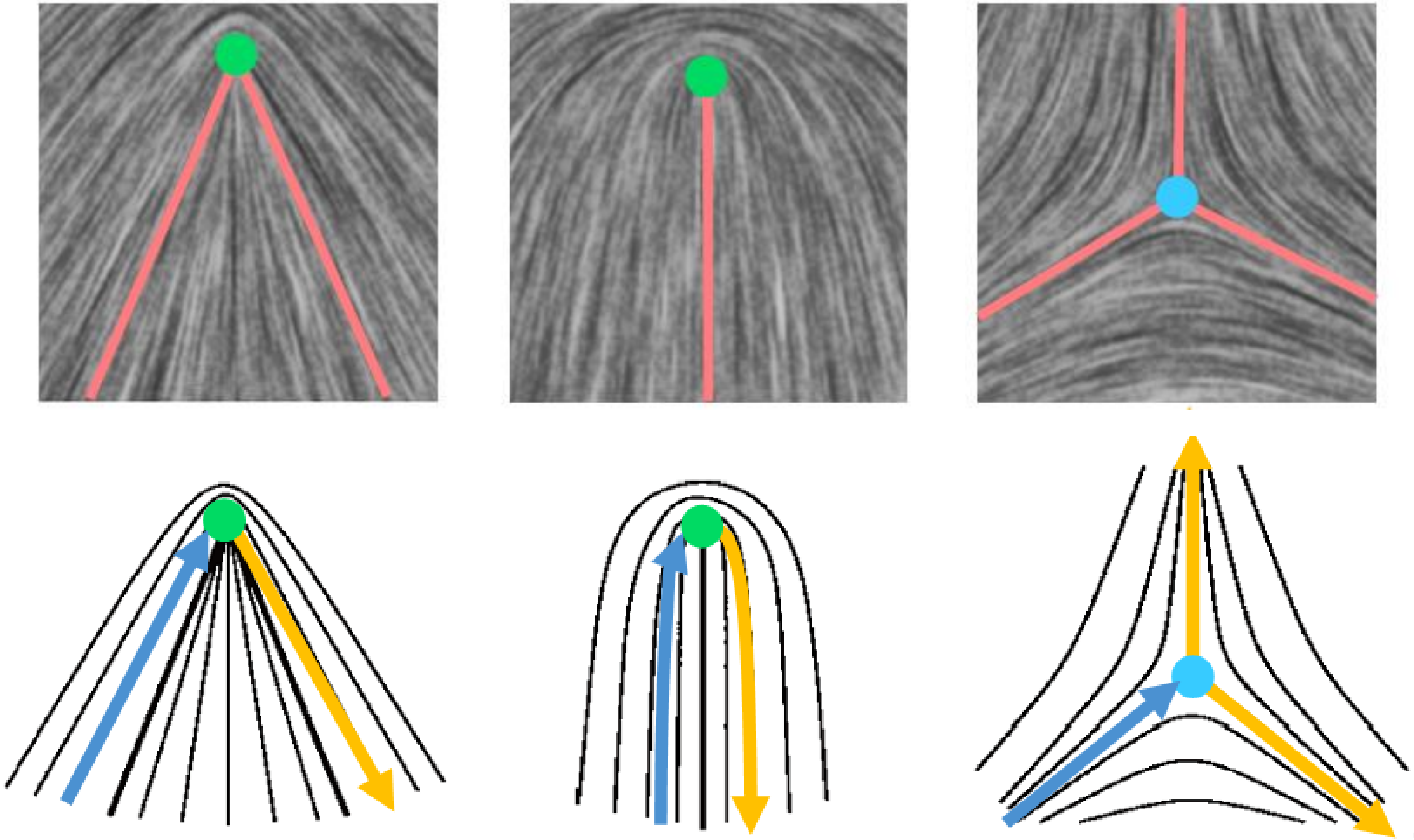
Global path planning

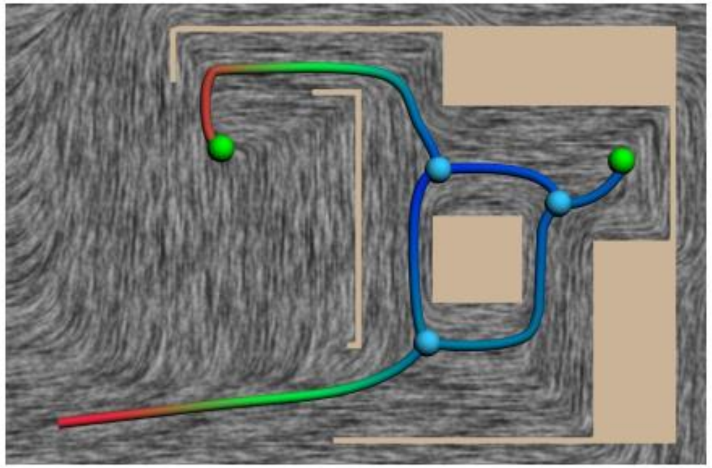
- Degenerate points



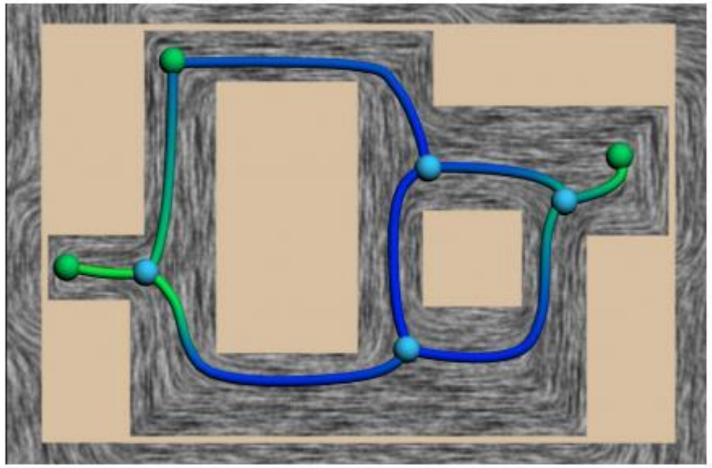
(a) Wedge-I (b) Wedge-II (c) Trisector

Global path planning

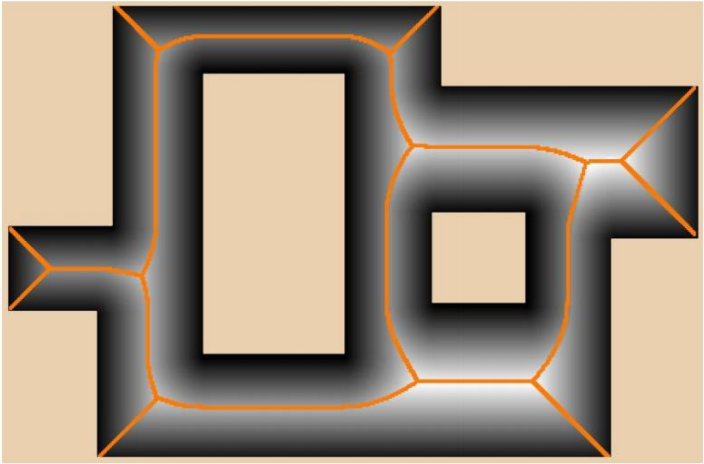
- Topological **graph** of tensor field
  - Node: Degenerate points
  - Edge: Separatrix lines connecting degen. points



For a partial scene



For the full scene

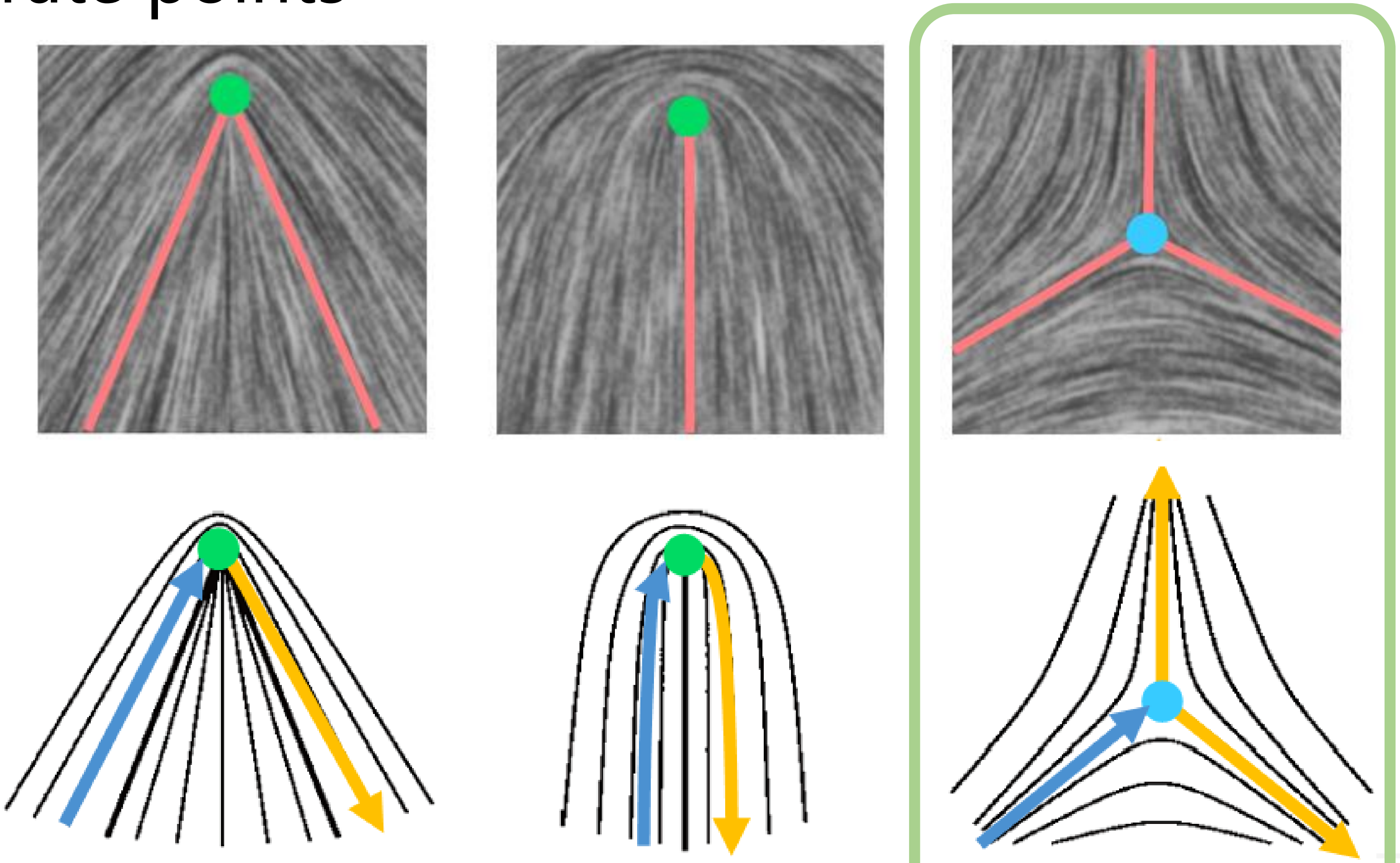


Medial axis

Robot path finding → Finding paths over the field topo. graph !

Global path planning

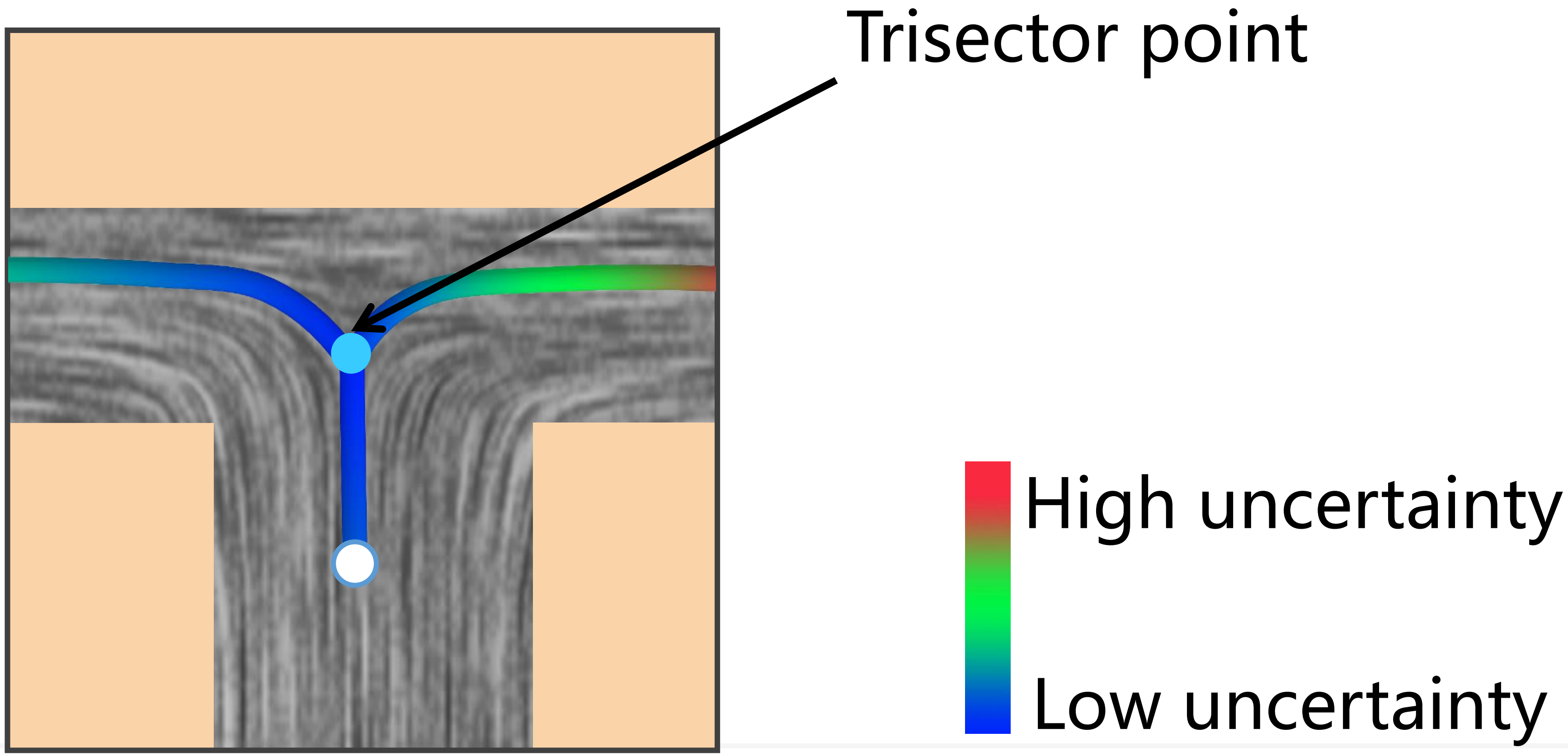
- Degenerate points



(a) Wedge-I (b) Wedge-II (c) Trisector

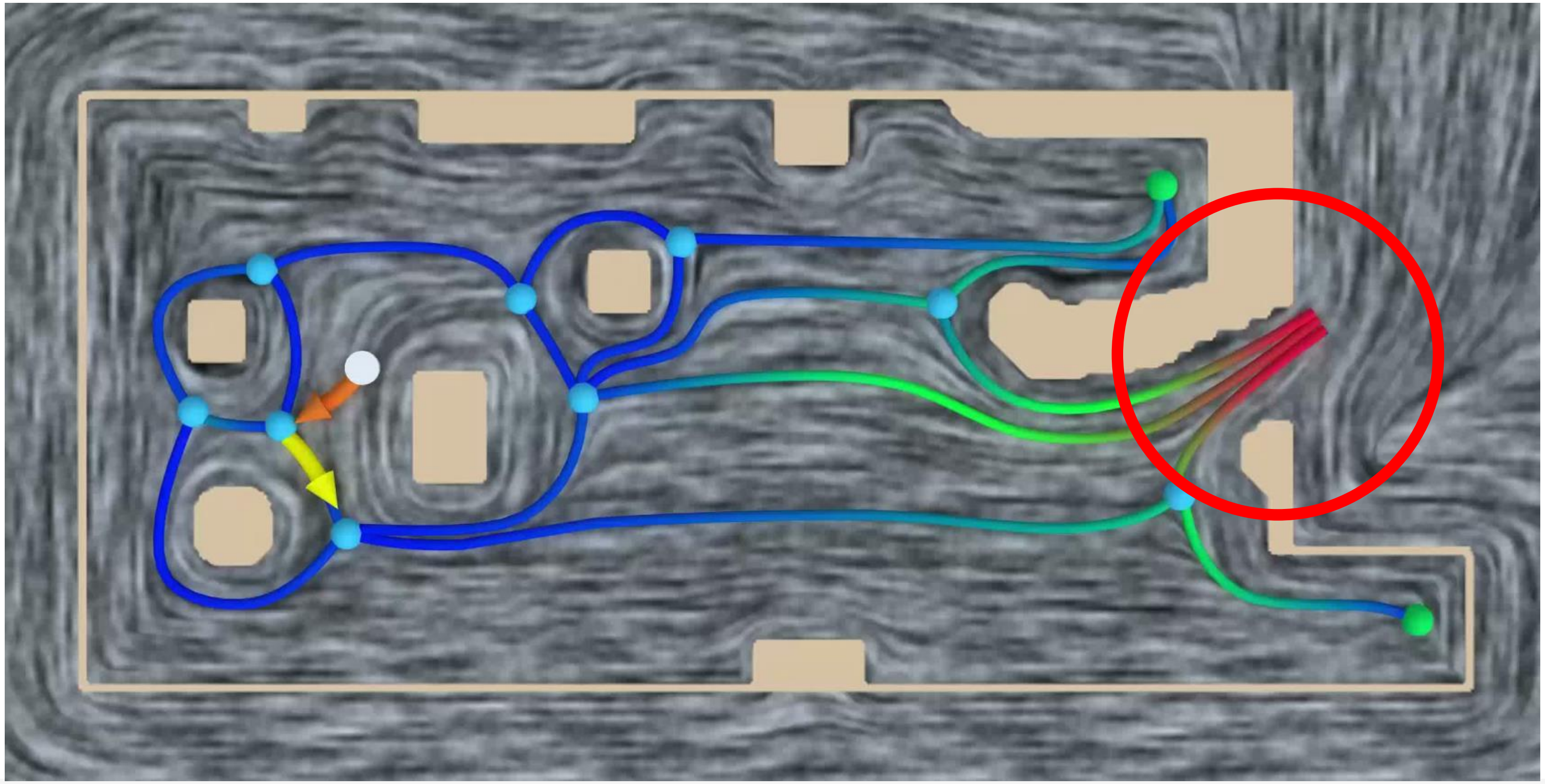
Global path planning

- How to select brunch at a trisector?



Global path planning

- Path routing with field topology



Global path planning

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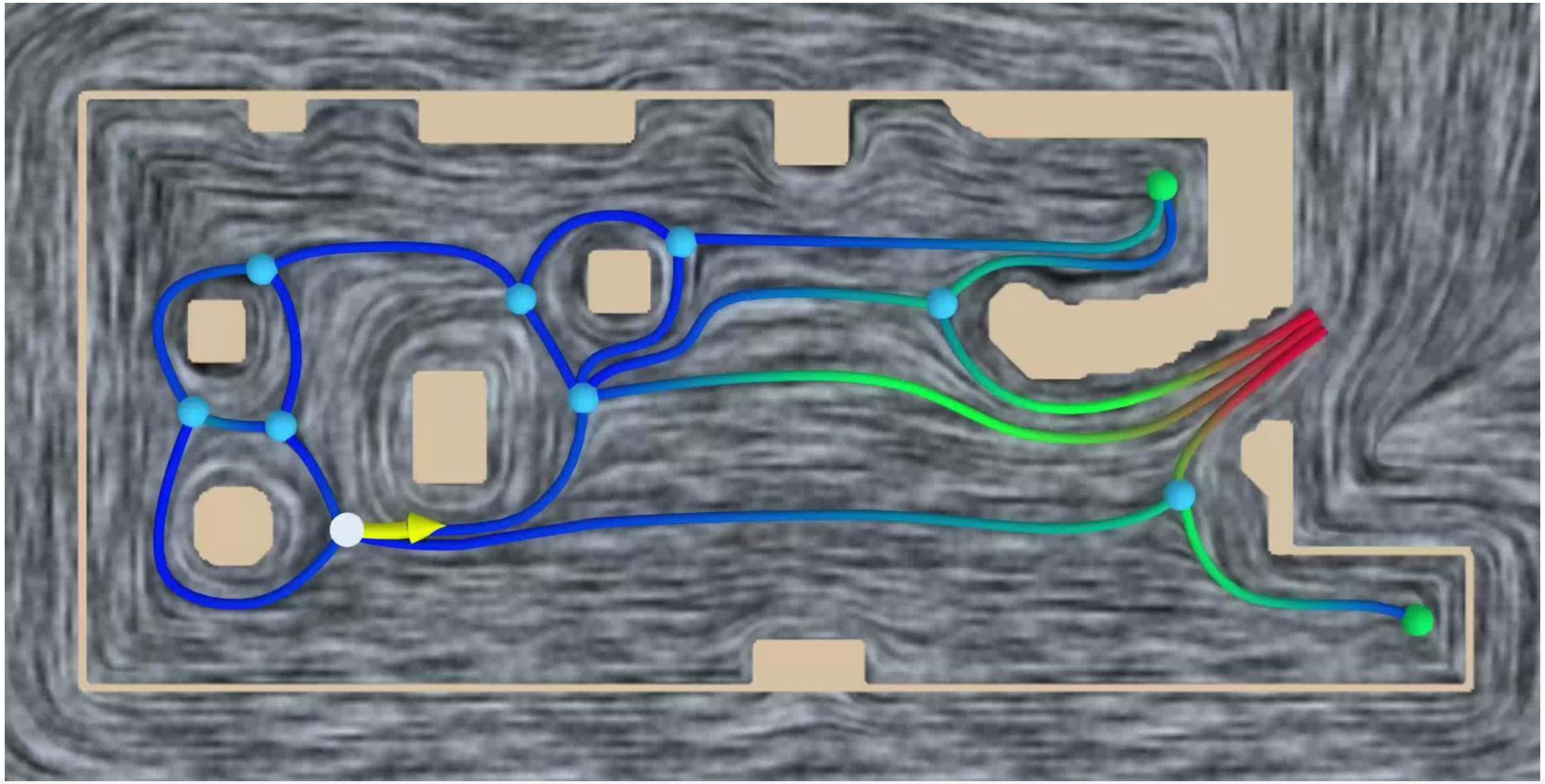

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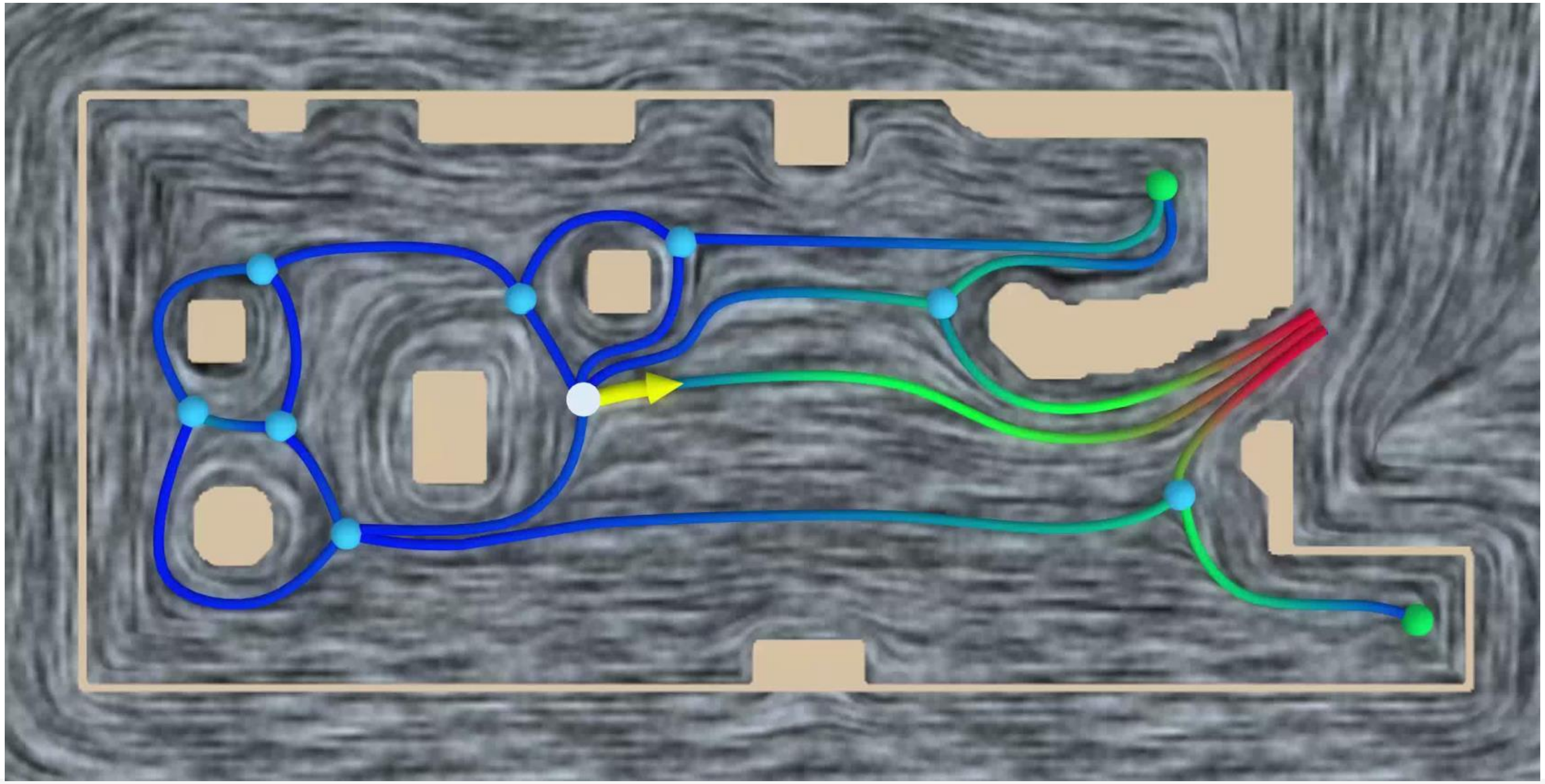

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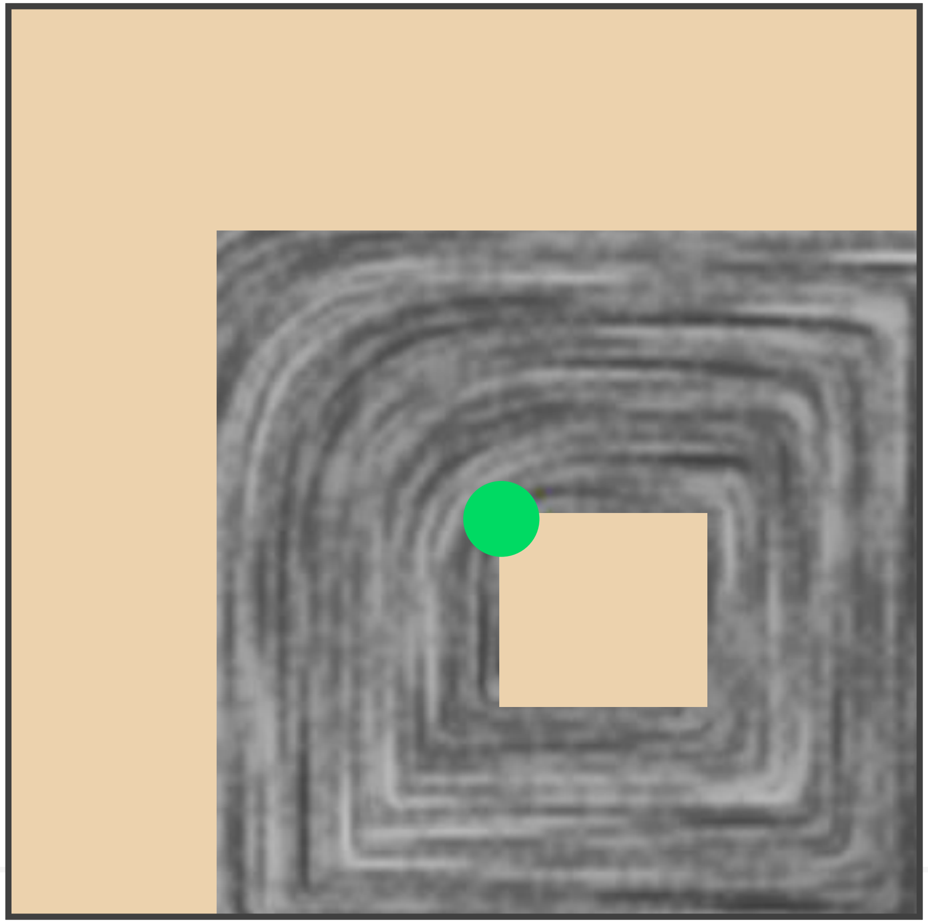
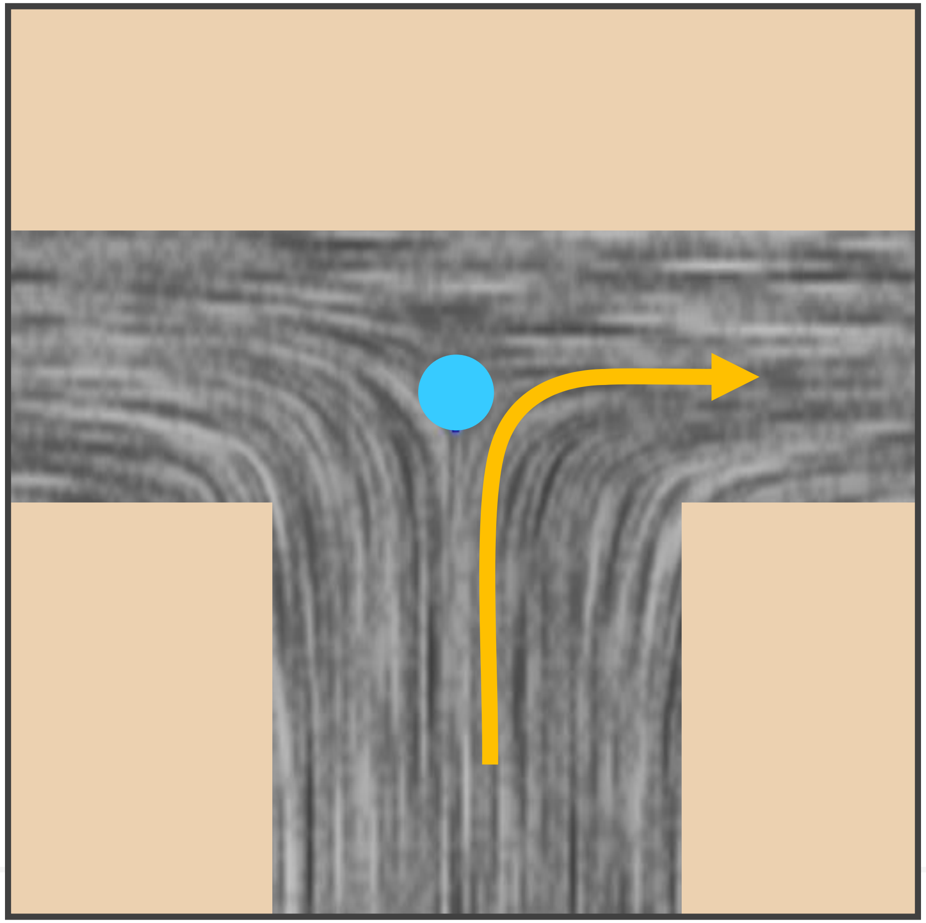
Field topology control

- Movement of a degenerate point



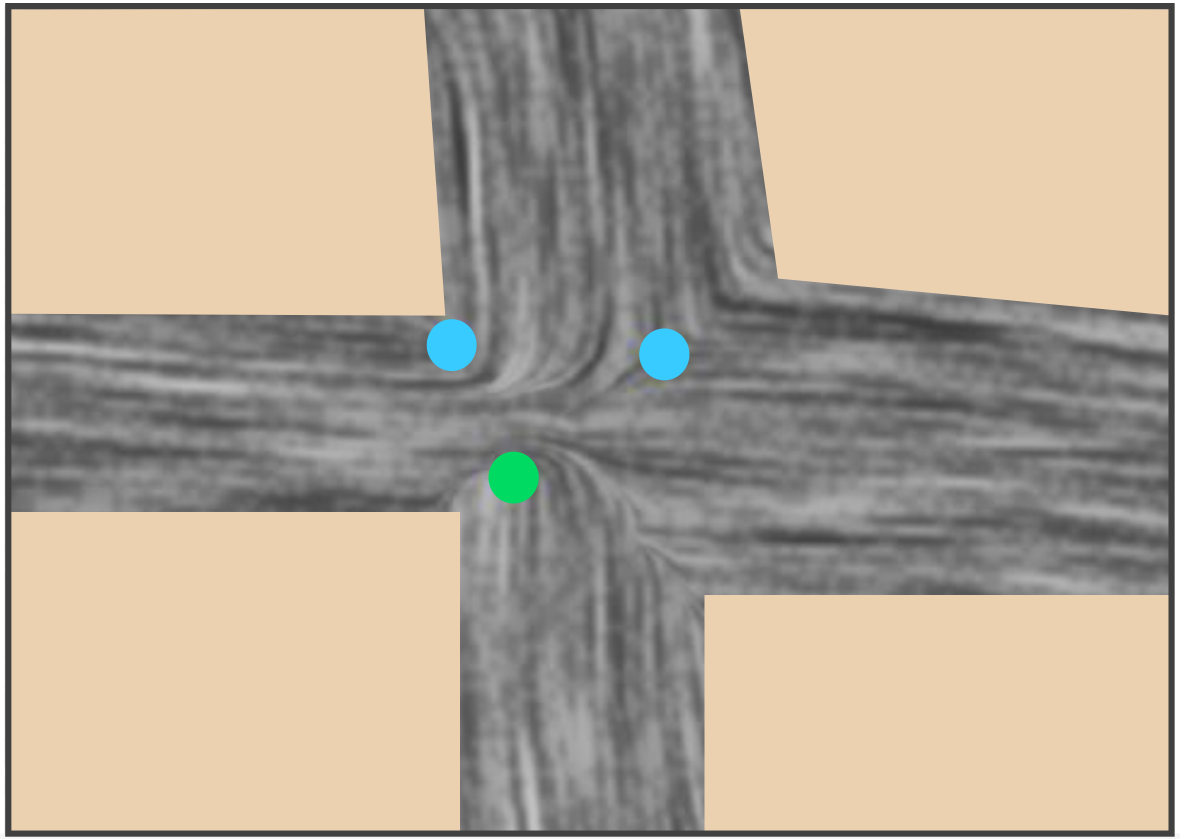
Field topology control

- Movement of degenerate points



Field topology control

- Cancellation of degenerate pairs



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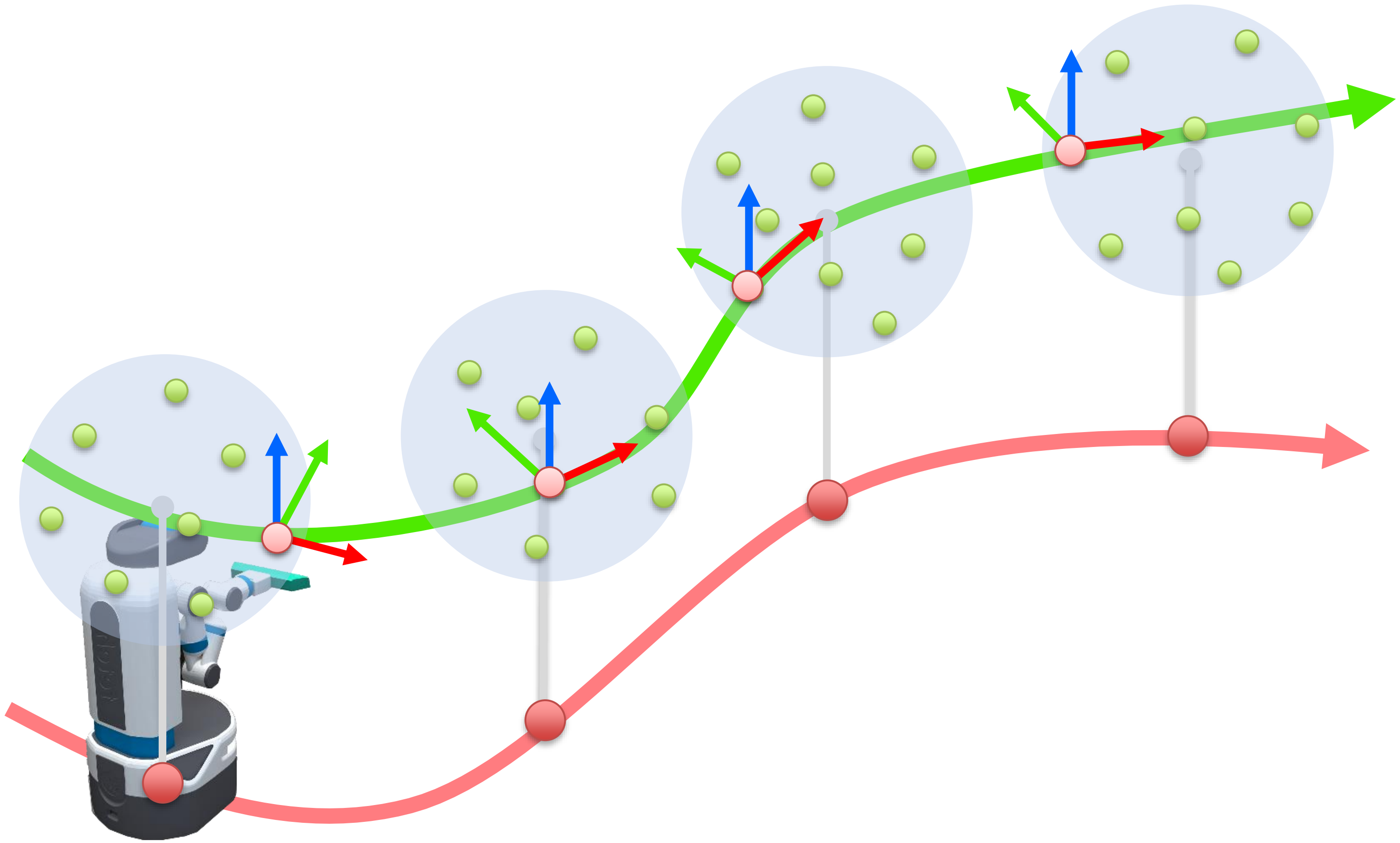
Camera Trajectory Optimization



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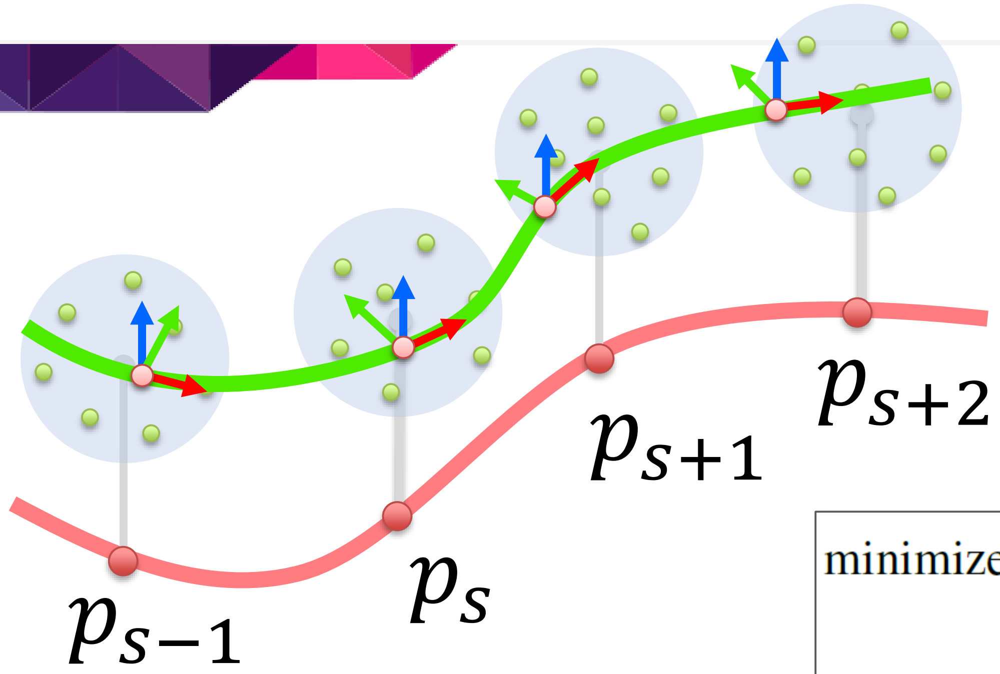
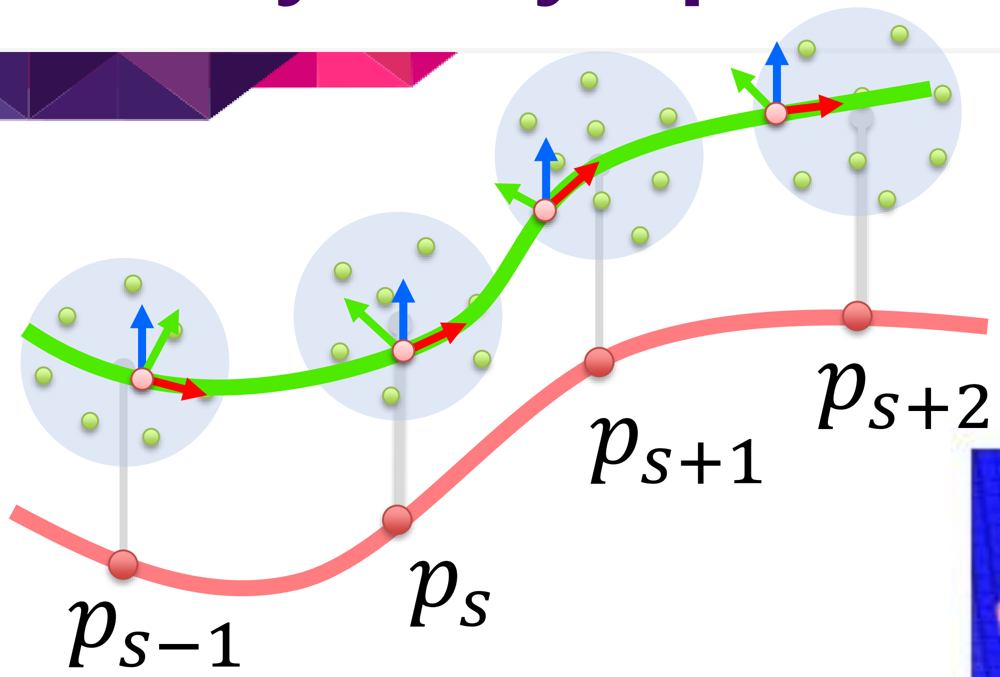


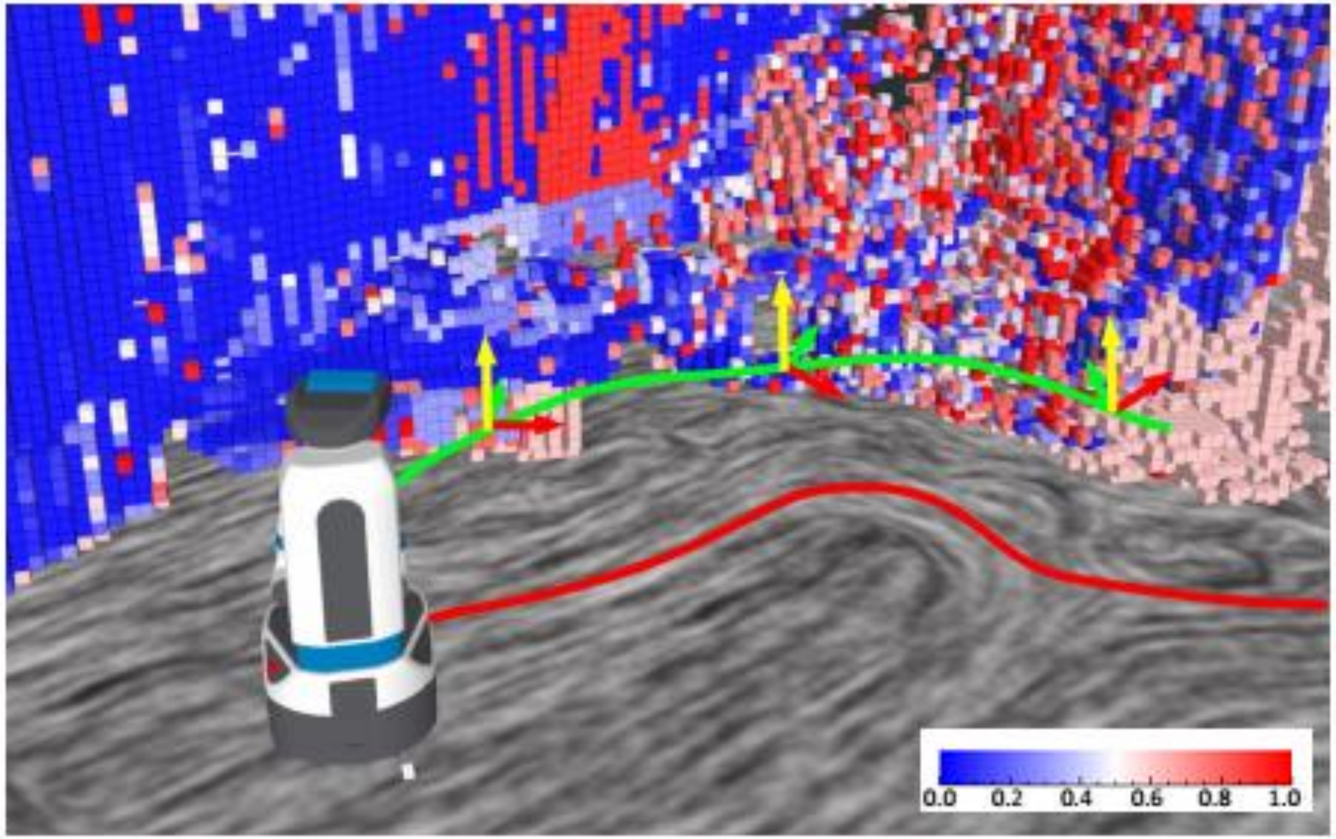
- Visibility to unknown
- Linear speed
- Angular speed

0-1 integer programming

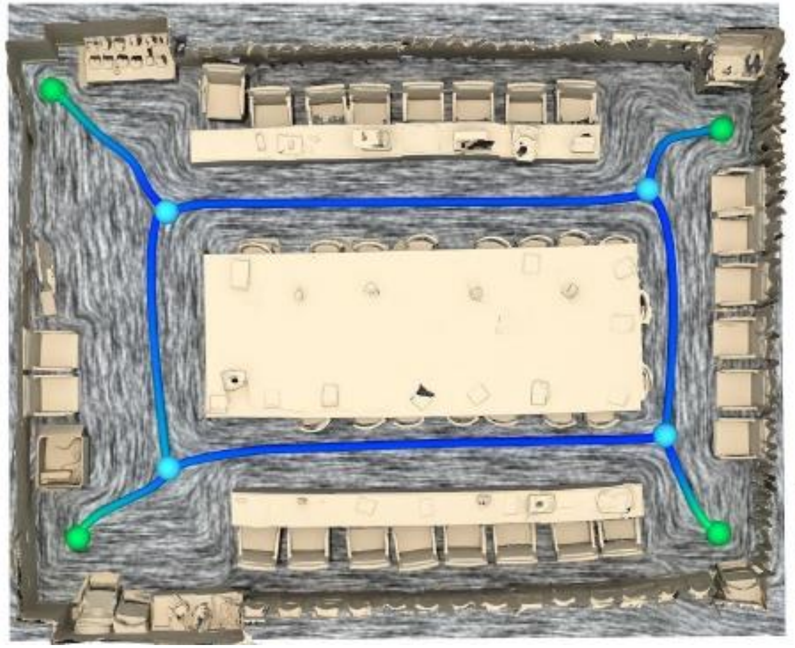
$$
\begin{aligned}
\text{minimize} \quad & E = -\,\omega_{\mathrm{V}} \sum_s \sum_i V(q_s^i, a_s^i)\, x_s^i \\
& + \omega_{\mathrm{L}} \sum_s \sum_{i,j,k} (q_{s-1}^i - 2q_s^j + q_{s+1}^k)\, x_{s-1}^i x_s^j x_{s+1}^k \\
& + \omega_{\mathrm{A}} \sum_s \sum_{i,j,k} (a_{s-1}^i - 2a_s^j + a_{s+1}^k)\, x_{s-1}^i x_s^j x_{s+1}^k, \\
\text{subject to} \quad & (q_{s+1}^i - q_{s-1}^j)\, x_{s+1}^i x_{s-1}^j < 2v_{\mathrm{m}}, \\
& (a_{s+1}^i - a_{s-1}^j)\, x_{s+1}^i x_{s-1}^j < 2a_{\mathrm{m}}, \\
& x_s^i \in \{0, 1\}, \quad \textstyle\sum_k x_s^k = 1, \\
& s = 1, \ldots, S-1, \quad i, j = 1, \ldots, C.
\end{aligned}
$$

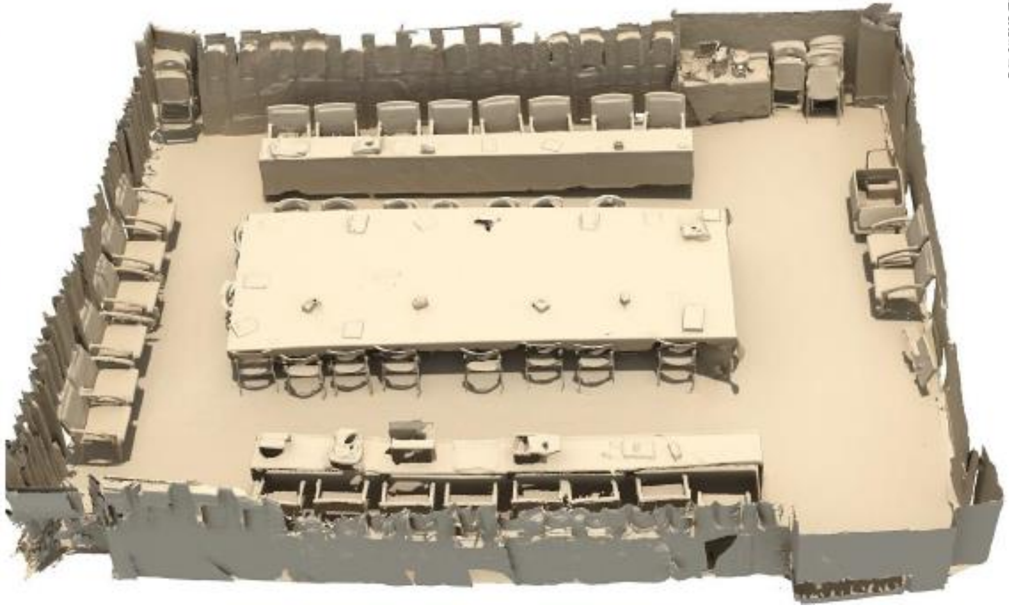
Camera Trajectory Optimization

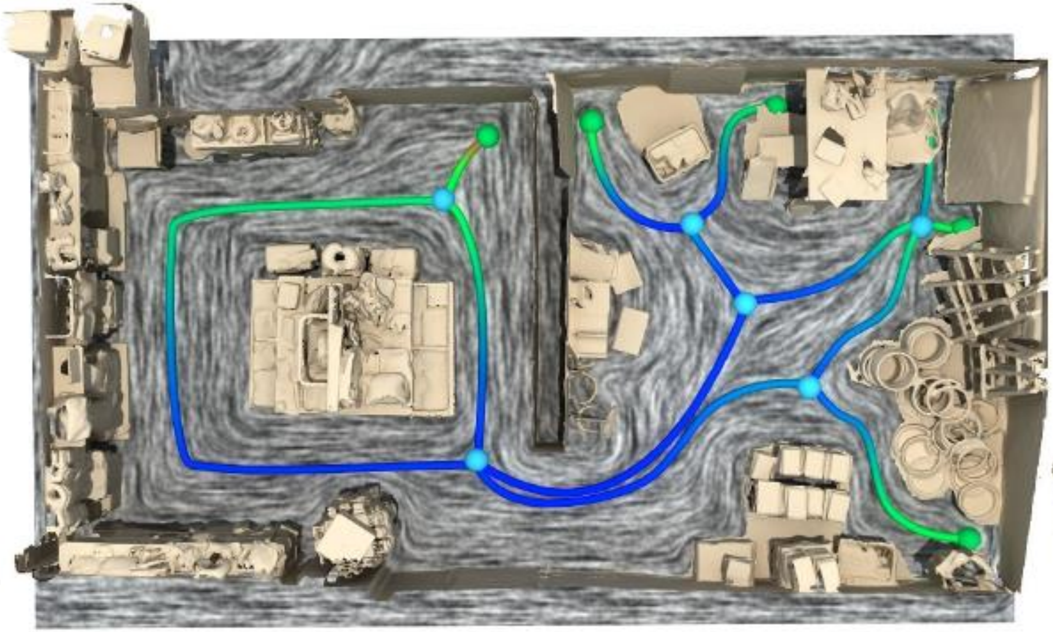


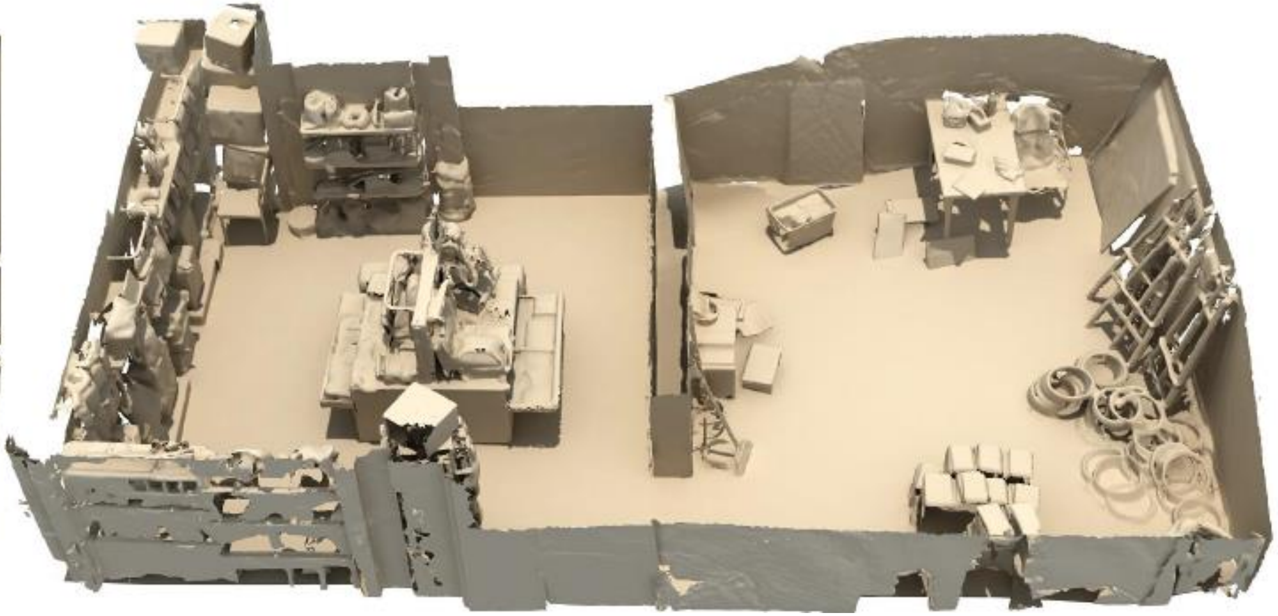


Results









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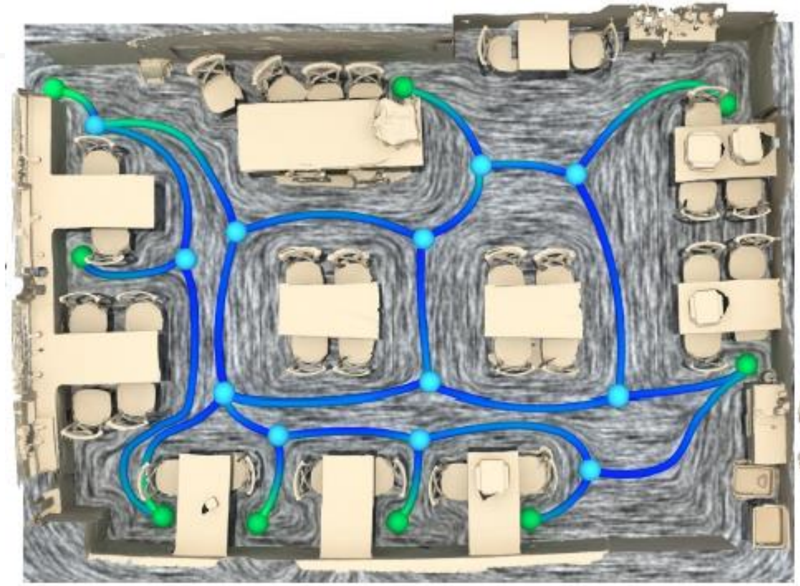
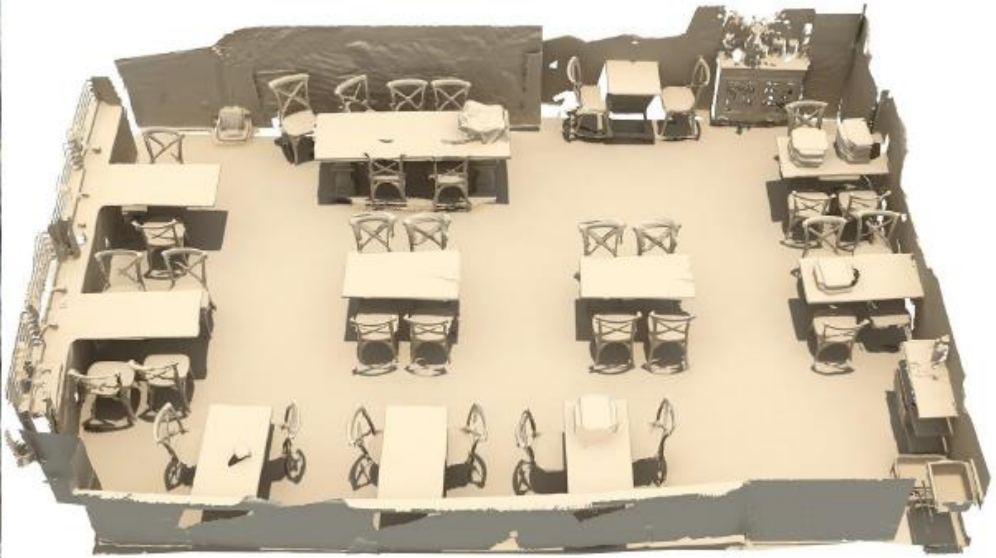
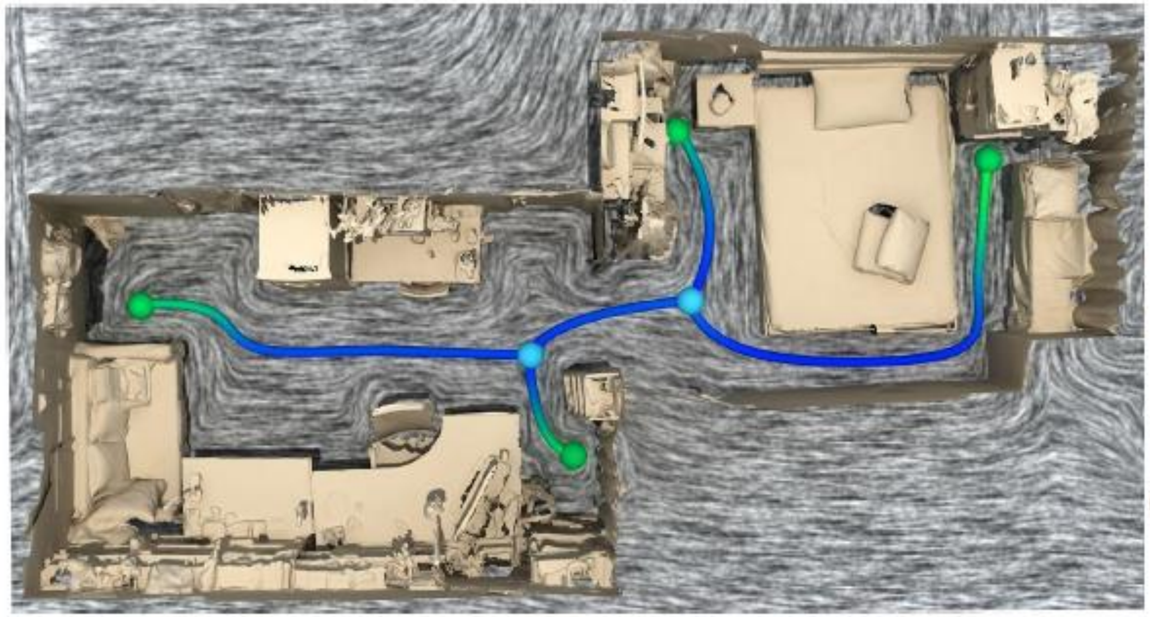
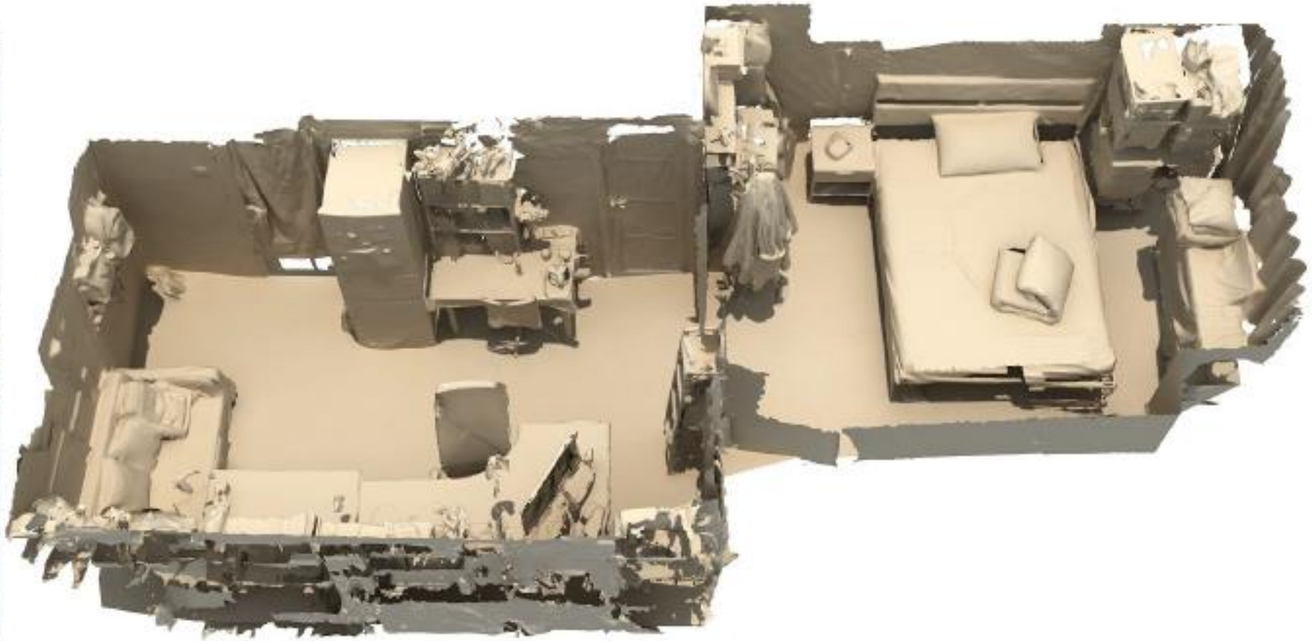


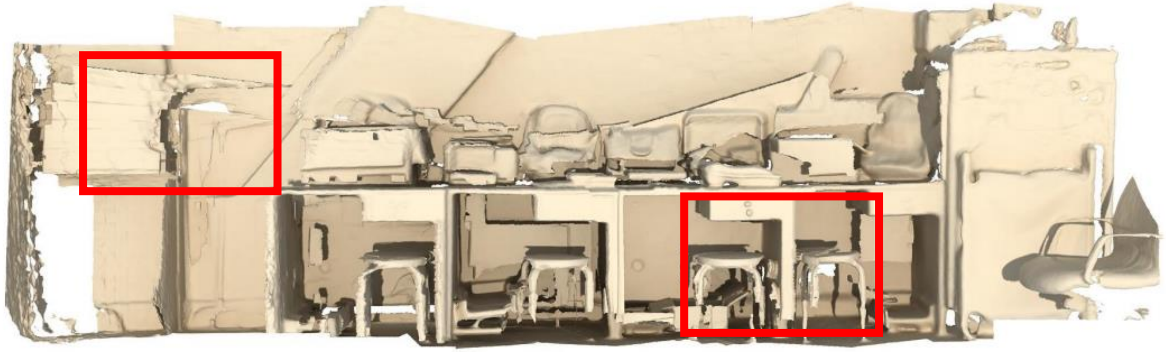






Results

- Scanning quality

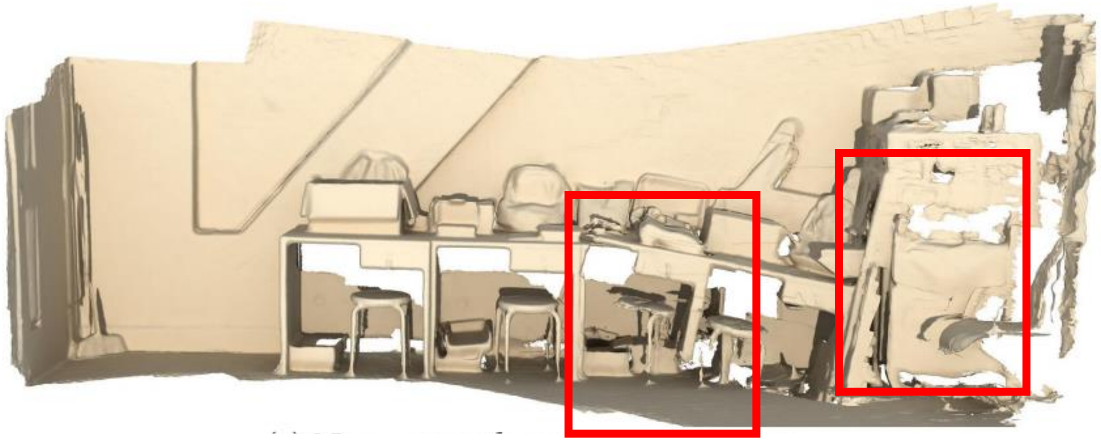


Scanned along **potential** field path

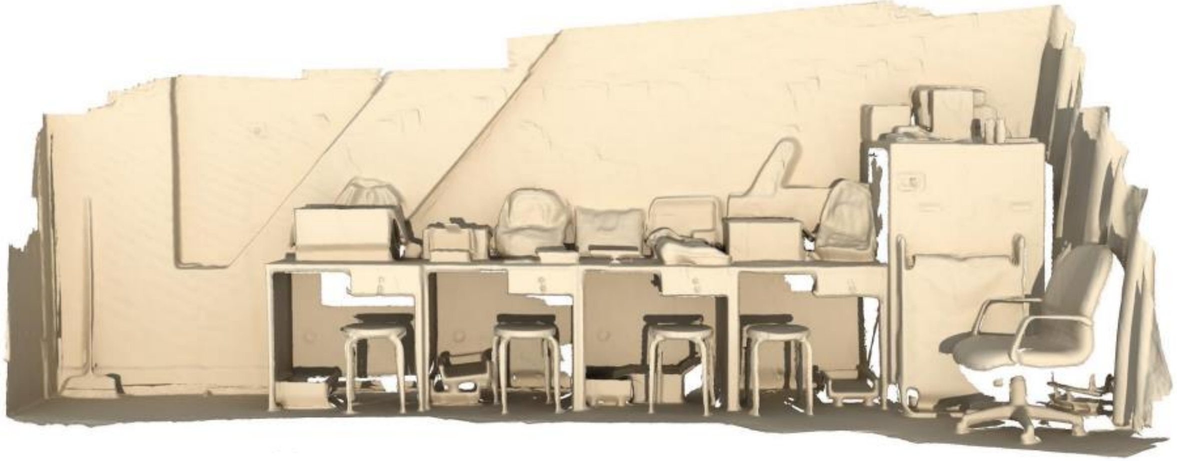
Scanned along **tensor** field path

Results

- Scanning quality



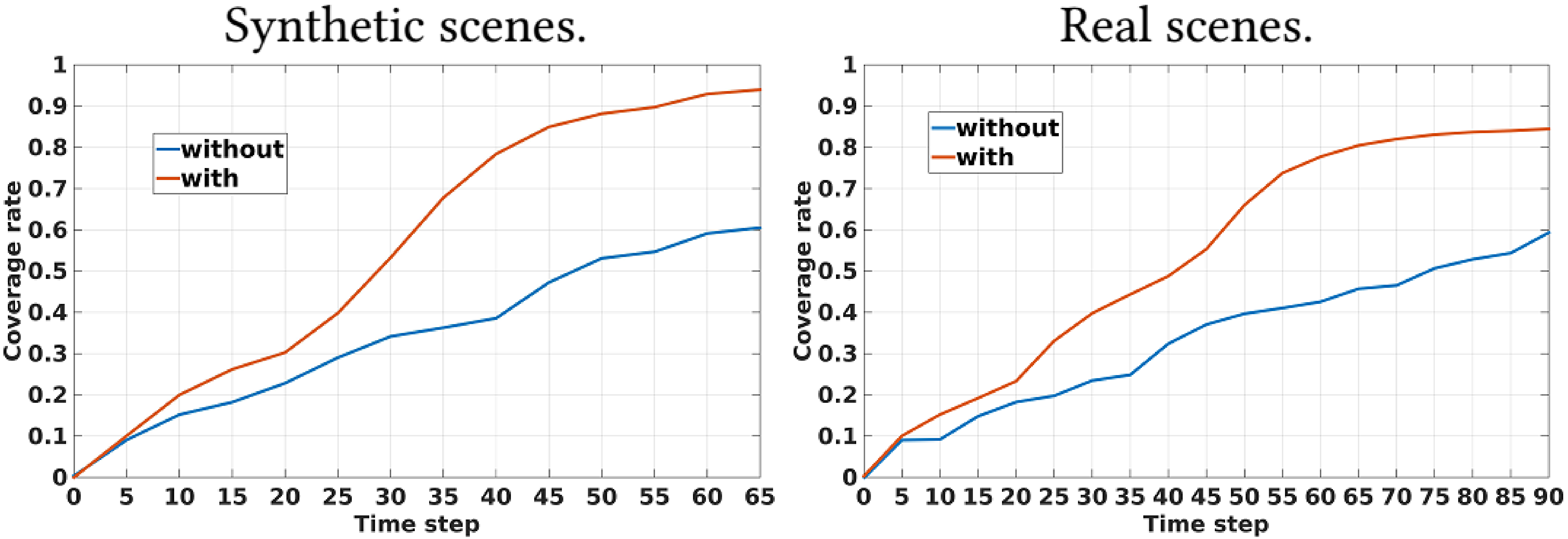
Non-smooth camera trajectory



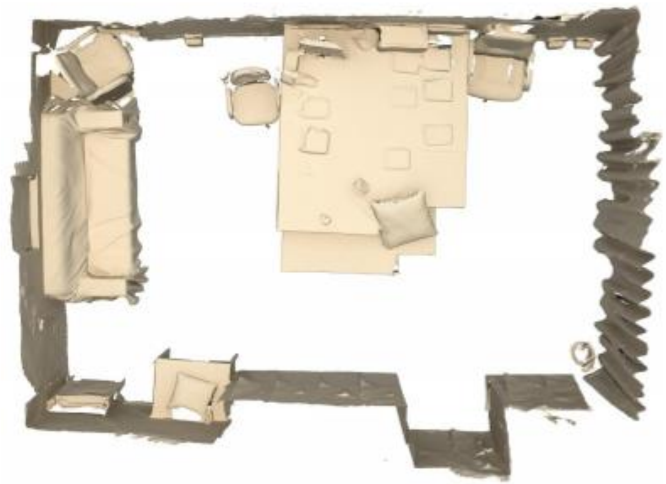
Optimized camera trajectory

Evaluation

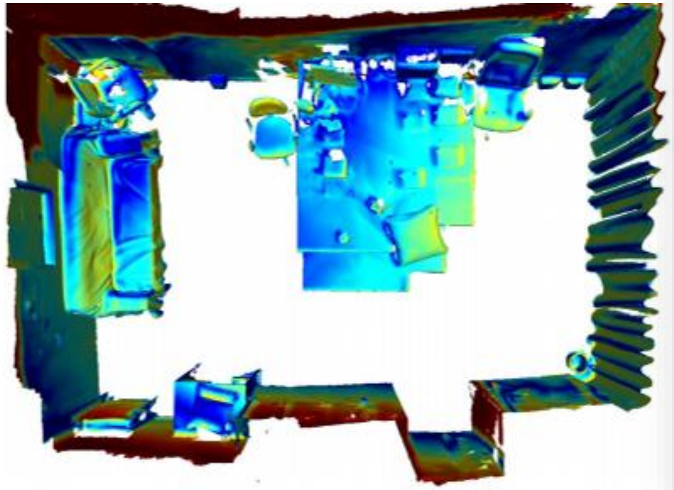
- Effect of global path planning



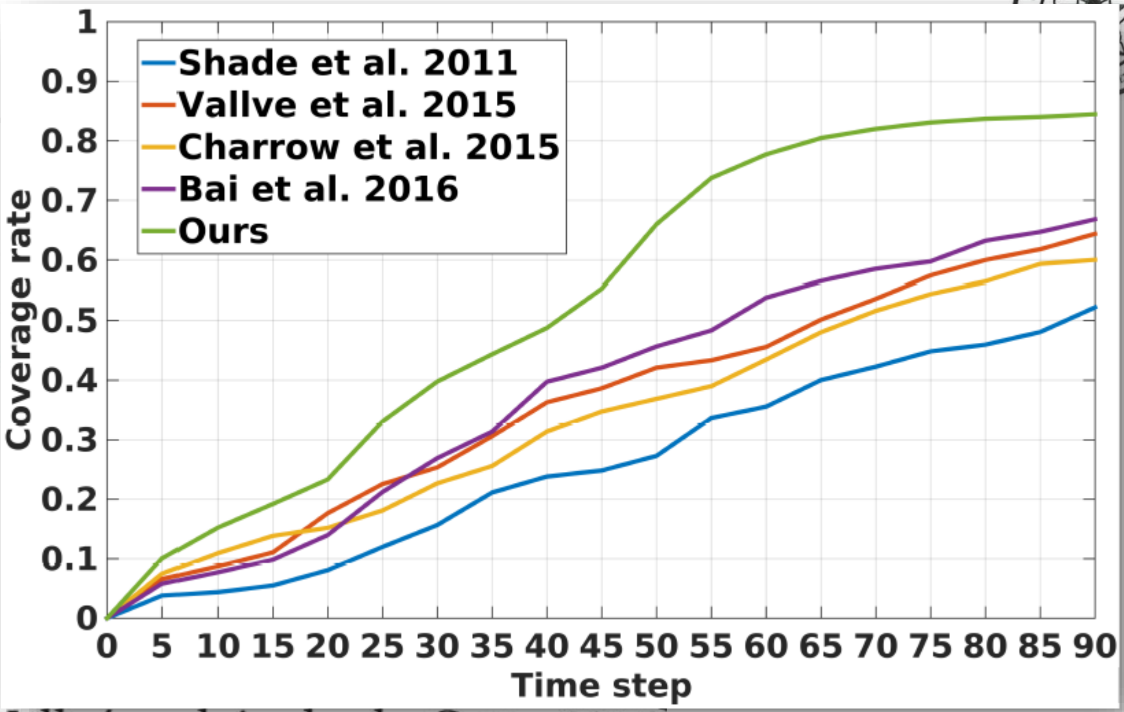
Comparison



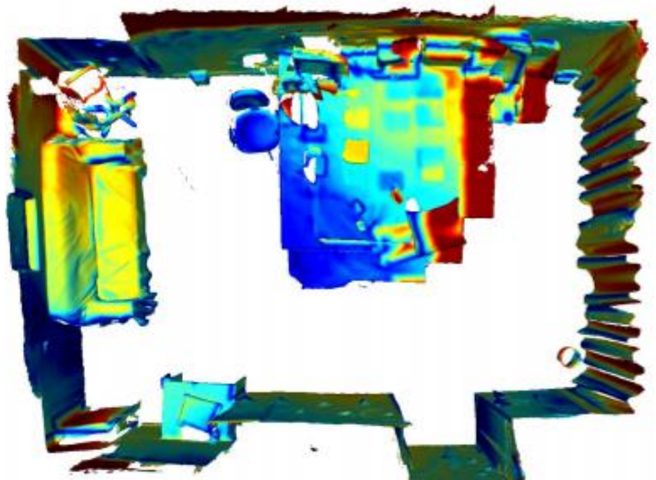
Pseudo-ground-truth



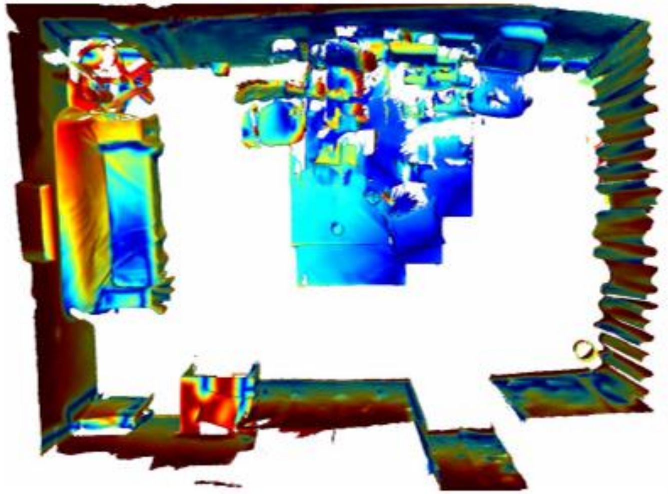
[Shade and Newman 2011]



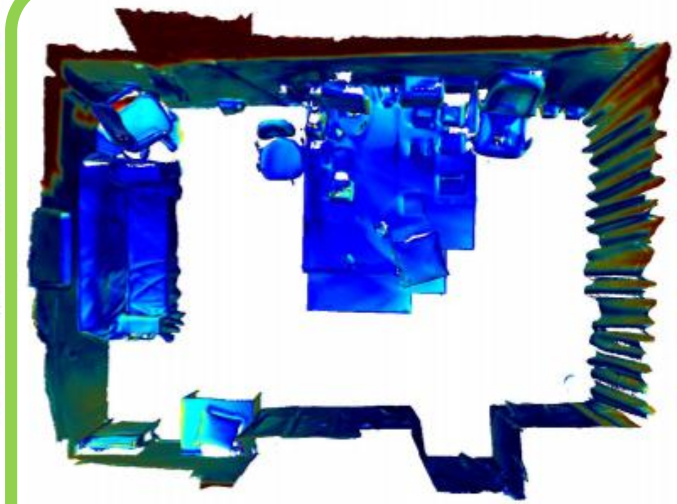
[Vallvé and Andrade-Cetto 2015]



[Charrow et al. 2015]



[Bai et al. 2016]



Ours

Future work

Field guidance over **non-planar ground surfaces**, such as terrains ?

Future work

Use **3D tensor fields** to guide robot grasping in complicated 3D environment ?

Thank you for attention!

Package available on ROS!

Try google:

“tensor field ros”

ROS.org

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Documentation Browse Software News

tensor_field_nav

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Contents

1. Introduction

Tensor_field_nav package is developed for autonomous mapping of unknown indoor scenes by a mobile robot holding an RGBD camera. The key idea is to utilize 2D directional fields to guide robot movement. We compute and update a geometry-aware tensor field constrained by the currently reconstructed scene. The 3D scene geometry (i.e., the known surfaces) is projected to the floor plane. A set of 2D tangential constraints along the projected boundaries is extracted and used to compute/update the tensor field. The robot path is formed by particle advection over the tensor field, which is inherently obstacle avoiding.

During online scanning, the tensor field is updated in real-time, conforming to the incrementally reconstructed scene. To ensure a smooth robot path when advecting over the time-varying field, we propose a space-time optimization of tensor fields via imposing both spatial smoothness and temporal coherence. There are several important advantages of tensor field guided navigation. First, tensor fields are orientation-free and thus contain much less singularities (degenerate points), as compared to vector fields which are predominantly used in the literature. Fewer singularities lead not only to smoother path advection, which is critical for quality reconstruction, but also to more efficient navigation due to less ambiguity. In addition, tensor fields are sink-free, avoiding the issue of local trapping. Most importantly, the topological skeleton of a tensor field, comprised of all degenerate points and the separatrices connecting them, can be viewed as a routing graph. With this global structure, one can achieve global path planning for efficient scene scanning.