Multi-Robot Collaborative Dense Scene Reconstruction

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Background

Scanning the World

3D content creation

robotics

Background

Real-Time 3D Reconstruction

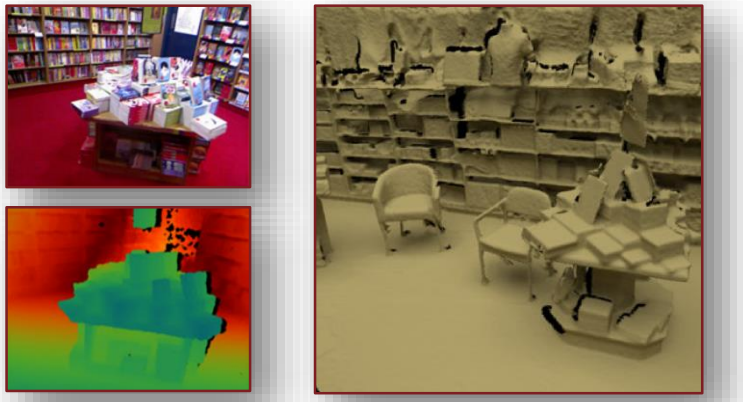
Hardware

Kinect

Xtion

RealSense

Software

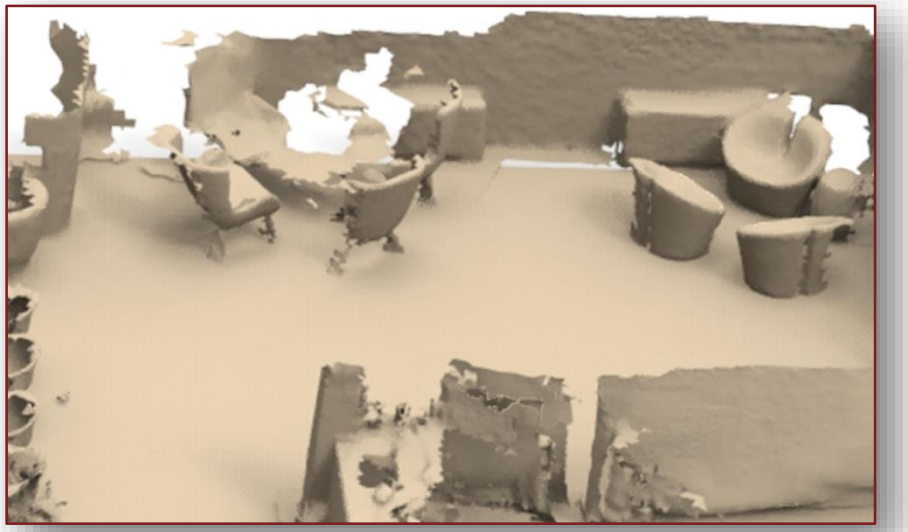


VoxelHashing [Nießner et al.]

BundleFusion [Dai et al.]

Problems

Hardly User-Friendly

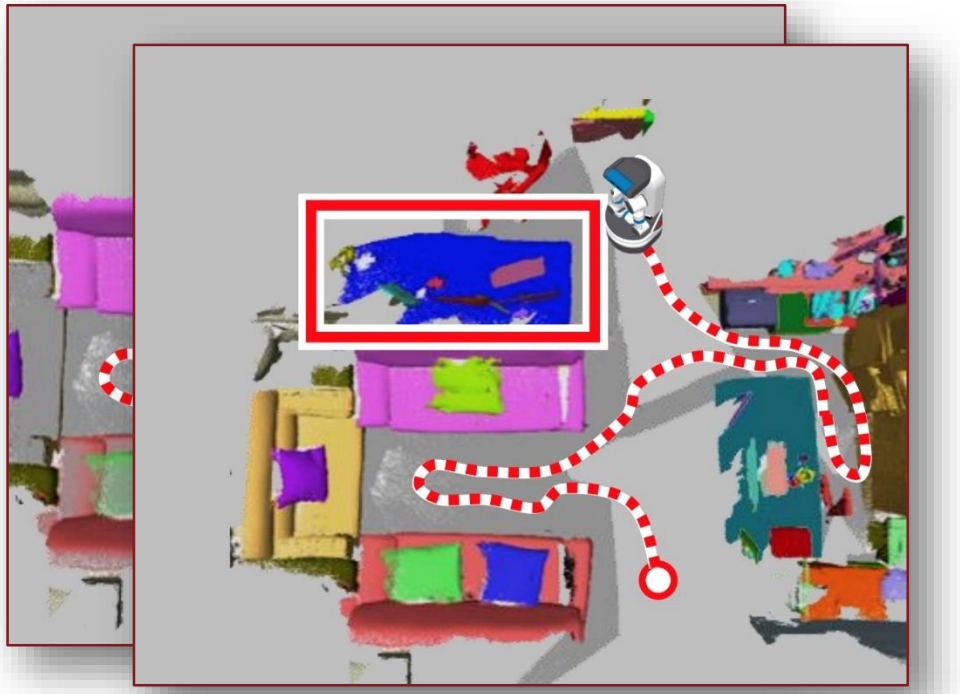


Reconstructions suffer from incomplete regions scanned by a rookie user.

Motivation

Auto-Scan

Xu et al. SIGGRAPH Asia 2015

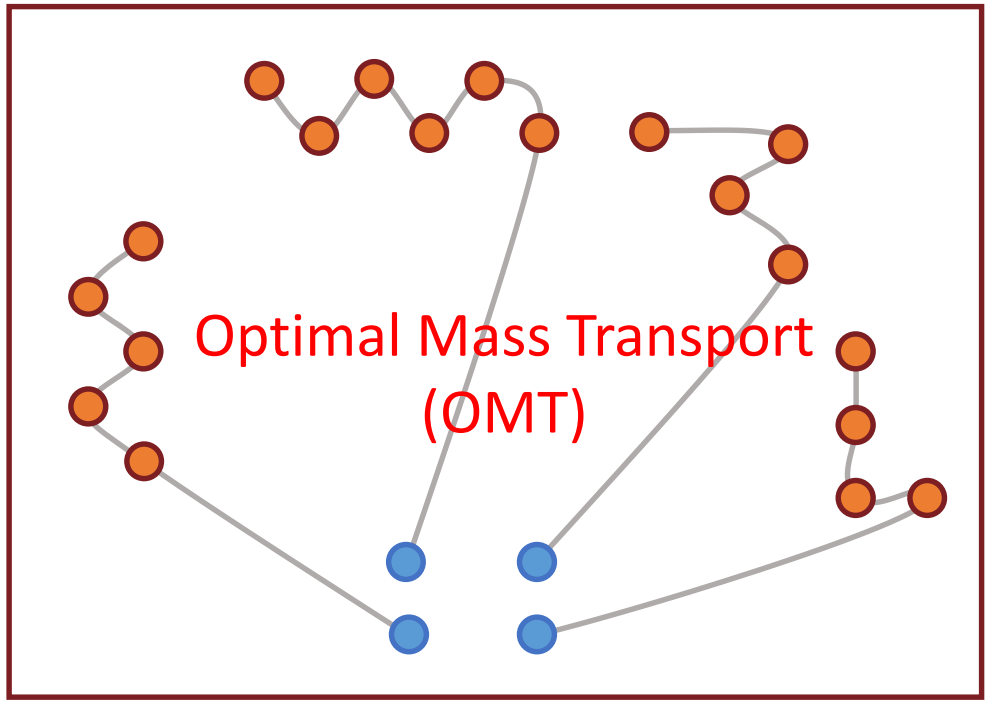


Liu et al. SIGGRAPH 2018

Motivation

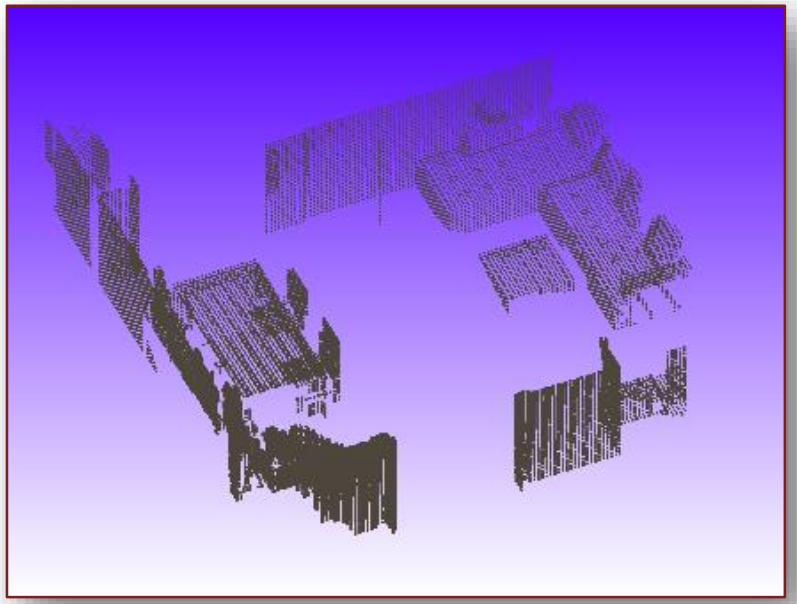
Multi-Robot Collaborative Auto-Scan

Progressive Reconstruction



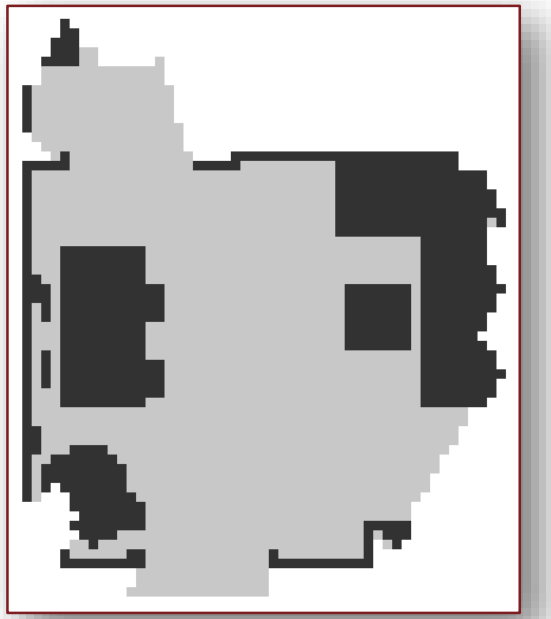
scanning resources scanning targets

Problem Statement



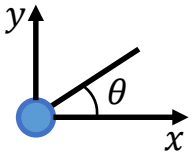
Reconstructed Region

Project to Floor Plane

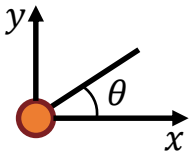


2D Occupancy Map

Robot Poses $\mathcal{R}_1, \dots, \mathcal{R}_R$.
$\mathcal{R}_i = (x_i, y_i, \theta_i) \in SE(2)$

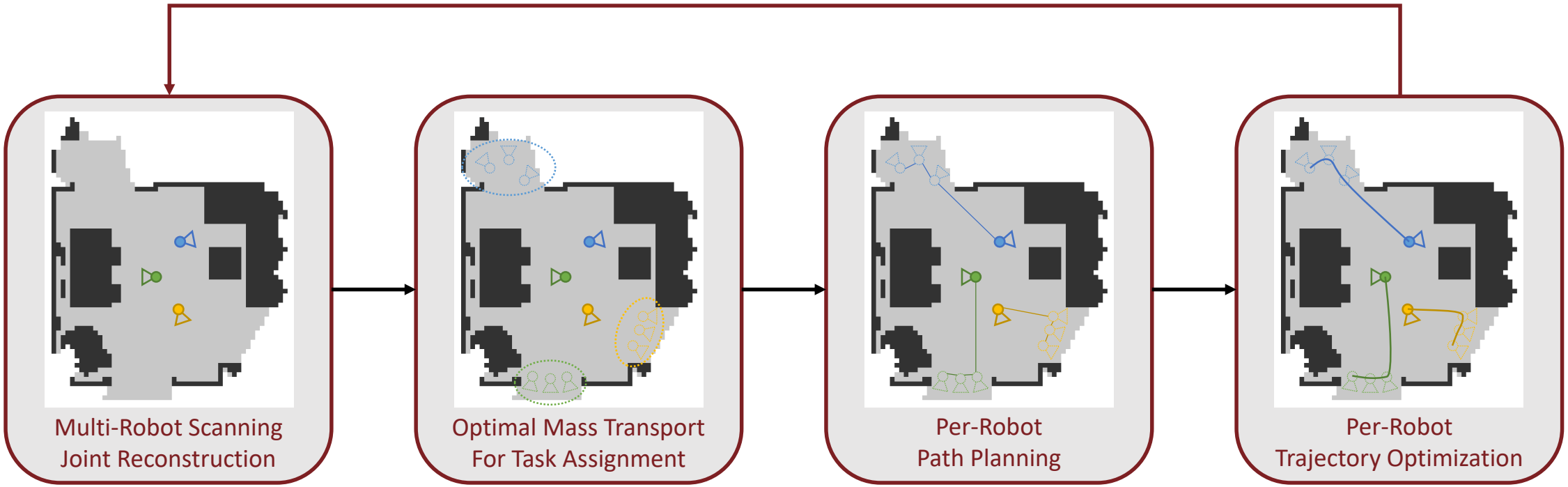


Scanning tasks $\mathcal{T}_1, \dots, \mathcal{T}_T$.
$T_j = (x_j, y_j, \theta_j) \in SE(2)$



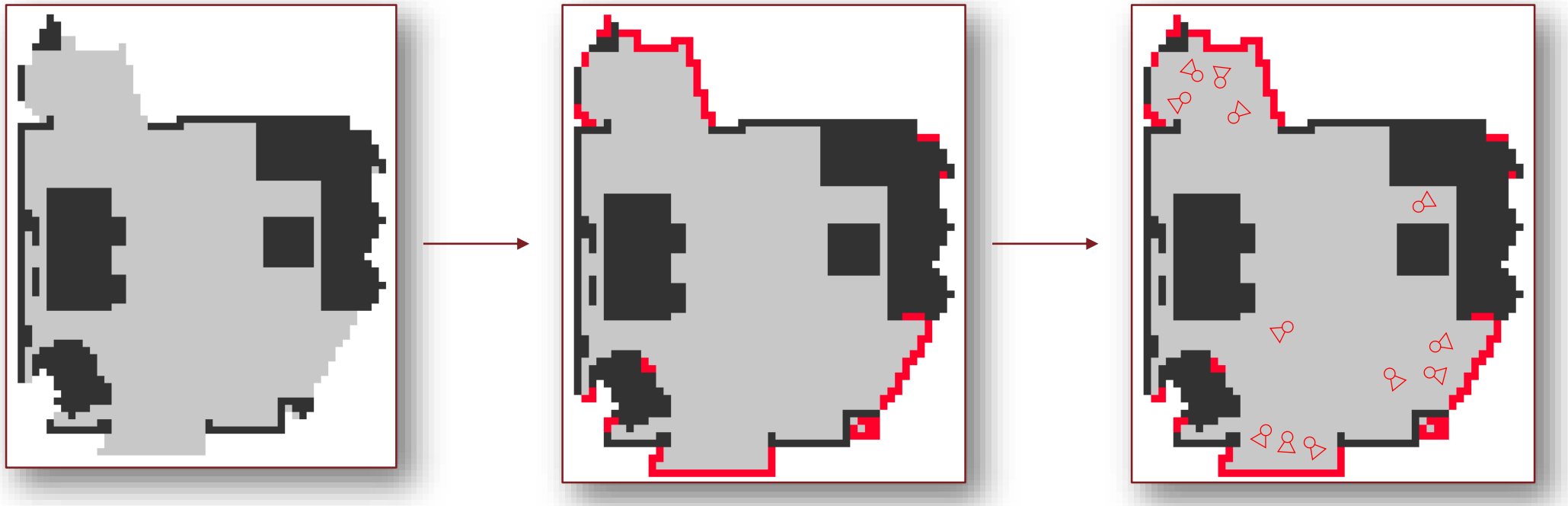
Method

Pipeline: Scanning ⇌ Planning

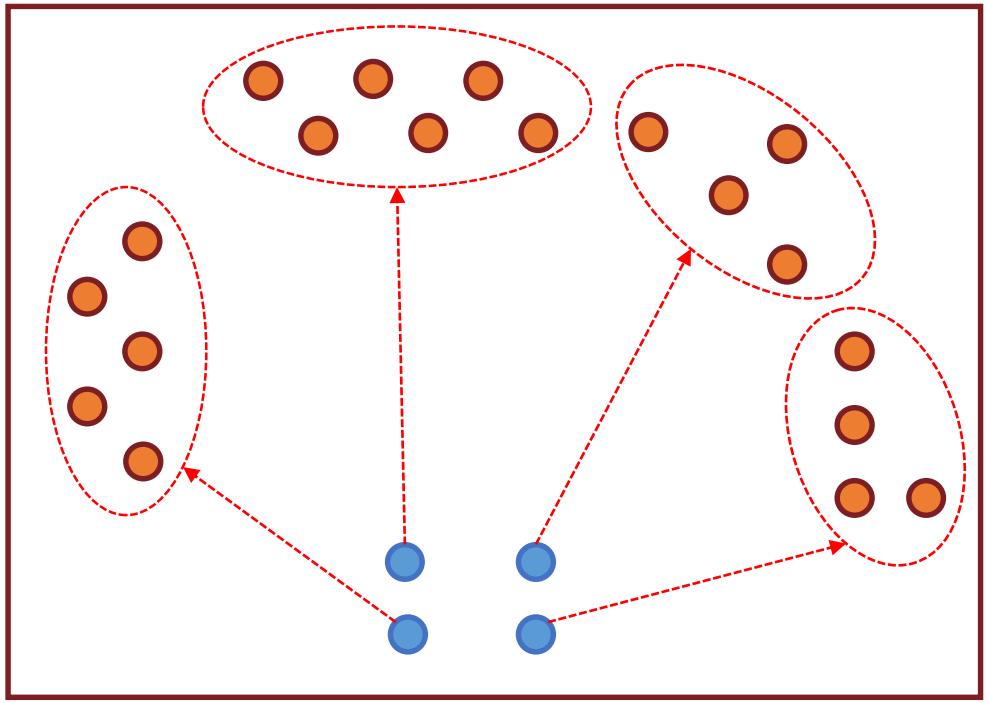


Method

Scanning Task Extraction



Collaboration Objective Formulation



Spatial distribution of robots as sources μ_{source}

Spatial distribution of tasks as targets μ_{target}

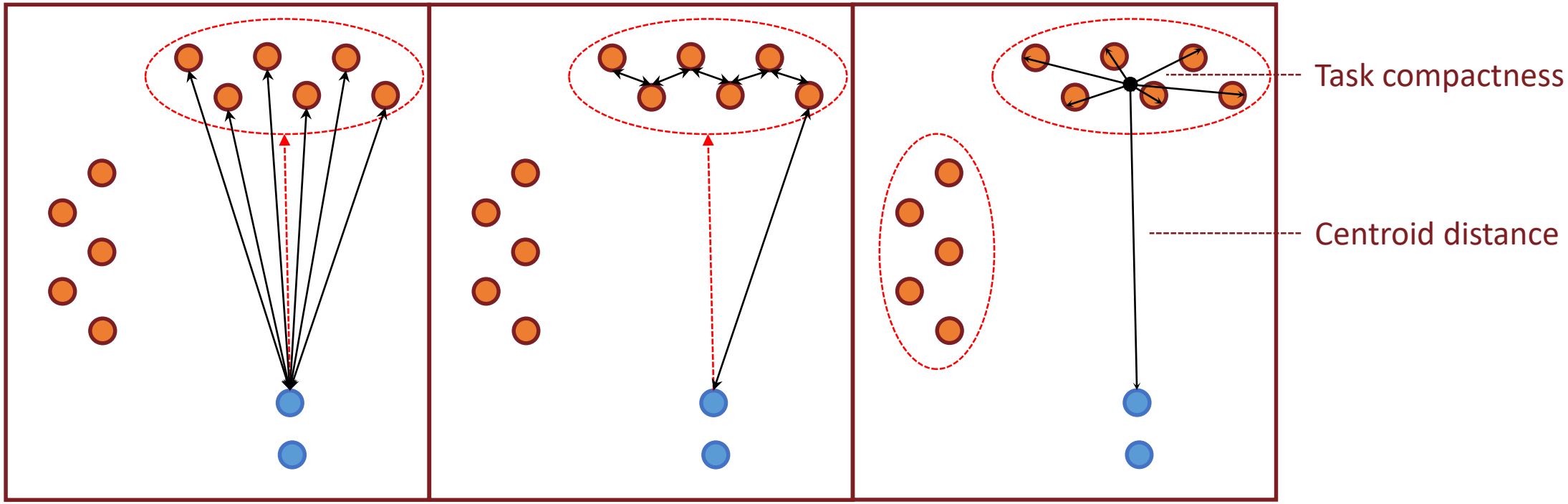
Finding a mapping T that minimize the objective:

$$\arg\min_{T} \int_{x \in SE(2)} \gamma(x, T(x))\, \mathrm{d}\mu_{source}$$

$$T: \mu_{source} \rightarrow \mu_{target}$$

Method

Cost Function Approximation



Distance from robot to task

Traveling Salesman Problem (TSP)

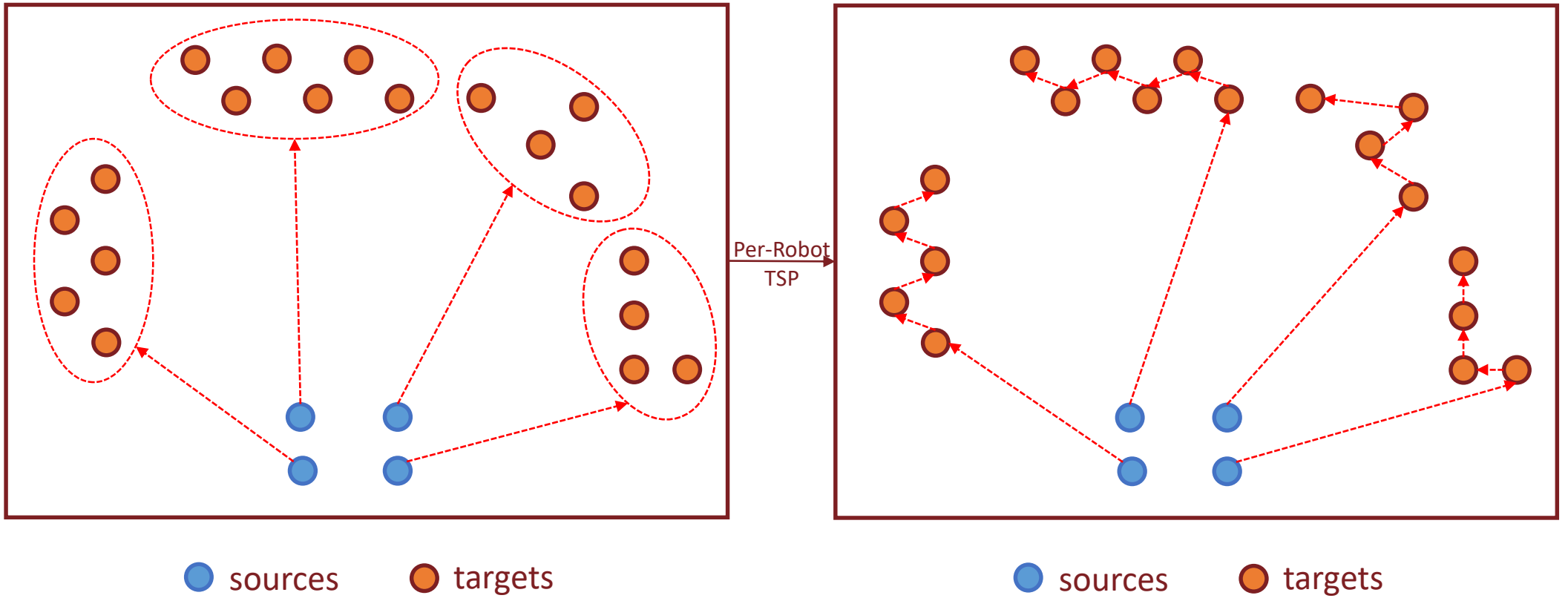
Approximation

Optimal Mass Transport(OMT) Formulation

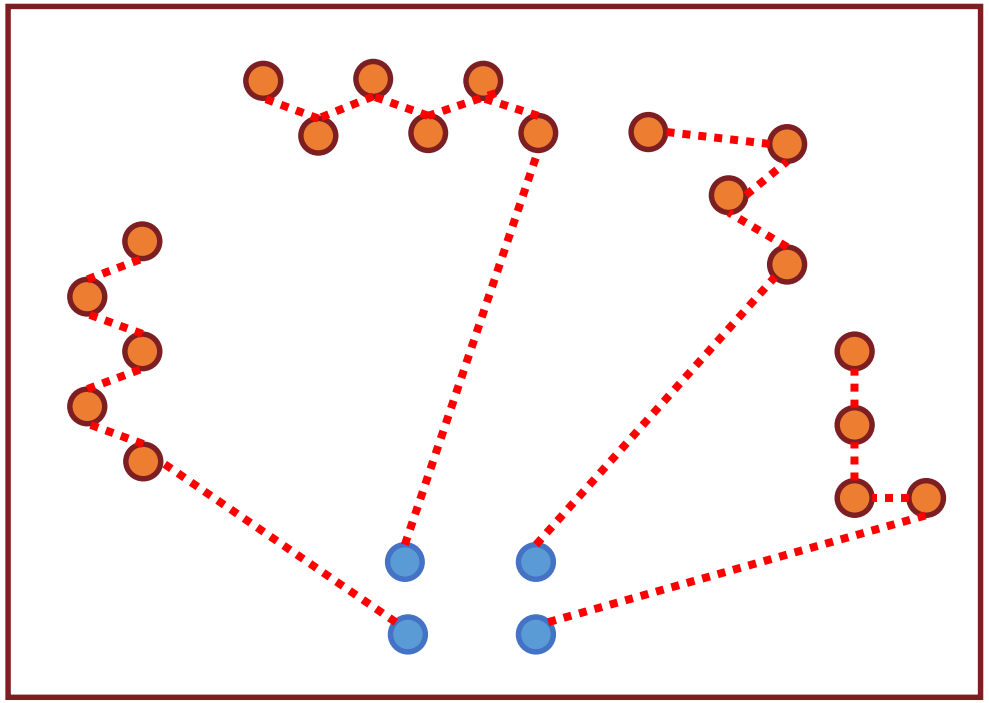
$$\min_{T} \underbrace{\sum_{r=1}^{R} \sum_{\mathcal{T}_k \in \Omega_r} \gamma(\mathcal{T}_k, \omega_r)}_{\text{compactness}} + \underbrace{\sum_{r=1}^{R} \gamma(\mathcal{R}_r, \omega_r)}_{\text{distance}} + \underbrace{\sum_{r=1}^{R} (|\Omega_r - C_r|)^2}_{\text{capacity}}$$

Method

Per-Robot Path Planning



Per-Robot Trajectory Optimization



For each path, sample a sequence of points
$P_r = \{P_1, \dots, P_N\}$

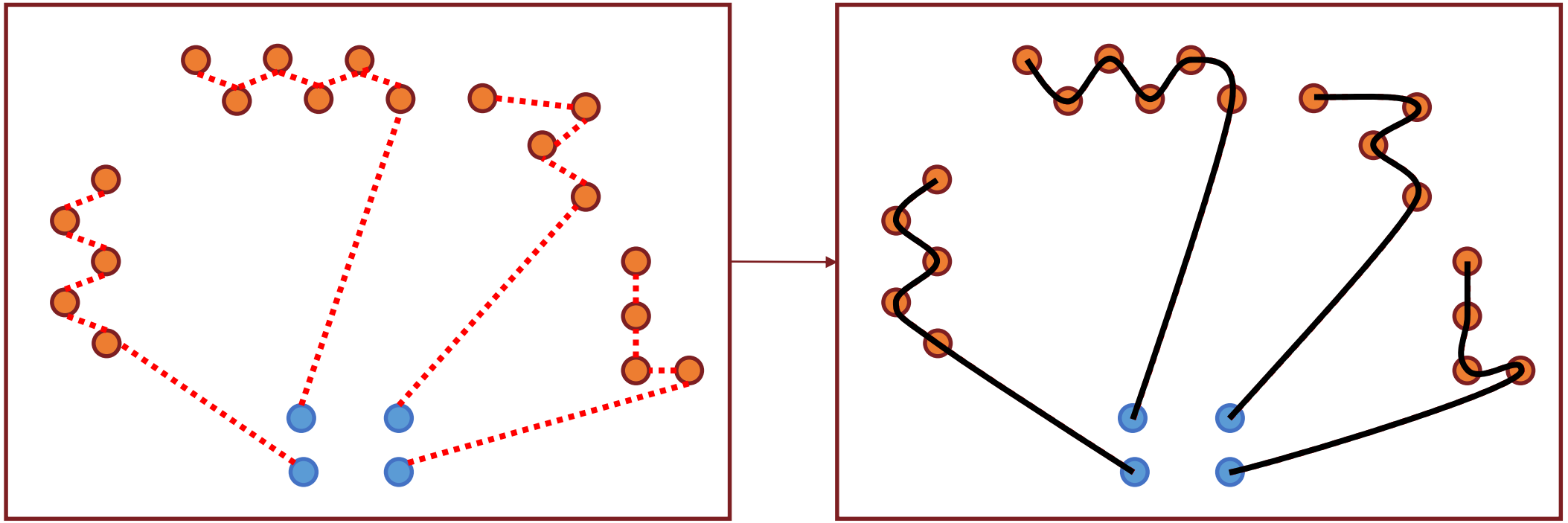
Optimize point positions by minimizing the energy function

$$\arg\min_{P_r} \sum_{i=1}^{N-1} \frac{2}{\eta(p_i) + \eta(p_{i+1})} \|p_i - p_{i+1}\|^2 + \lambda \sum_{t \in T_r} \|p_t - p_t^0\|^2$$

smooth penalty

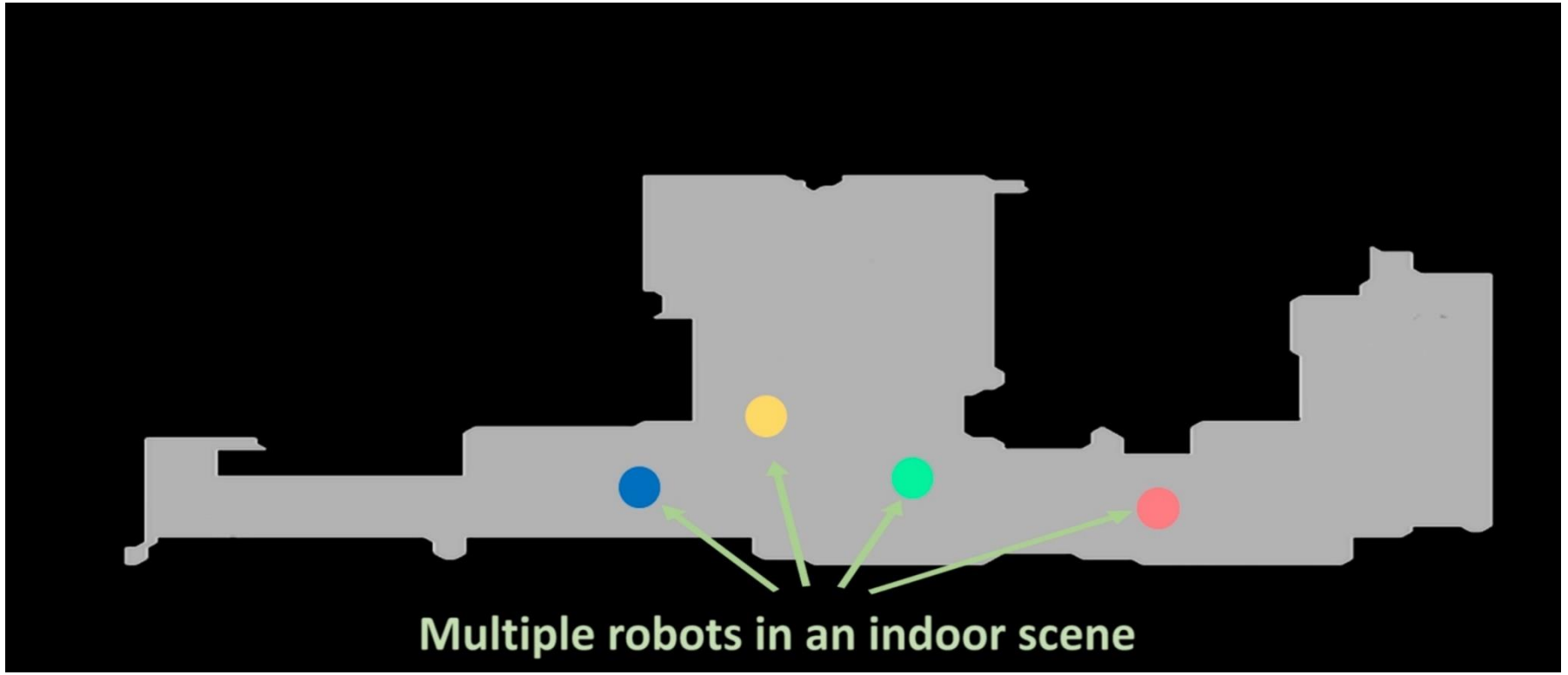
Method

Per-Robot Trajectory Optimization



Method

Progressively Scanning



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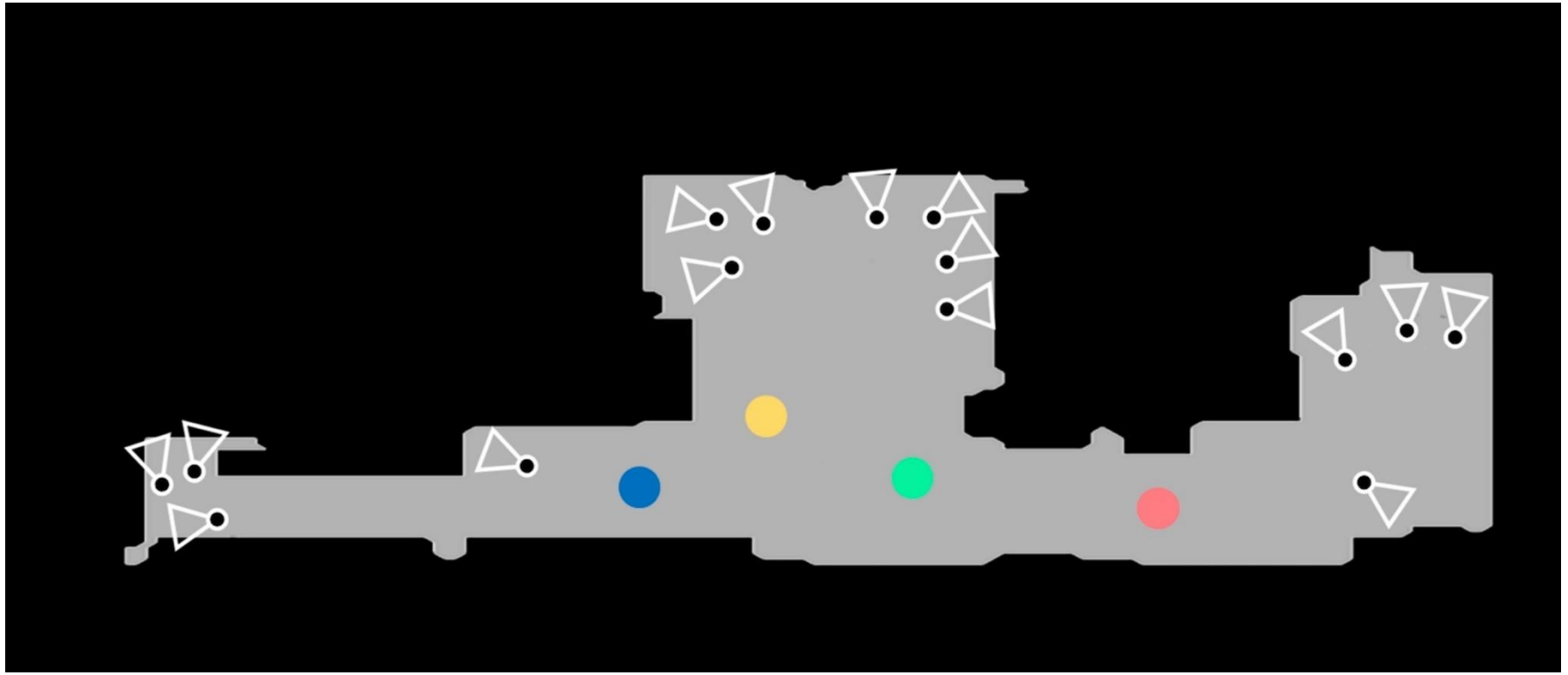

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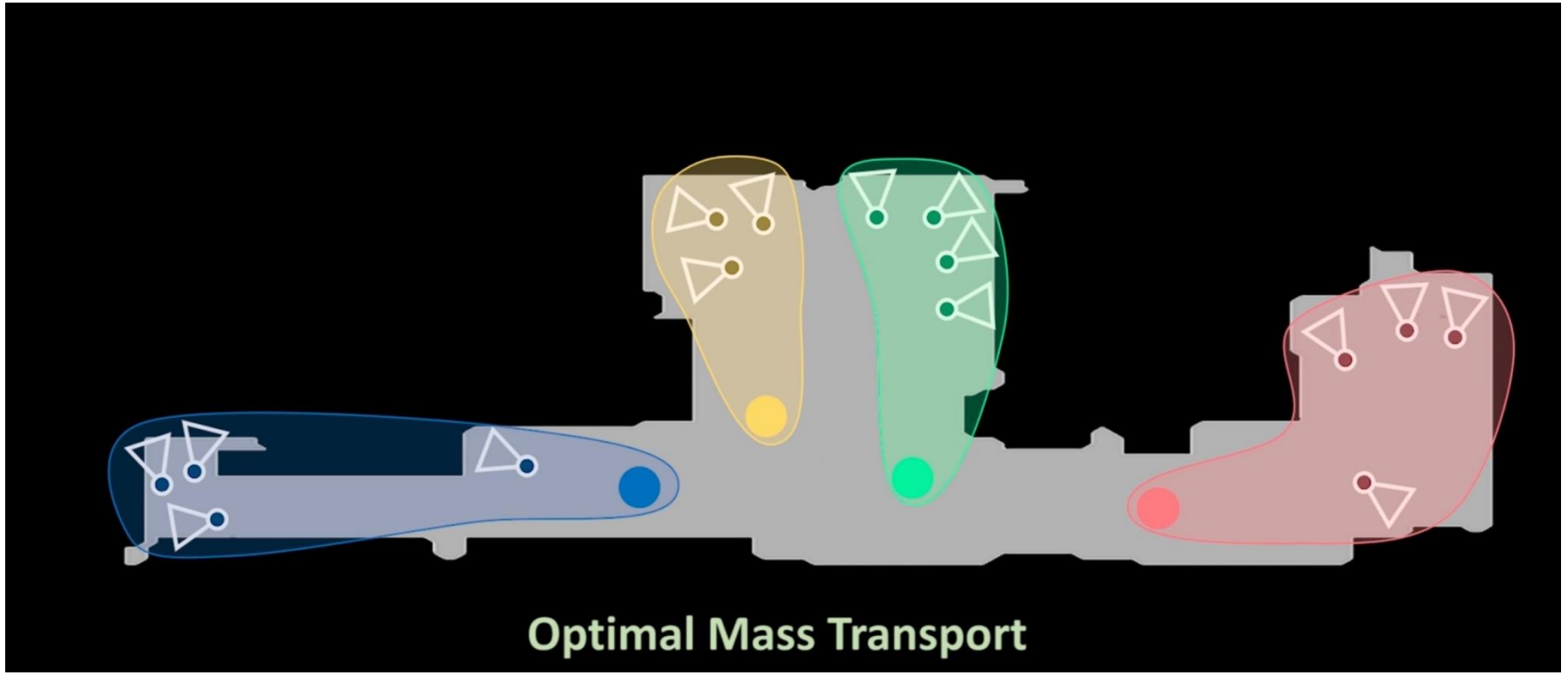

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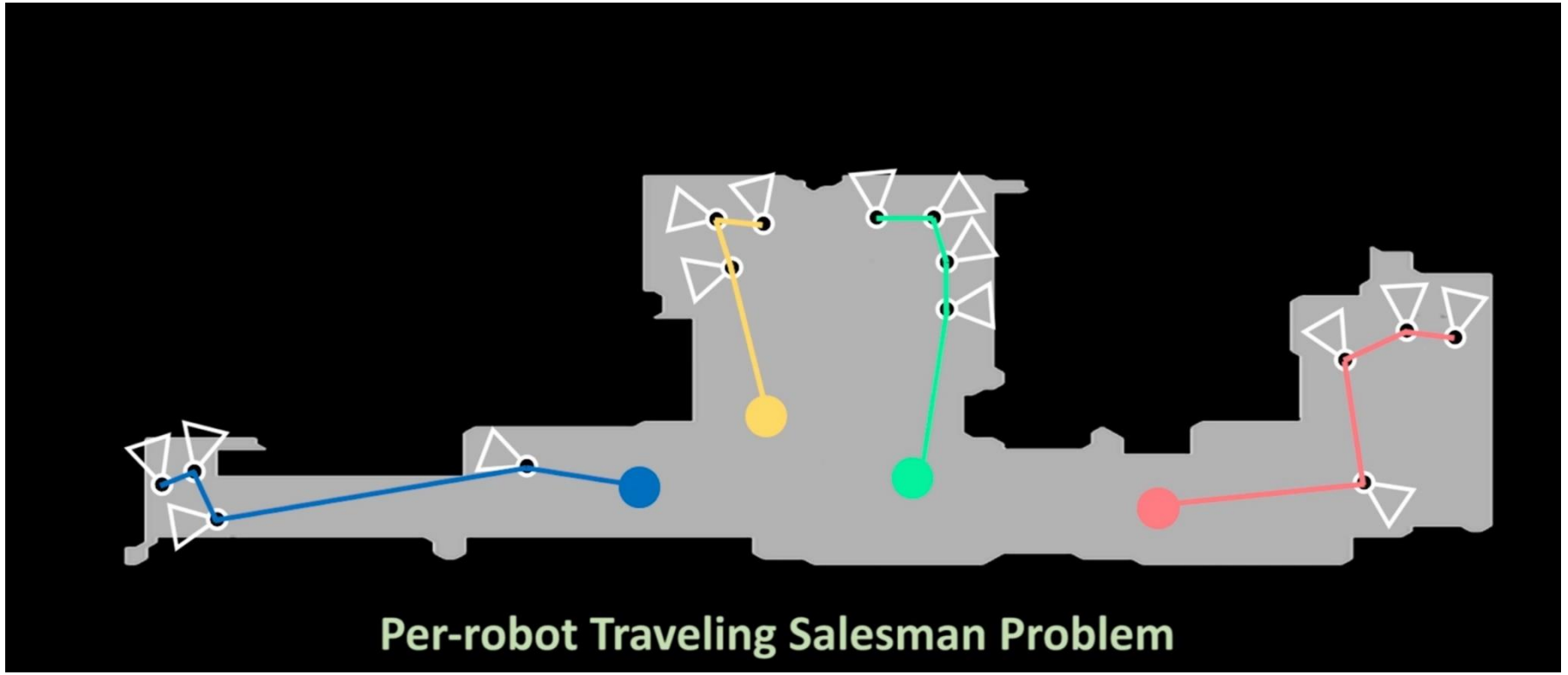
Progressively Scanning



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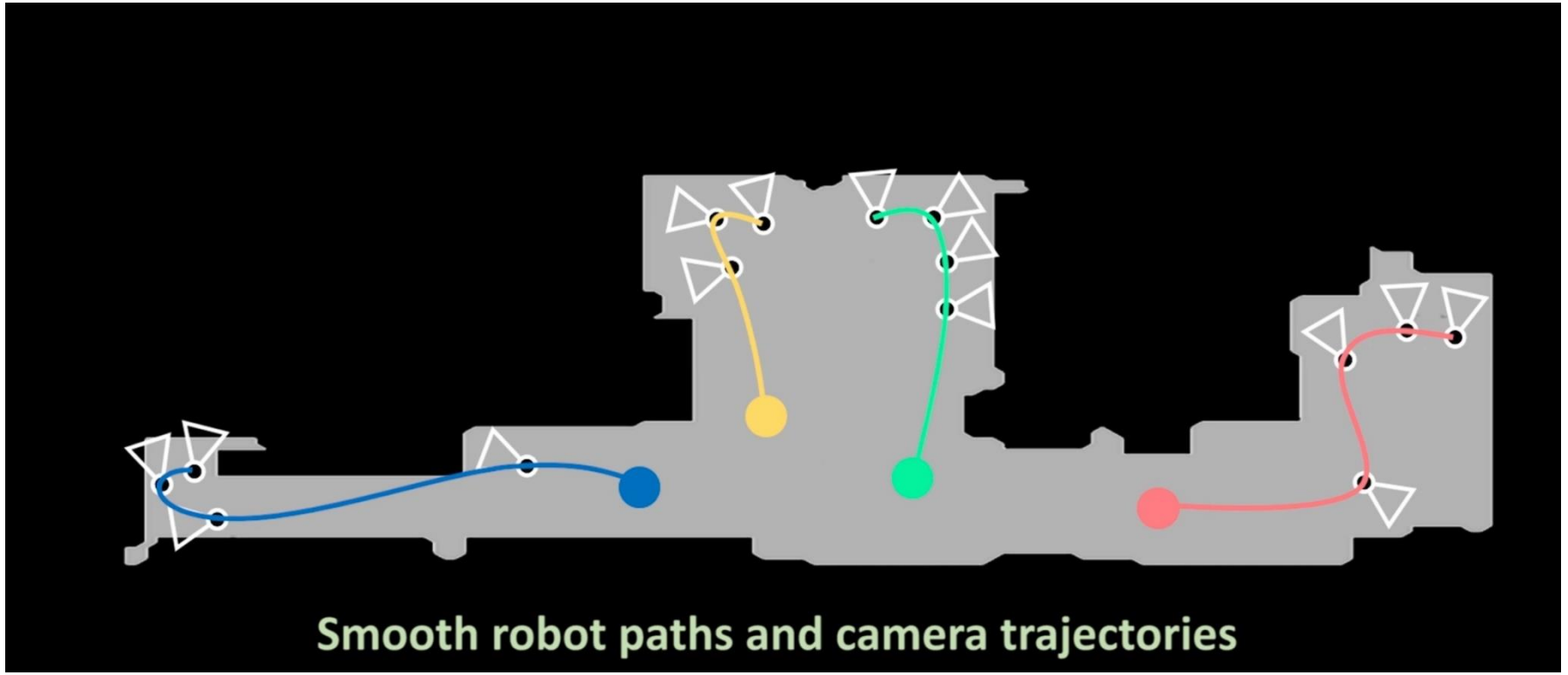
Progressively Scanning



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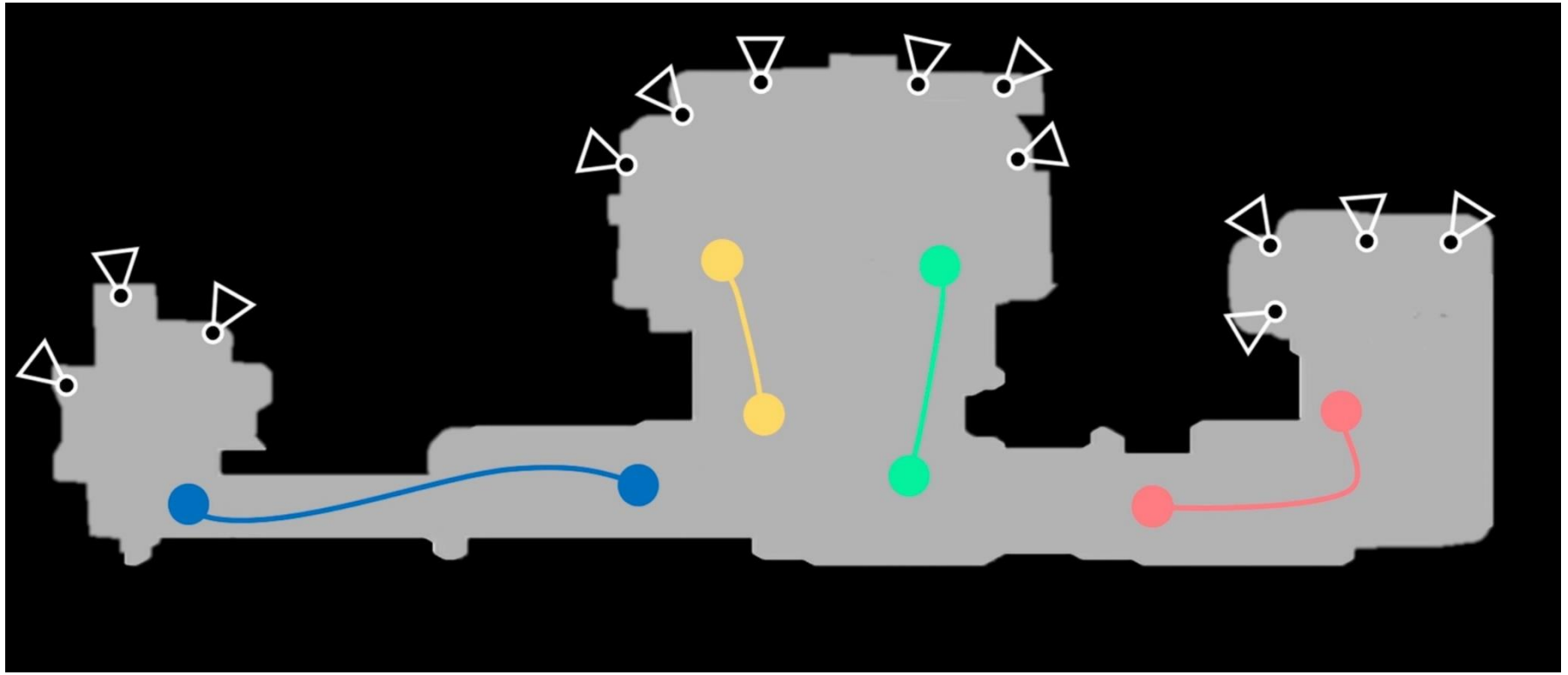
Progressively Scanning



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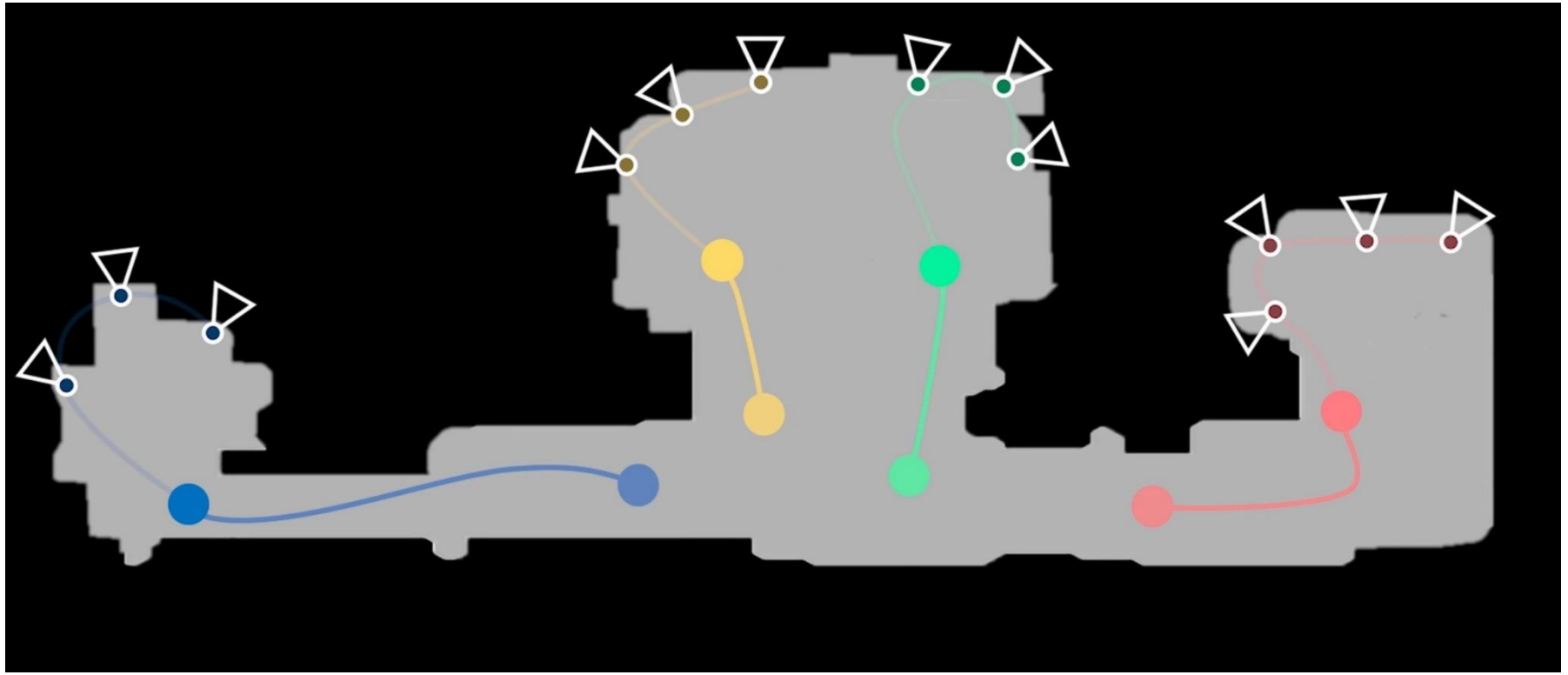

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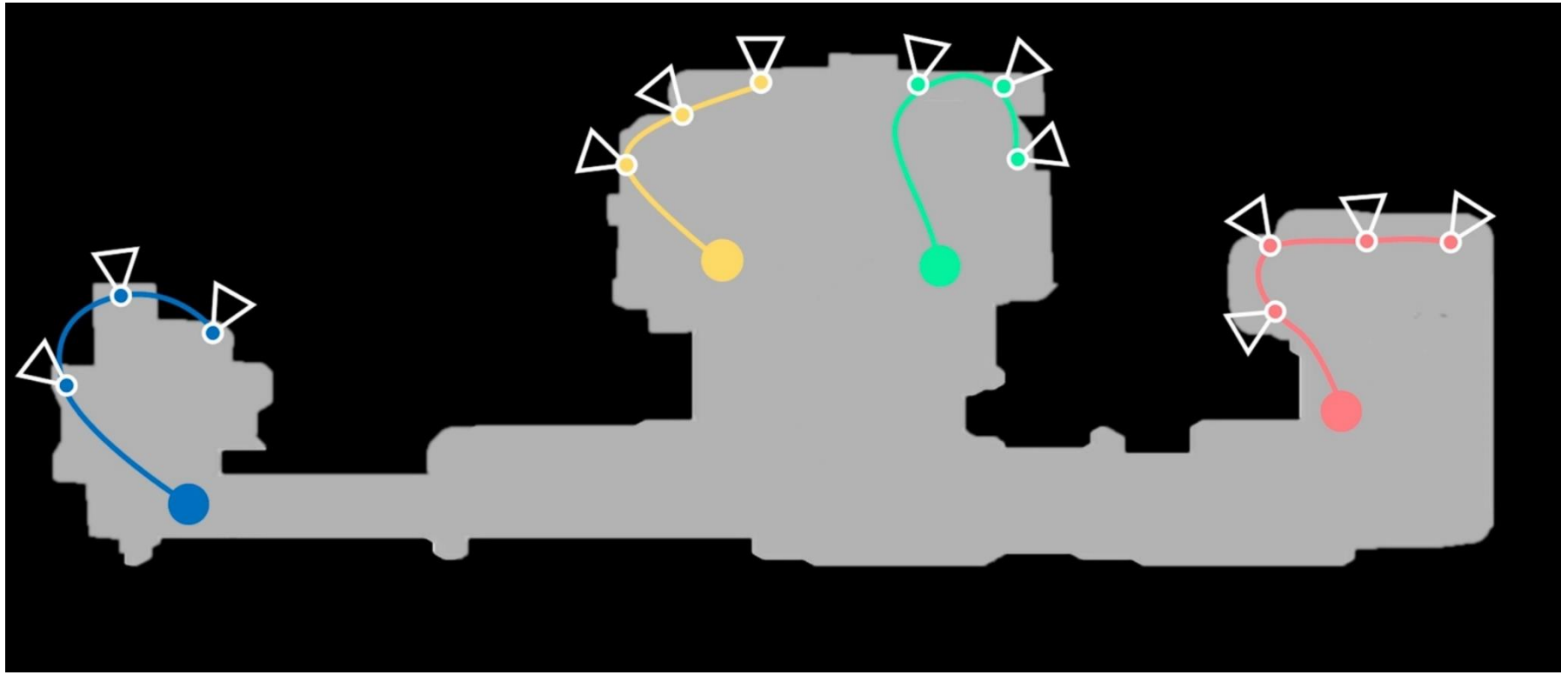
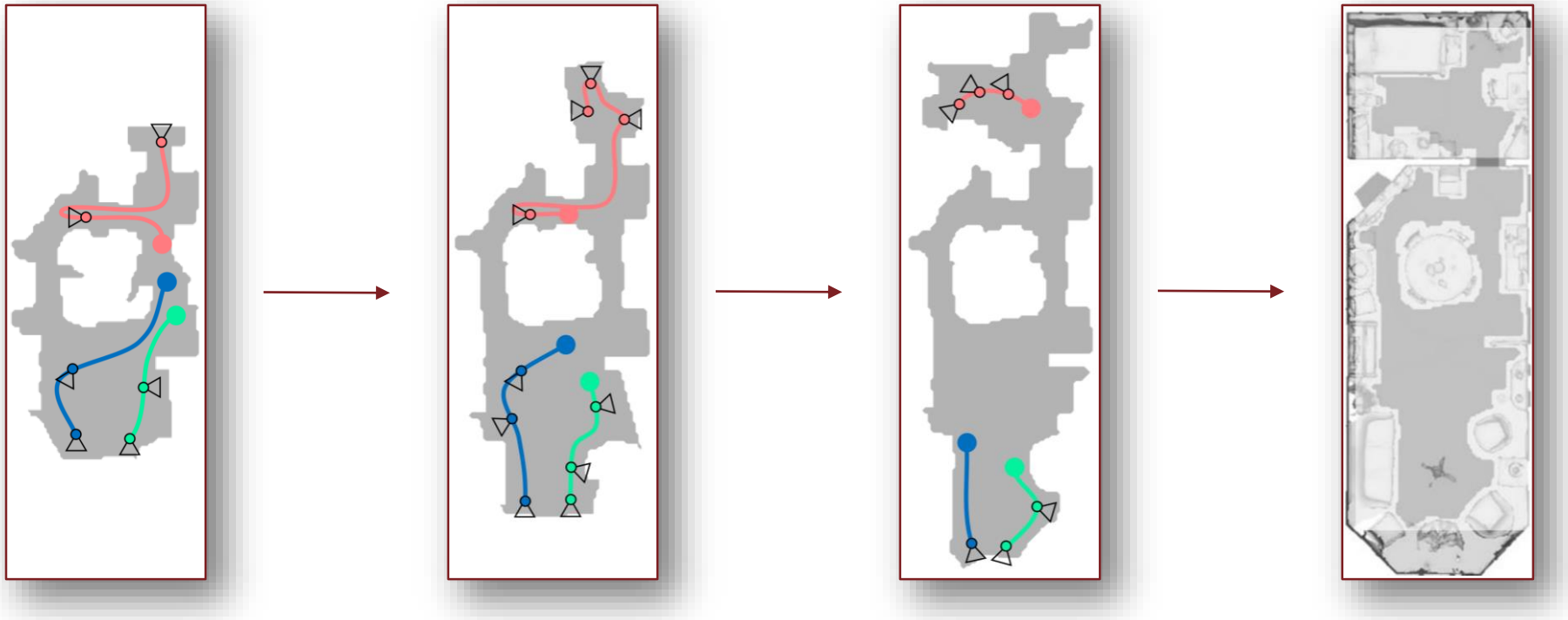


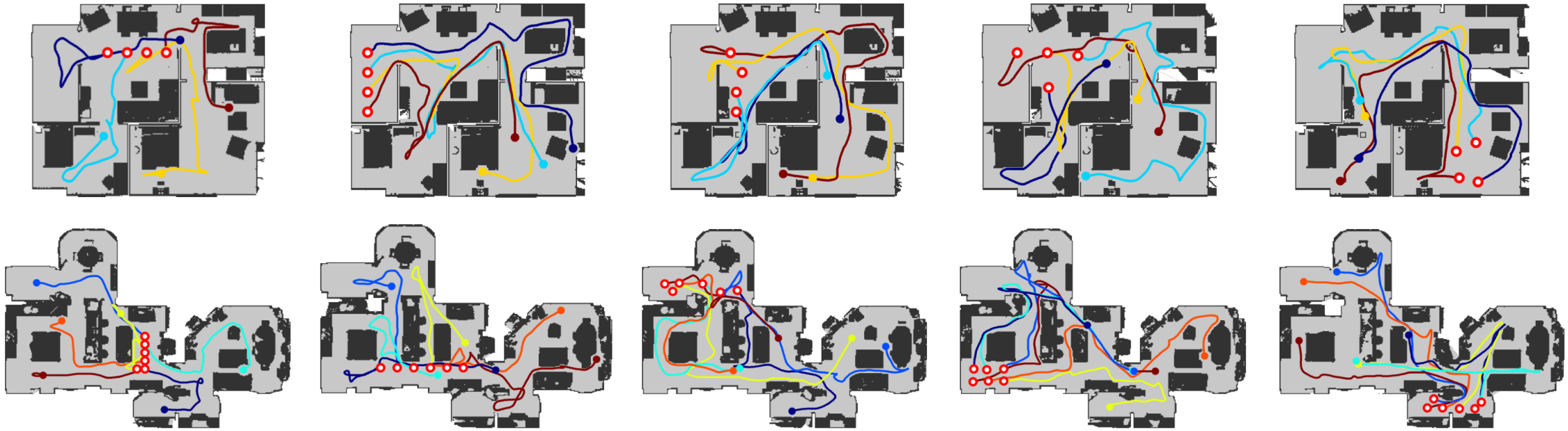
Method

Progressively Scanning



Results

Final Paths with Different Initializations

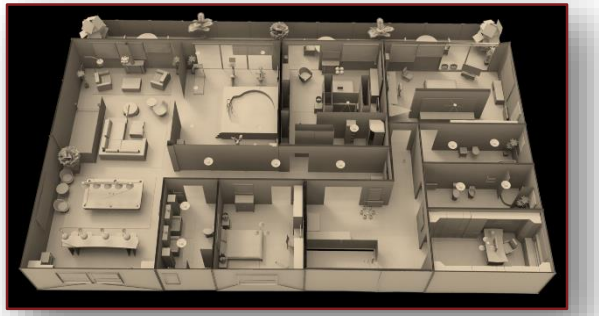


Evaluation

Benchmarks and Evaluation Metrics

Collect and format virtual scene models from SUNCG and Matterport3D





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Evaluation Metrics

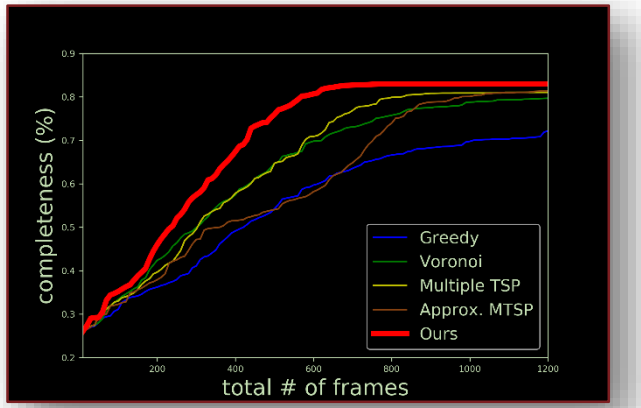
- Completeness
- Accuracy
- Total energy consumption
- Load balance

Evaluation

Quality Comparisons

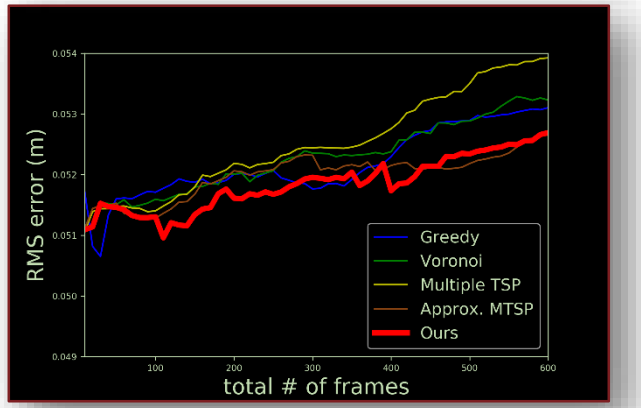
Completeness

$$\varphi_{\mathcal{G}\to\mathcal{S}} = \frac{100}{\sum A(g)} \sum_{g\in\mathcal{G}} A(g) \min_{s\in\mathcal{S}} \|s-g\|_2^0$$



Accuracy (RMS error)

$$\varphi_{\mathcal{S}\to\mathcal{G}} = \frac{1}{\sum A(s)} \sum_{s\in\mathcal{S}} A(s) \min_{g\in\mathcal{G}} \|s-g\|_2$$

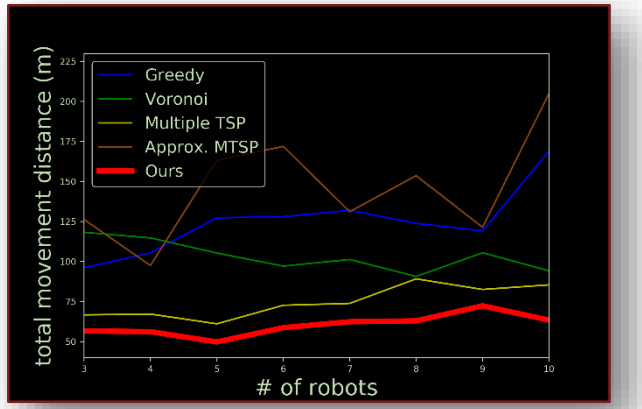


Evaluation

Efficiency Comparisons

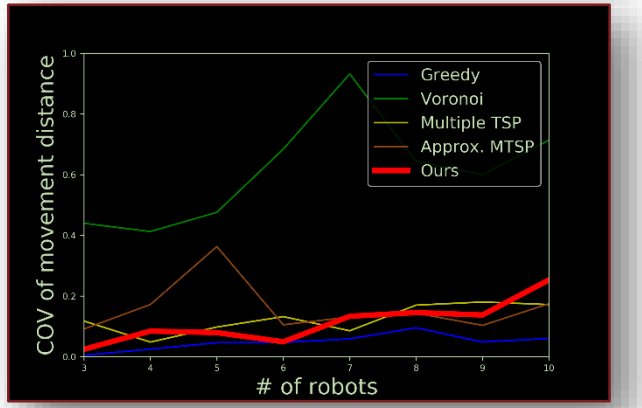
Total Energy Consumption

Total Movement Distance



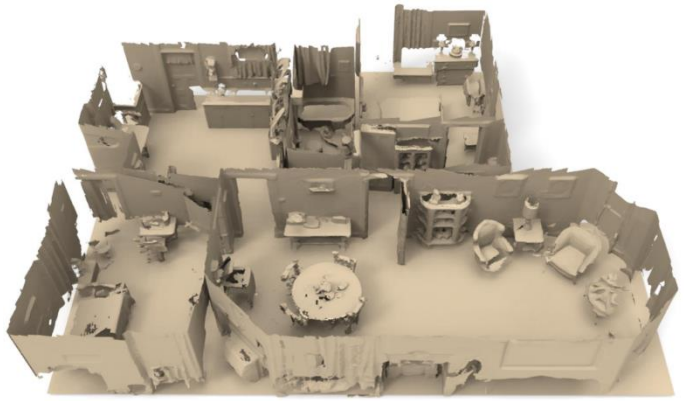
Load Balance

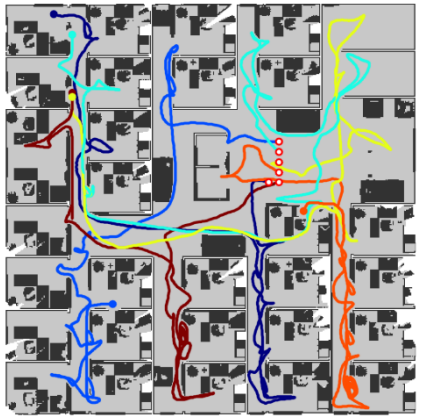
Coefficient of Variation

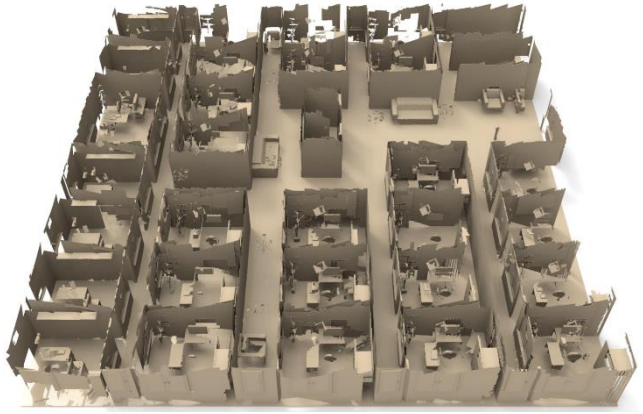


Results

Trajectories and Reconstruction

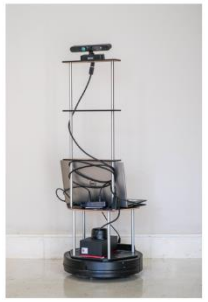


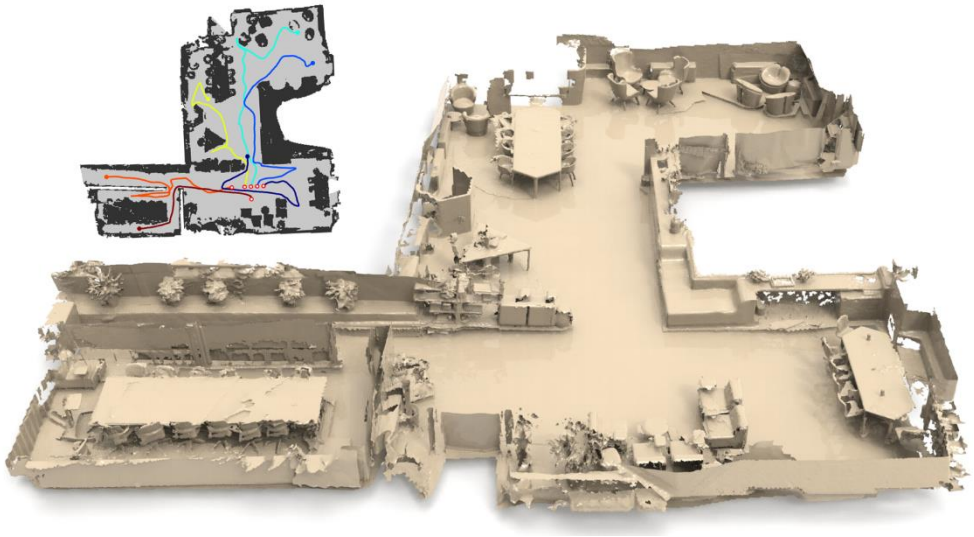




Results

Real-World Experiment





Results

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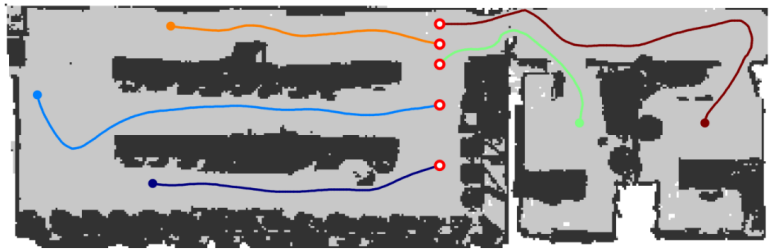

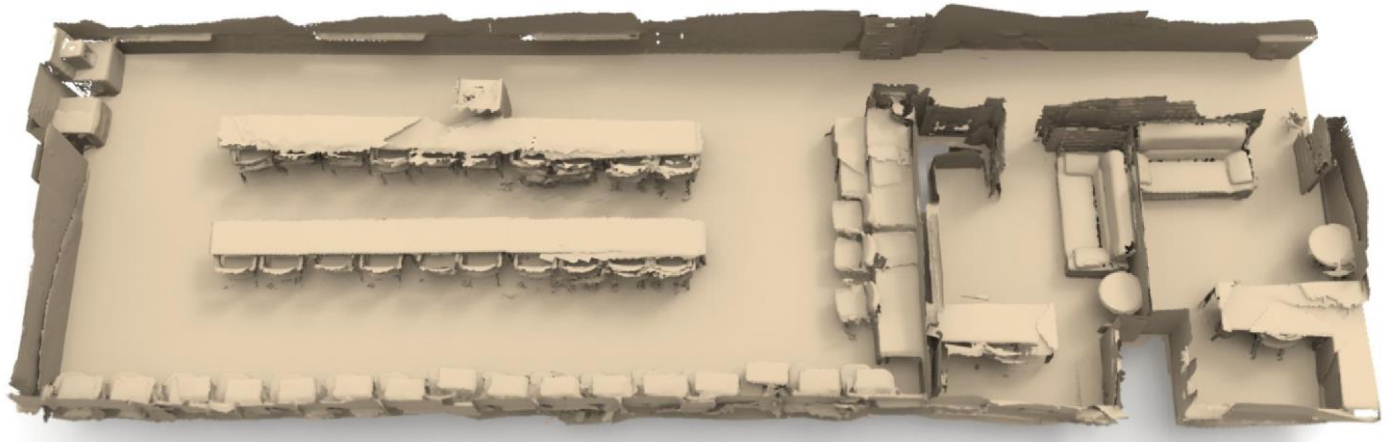

Conclusion

Contributions

- Formulation

  Optimal Mass Transport formulation tailored for multi-robot scanning of unknown indoor environments.

- Optimization

  Efficient solution to multi-robot scan planning based on a divide-and-conquer scheme that interleaves task assignment and path optimization.

- Code and Benchmark Will Be Released!

Conclusion

Future Works

- Task View Smoothness
- Discrete Approximate OMT Cost

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Thank you!