SERC RESEARCH REVIEW 2023 | NOVEMBER 15, 2023

Learning Enhanced Autonomous Navigation for GPS-Denied Vehicles

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SYSTEMS ENGINEERING RESEARCH CENTER

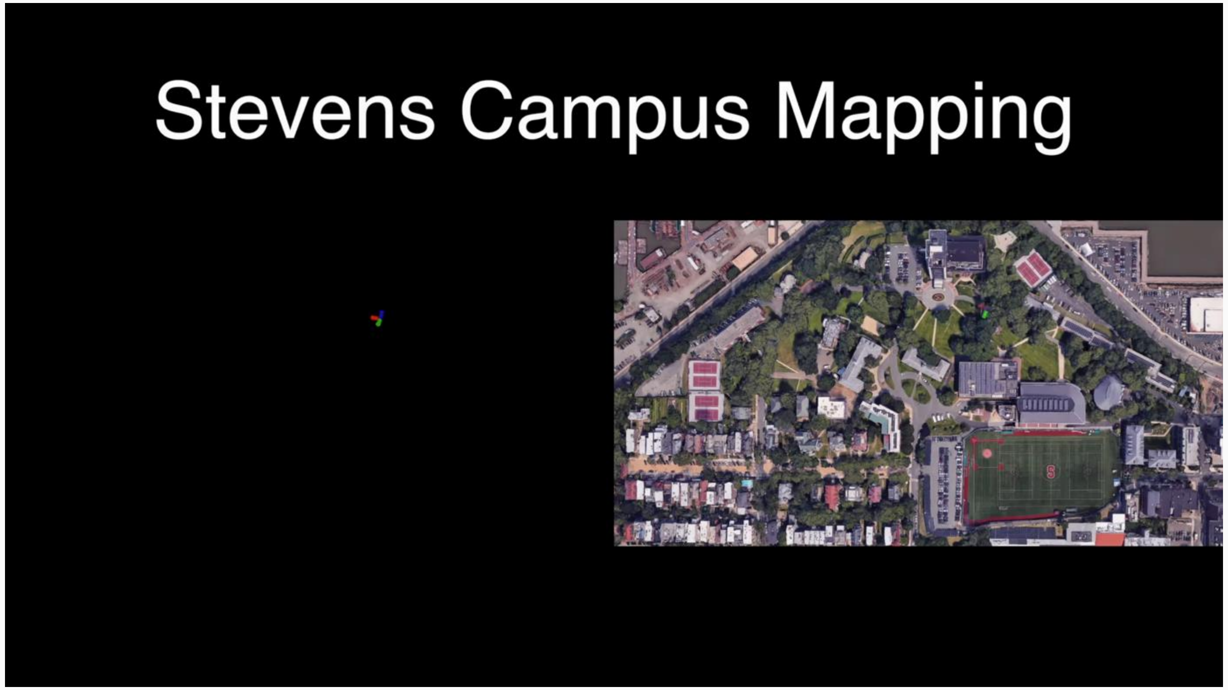
Original Project Goals

1. Develop a **multi-robot localization and mapping framework** that allows a team of unmanned ground vehicles (UGVs) to build more accurate, comprehensive LIDAR-based maps in GPS-denied environments by **regularly exchanging information.**

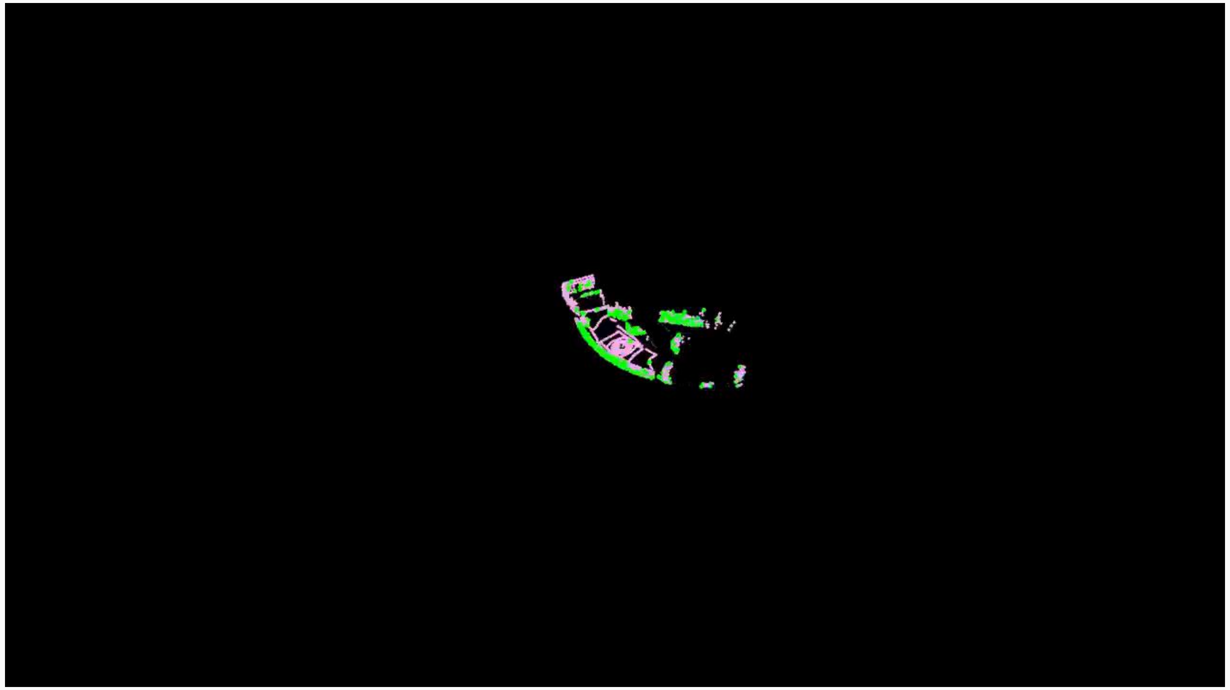
2. Implement **autonomous multi-robot exploration**, which allows the UGVs to leverage their cooperative localization and mapping capability to efficiently build a complete map of an unknown, GPS-denied environment within a set of specified boundaries.

3. Integrate **machine learning tools into the above capabilities** to facilitate both efficient planning and decision-making, using graph networks, and the construction of predictive perceptual data products, such as learning-enhanced grid maps and terrain traversability maps, that will enable high-performance motion planning.

Toward Comms-Efficient Multi-Robot Localization and Mapping



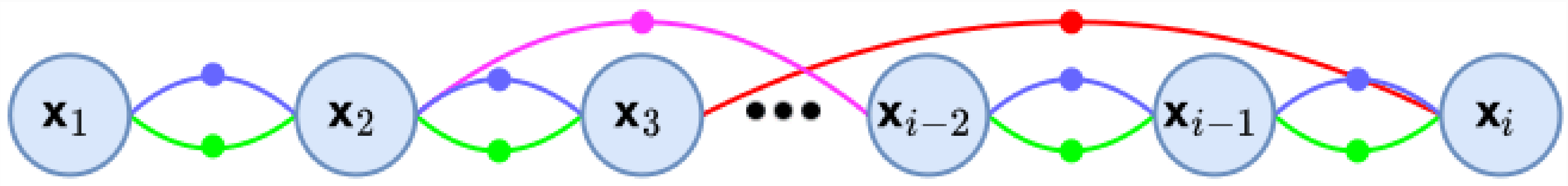
Mapping the Stevens Campus - *Hoboken, NJ*



Mapping an Underground Mine - *Louisville, KY*

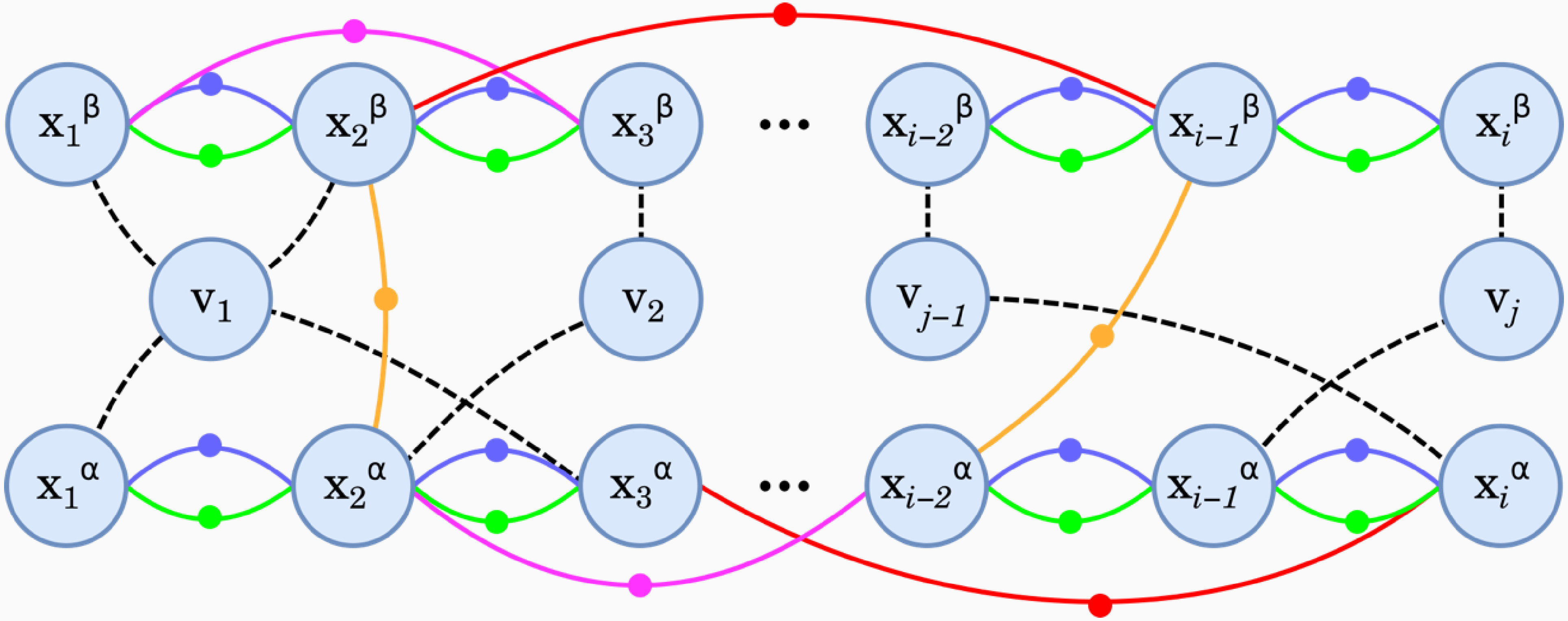
- Our *Lightweight, Ground-Optimized Lidar Odometry and Mapping* (**LeGO-LOAM**) algorithm supports high-performance mobile robot localization and mapping in GPS-denied environments over variable terrain

Factor Graphs for Robot Localization



blue factors	*odometry* measurements of consecutive poses;
green factors	*sequential scan matching* of two consecutive poses;
red factors	*point cloud* segment matching loop closures;
magenta factors	*pose matching* generated loop closures.

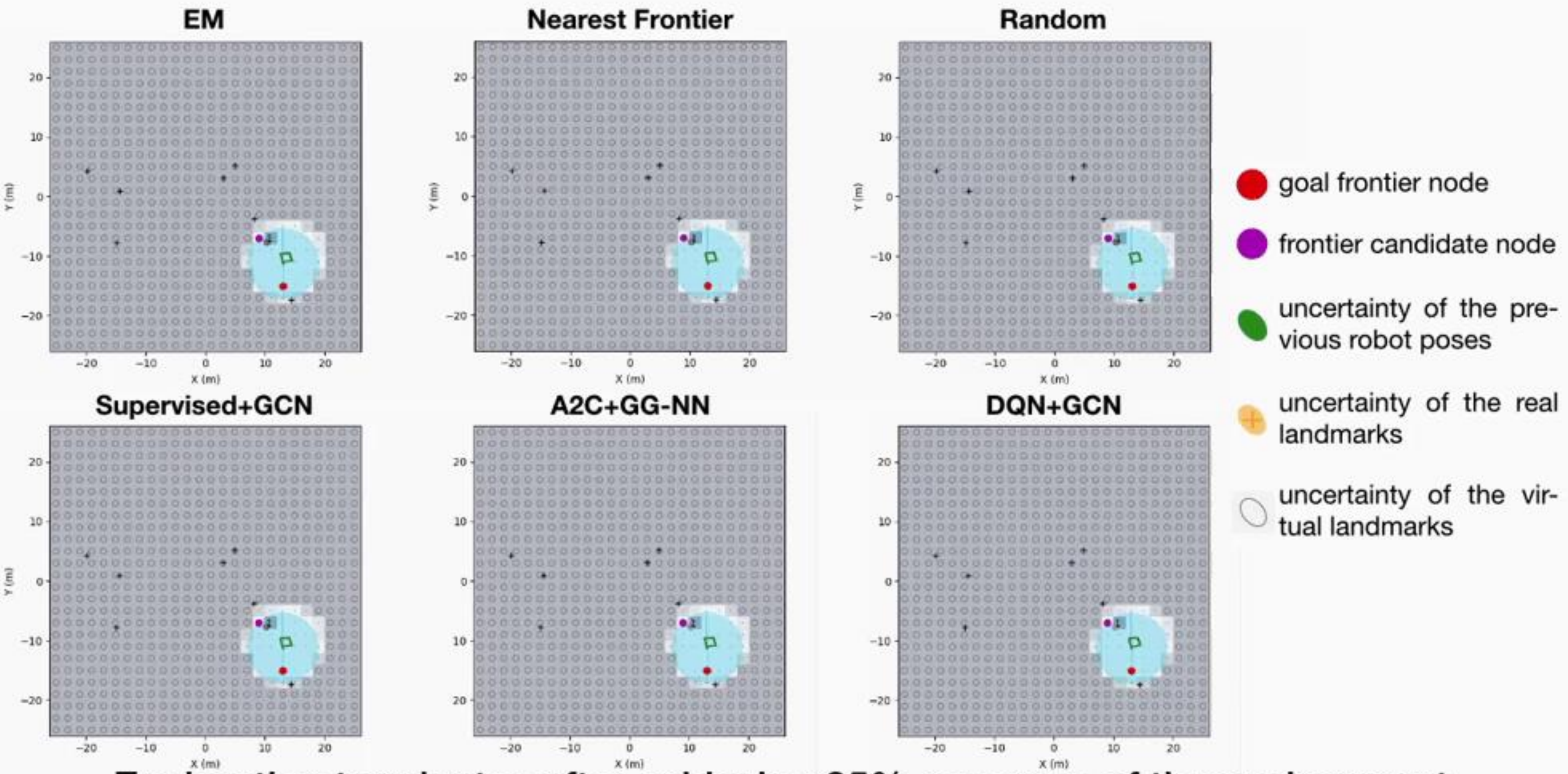
Factor Graphs for Multi-Robot Localization



blue factors	odometry measurements of consecutive poses;
green factors	sequential scan matching of two consecutive poses;
red factors	point cloud segment matching loop closures;
magenta factors	pose matching generated loop closures;
orange factors	loop closures generated by <u>inter-robot</u> scan matching.

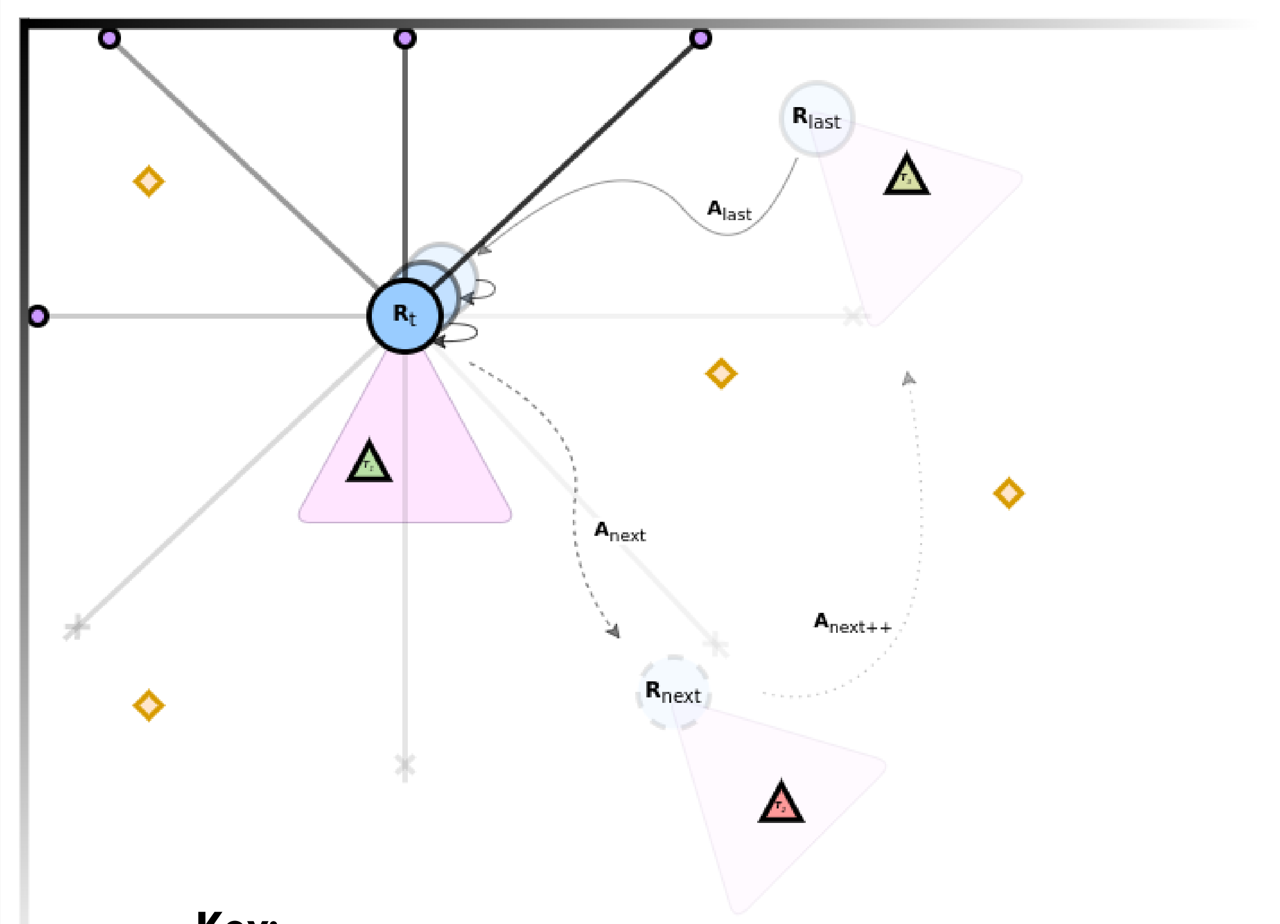
Autonomous Exploration and Mapping

Exploration Test on 40m x 40m Maps



Exploration terminates after achieving 85% coverage of the environment.

The Persistent Monitoring Problem



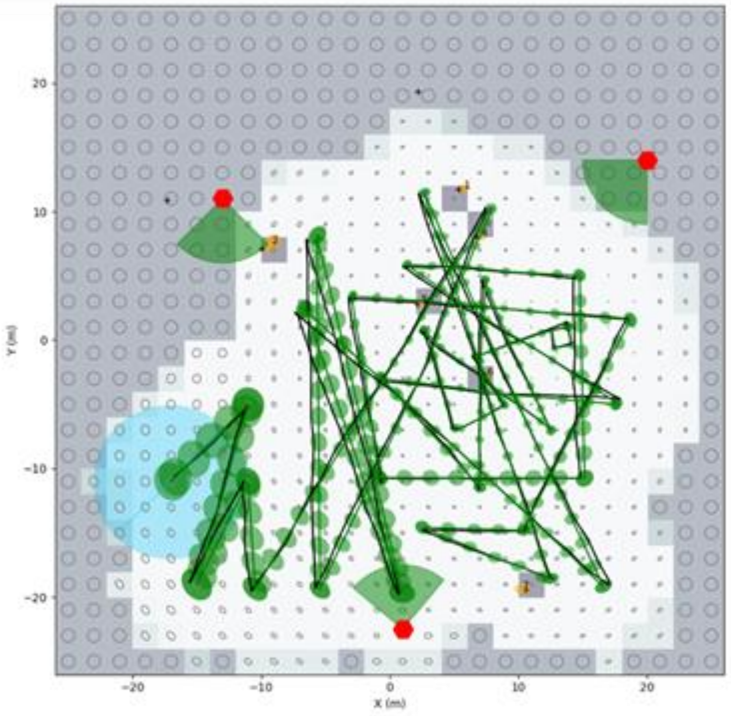
Key:

- <u>Circle</u>: *Robot Agent*
- <u>Triangle</u>: *Target Nodes*
- <u>Diamond</u>: *Landmark Node*

Goal:

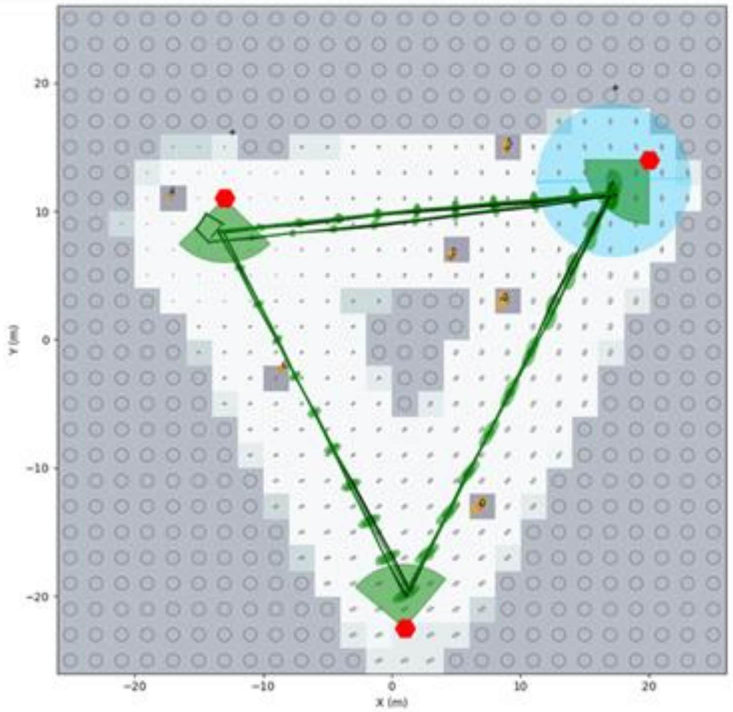
Using a team of one or more robots, observe a set of multiple target nodes in the environment as frequently as possible.

The Persistent Monitoring Problem: Simulation



Random Exploration

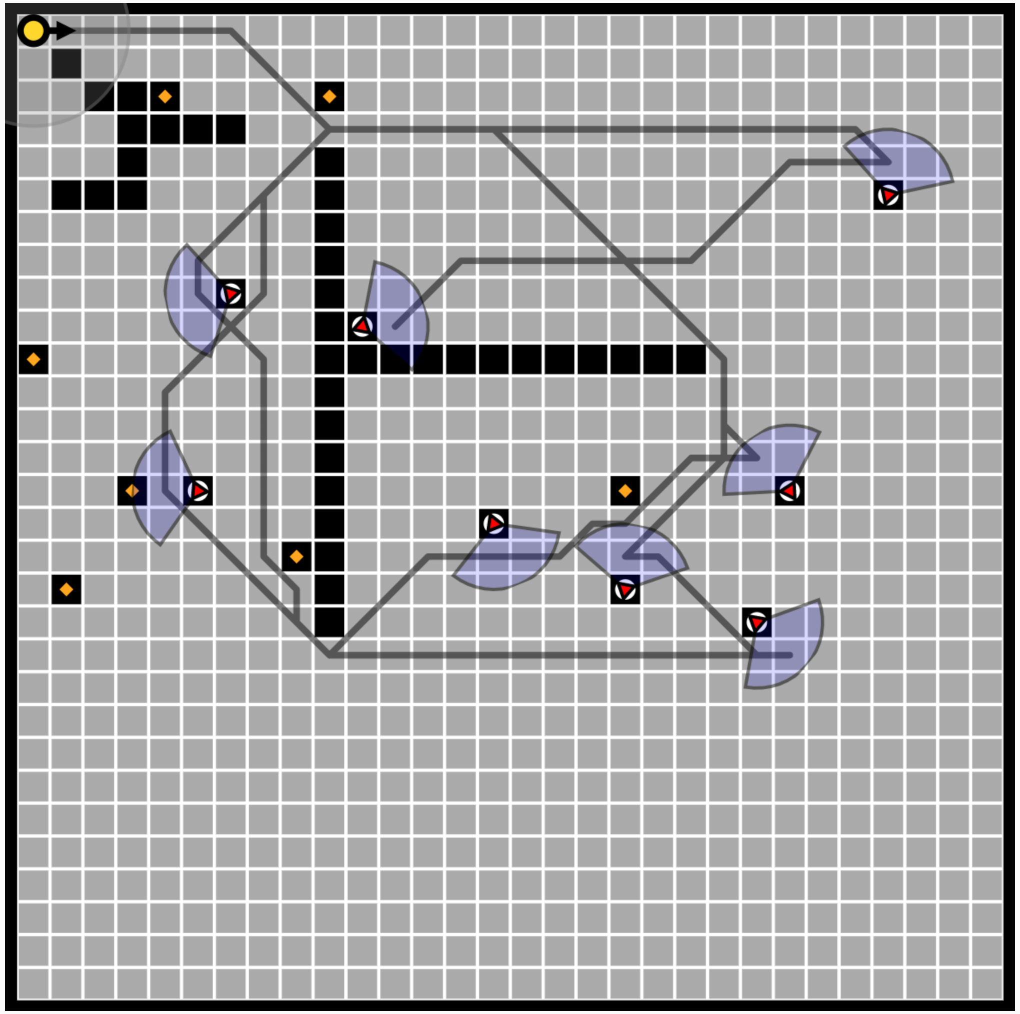
- Poor coverage of monitoring targets *(expected)*
- Large buildup of localization uncertainty



Direct Robot → Target Routing

- Optimal coverage of monitoring targets
- Mitigated buildup of localization uncertainty

The Persistent Monitoring Problem: Simulation



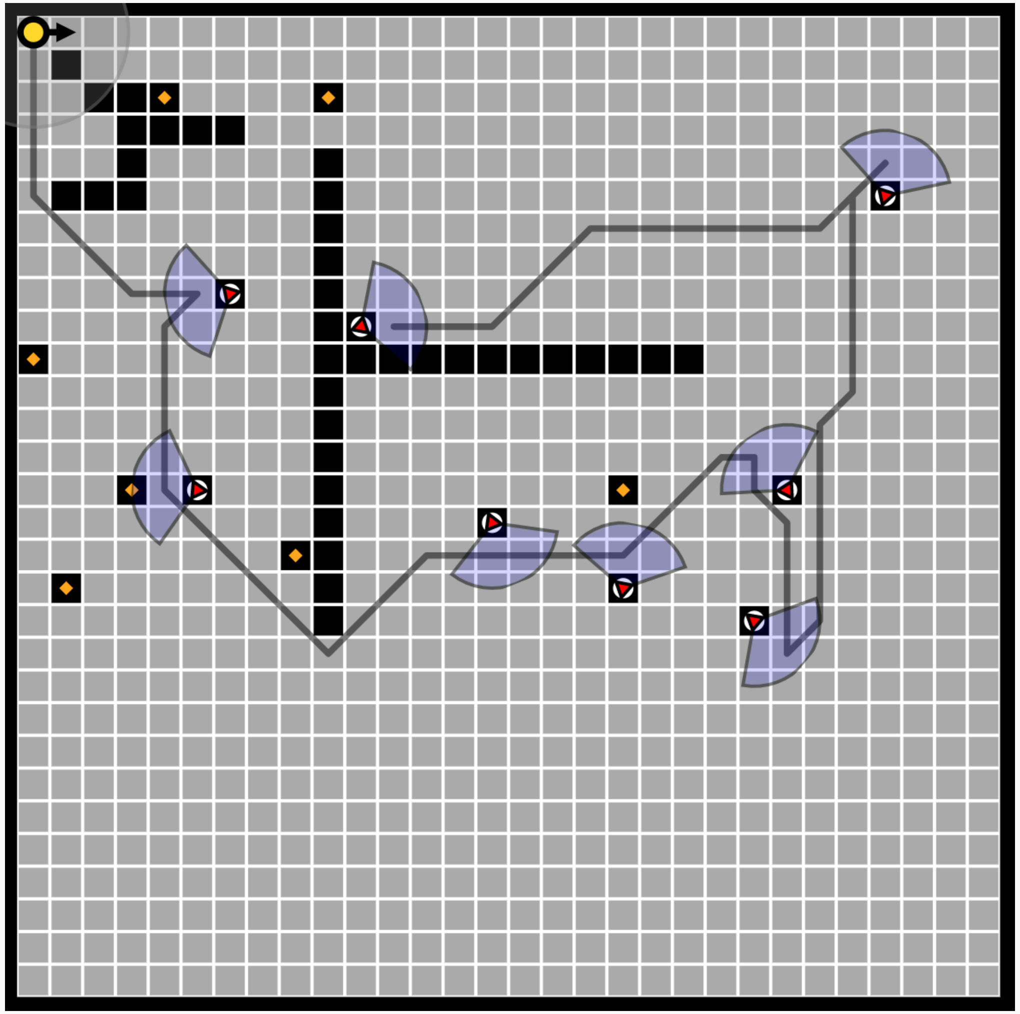
Next-Target Assignment:

- Optimal solution requires short and long-term reasoning, taking into account current agent state, environment structure, and agent uncertainty

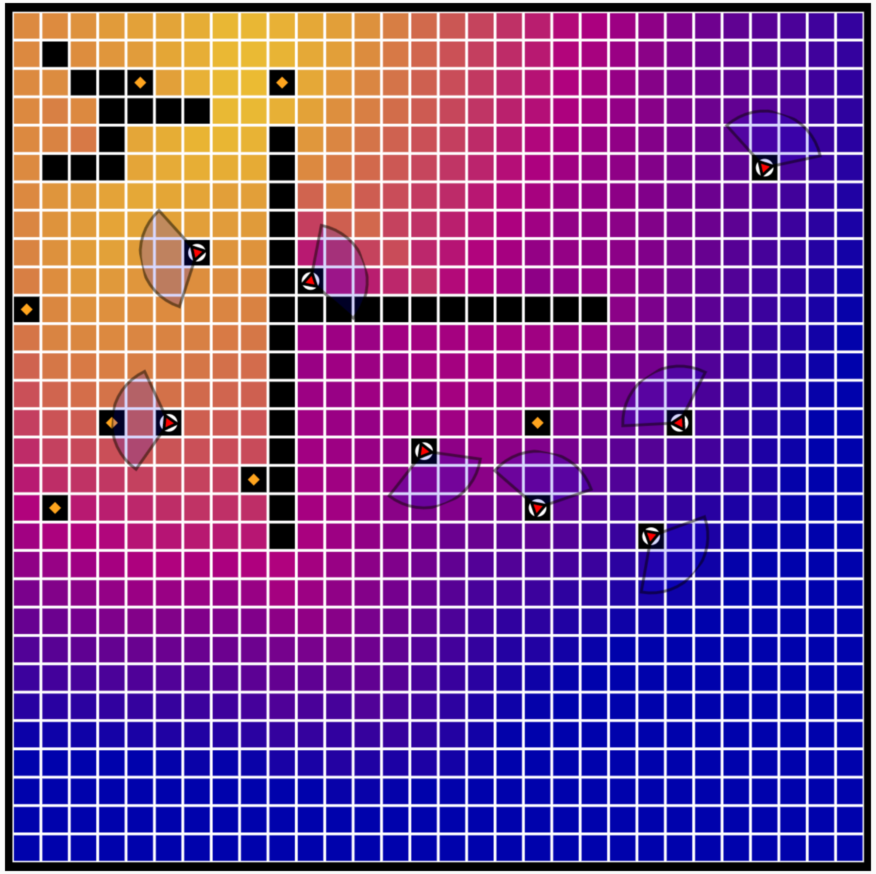
The Persistent Monitoring Problem: Simulation

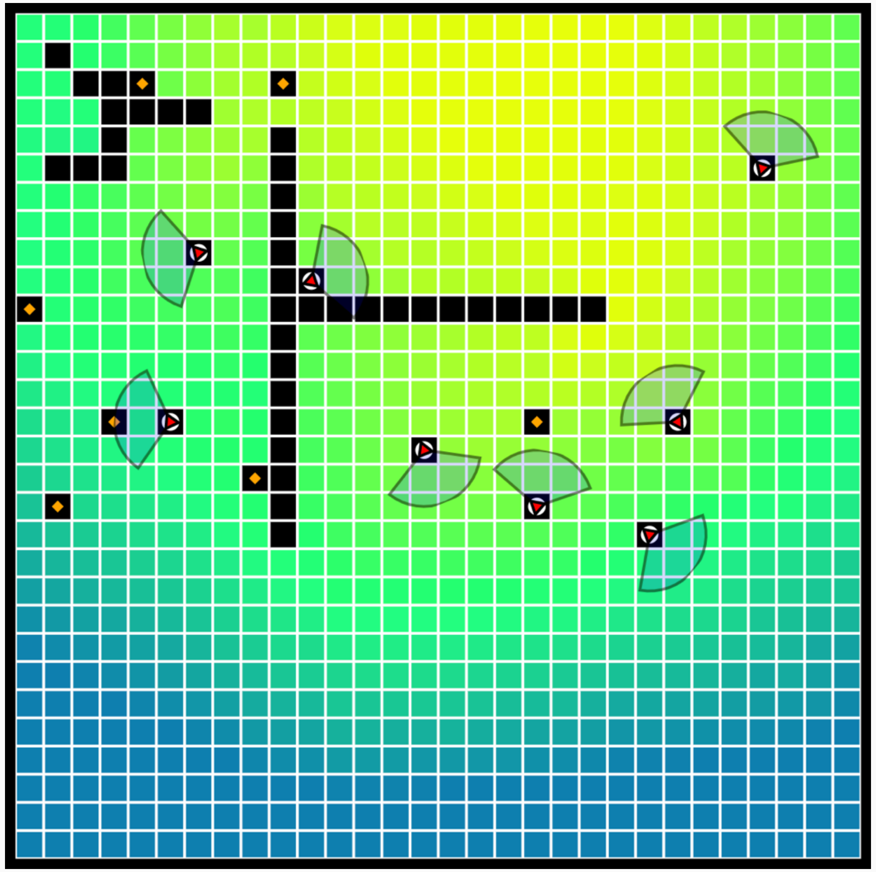
Next-Target Assignment:

- Optimal solution requires <u>short and long-term reasoning</u>, taking into account current agent state, environment structure, and agent uncertainty
- We may compute an optimal solution over any one of these parameters tractably, but jointly optimizing over all requires some degree of approximation



The Persistent Monitoring Problem: Simulation





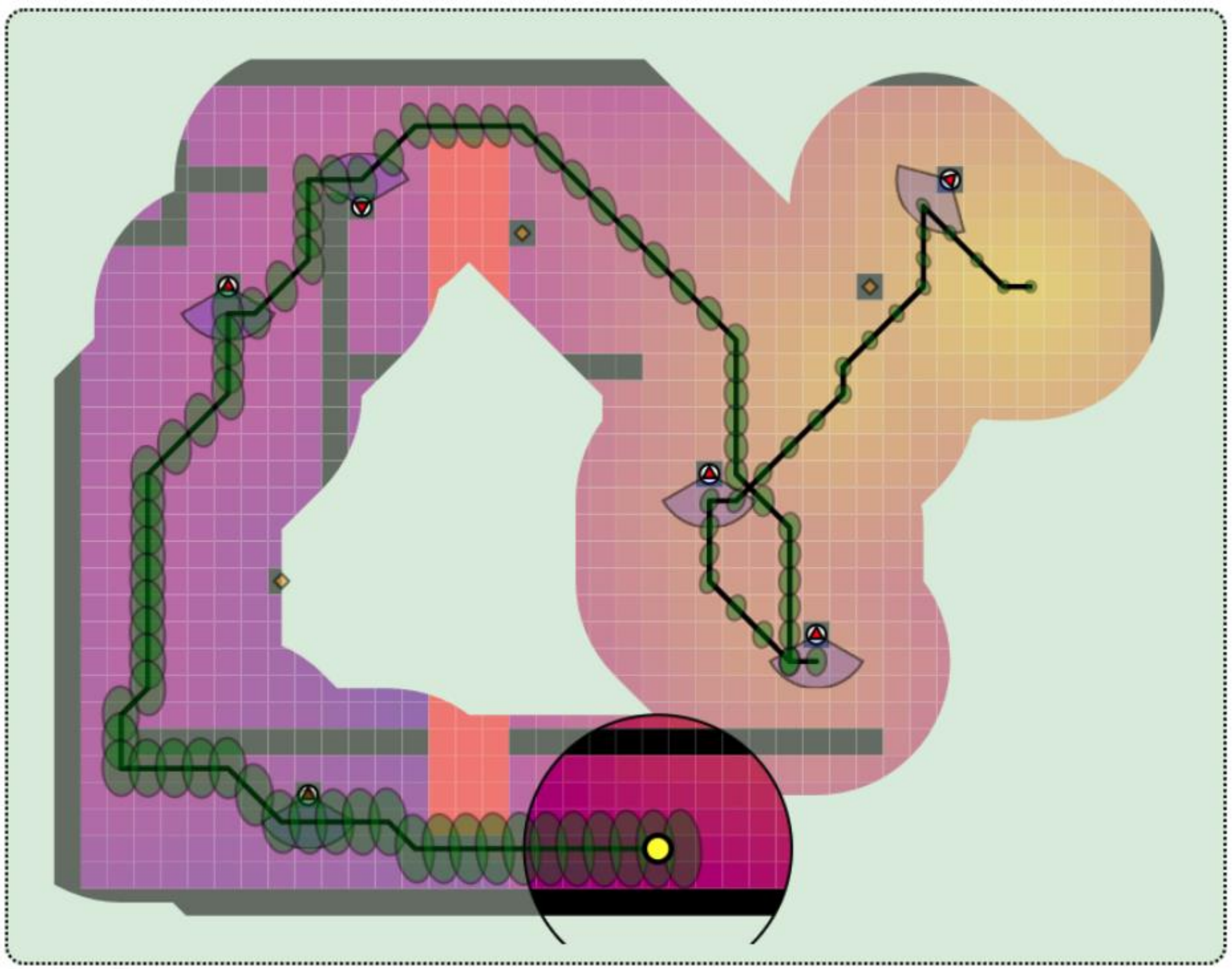
Examination of Target/Landmark Locality

Here, we visualize a generated costmap over the environment map, by means of evaluating positions on the map as a function of their distance from landmark/target nodes.

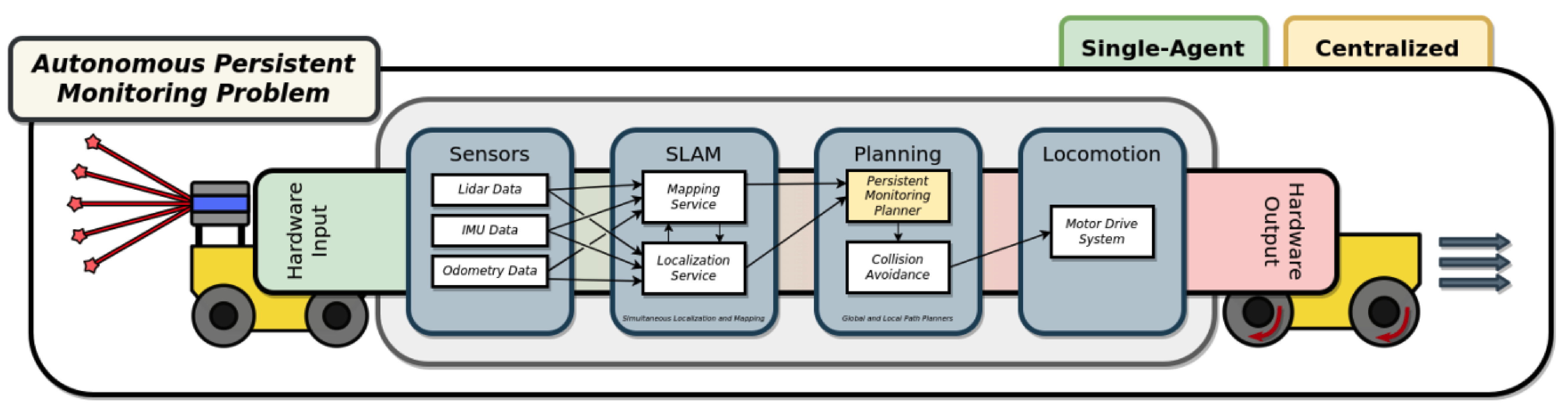
The Persistent Monitoring Problem: Simulation

Examining Localization Uncertainty

- Consideration of agent localization uncertainty as a function of distance/time during environmental traversal



The Persistent Monitoring Problem: System Architecture



High-Level Architectural Overview:

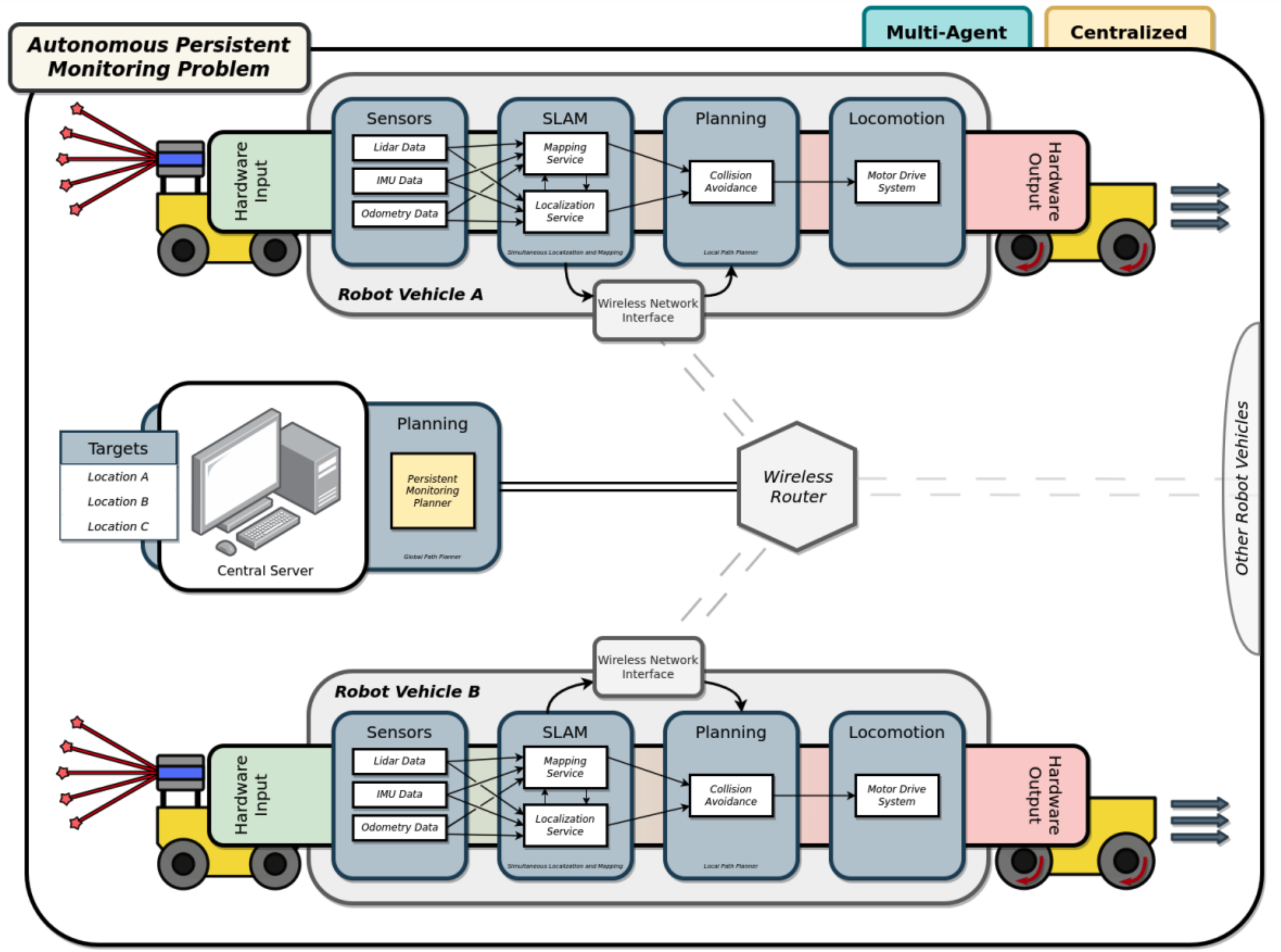
Persistent target monitoring is primarily a *planning task*, but must be integrated with a wider robot system architecture for execution in real-world environments

The Persistent Monitoring Problem: System Architecture

Multi-Agent Persistent Monitoring

To achive task coordination between multiple robot agents operating in parallel, we must consider new sources of problem complexity.

- Communication
  - Intermittent Connectivity
  - Bandwidth Limitations
- Shared State
  - De-Synchronization
  - Eventual Consistency

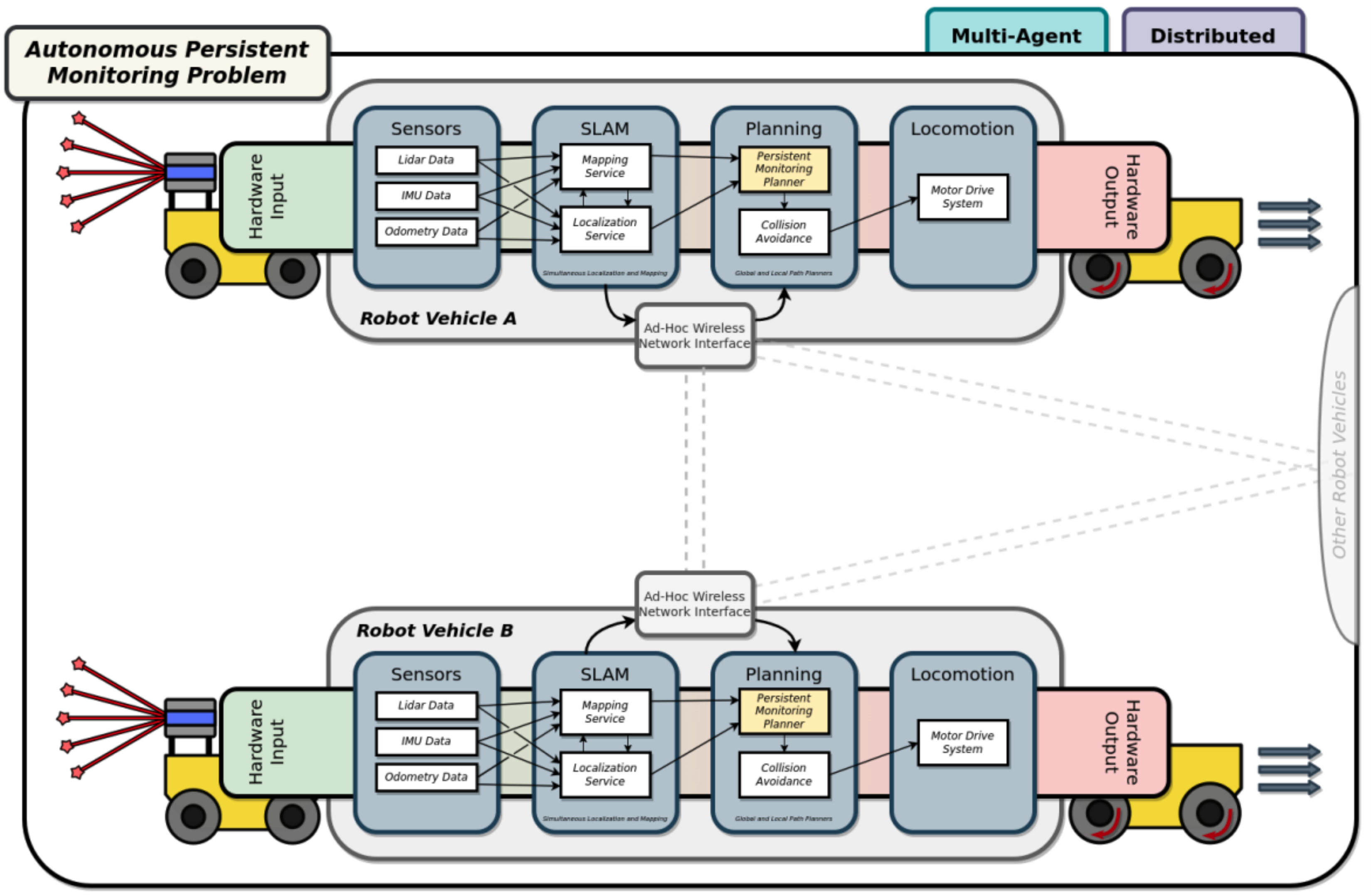


The Persistent Monitoring Problem: System Architecture

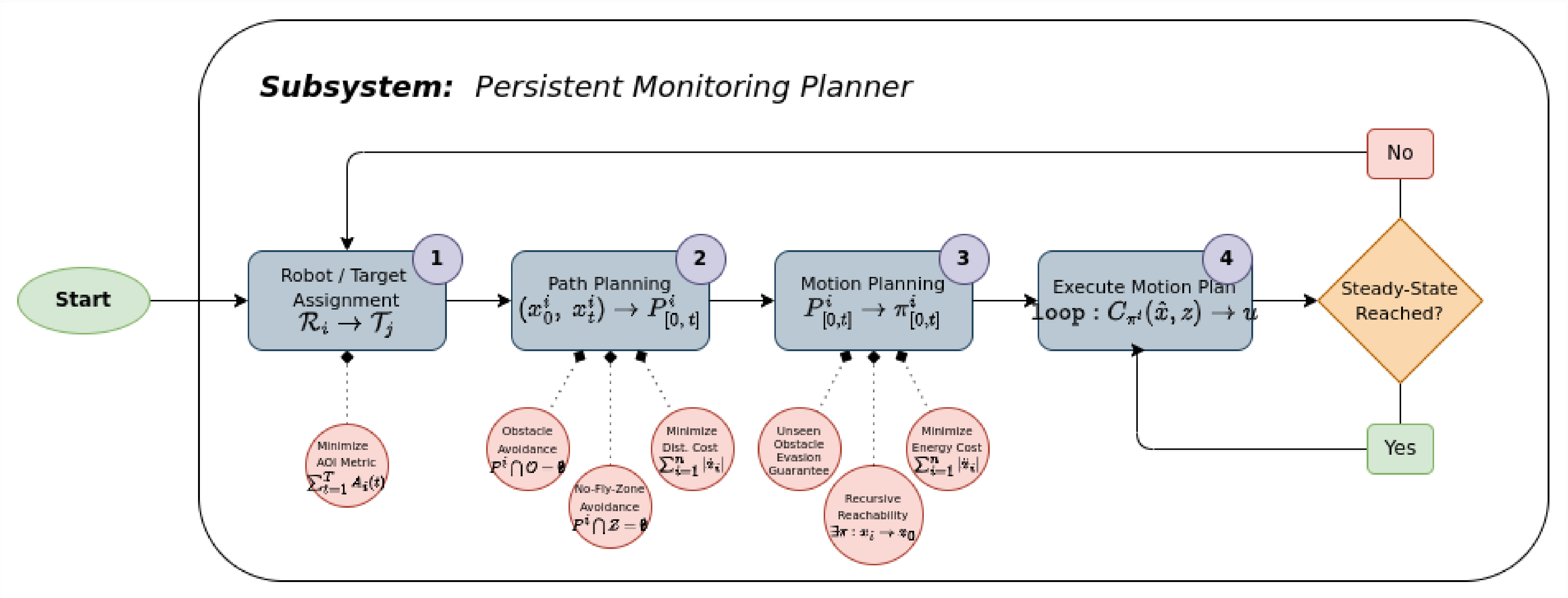
<u>Distributed</u> Multi-Agent Persistent Monitoring

Similar to centralized multi-agent system, but without single-point-of-failure base station.

- Communication
  - ***Very*** Intermittent Connectivity
  - Bandwidth Limitations
- *(Partially)* Shared State
  - De-Synchronization
  - Eventual Consistency



The Persistent Monitoring Problem, Up-Close



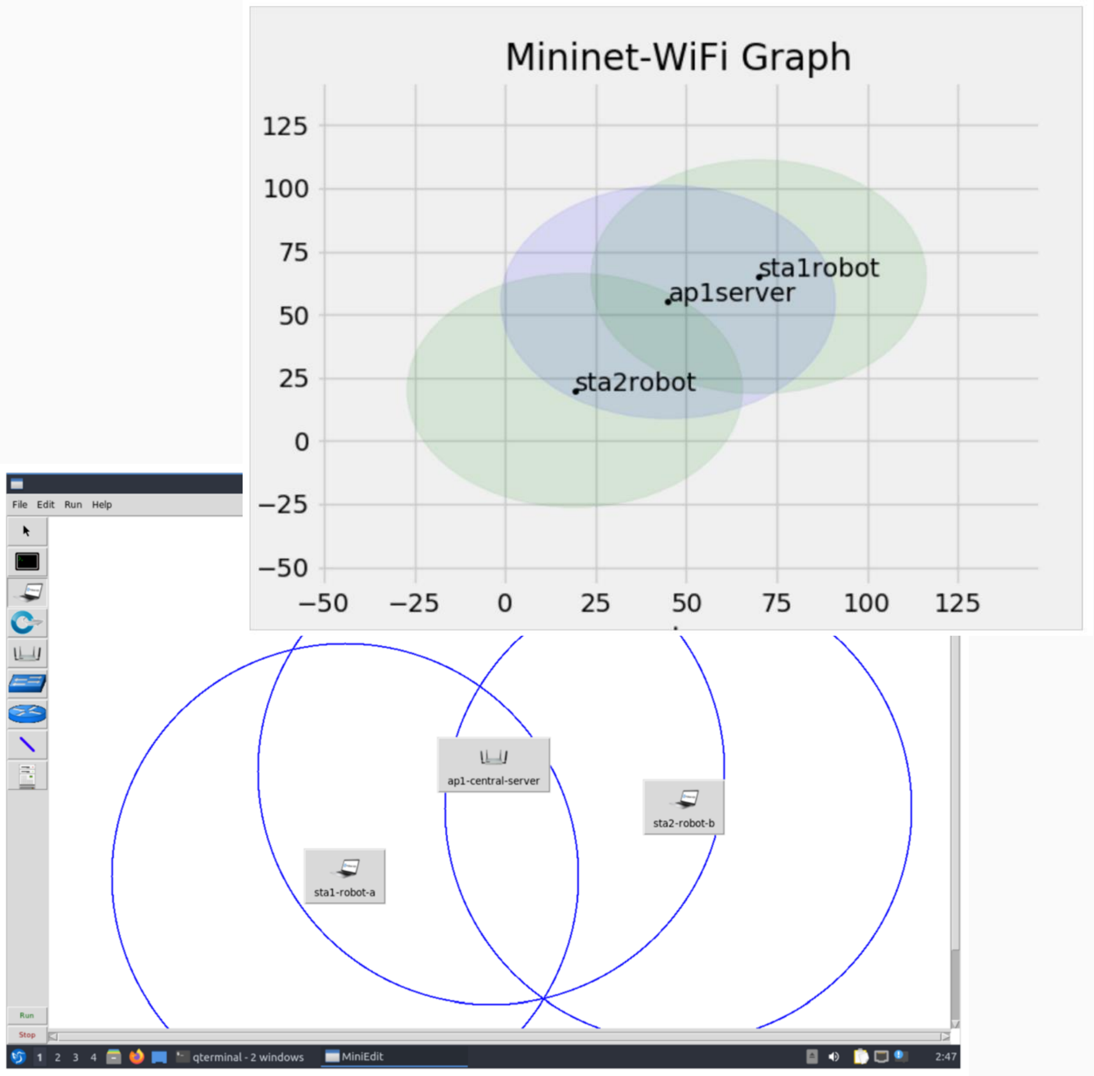
Towards Perpetual System "Liveness"

Unlike episodic exploration tasks, successful persistent monitoring requires not only that the system is efficient in operation, but also that it reaches a viable, repeatable steady-state, with high likelihood of success.

Towards Multi-Robot Validation: Network-Stack Virtualization

Multi-Agent Communication is Complex

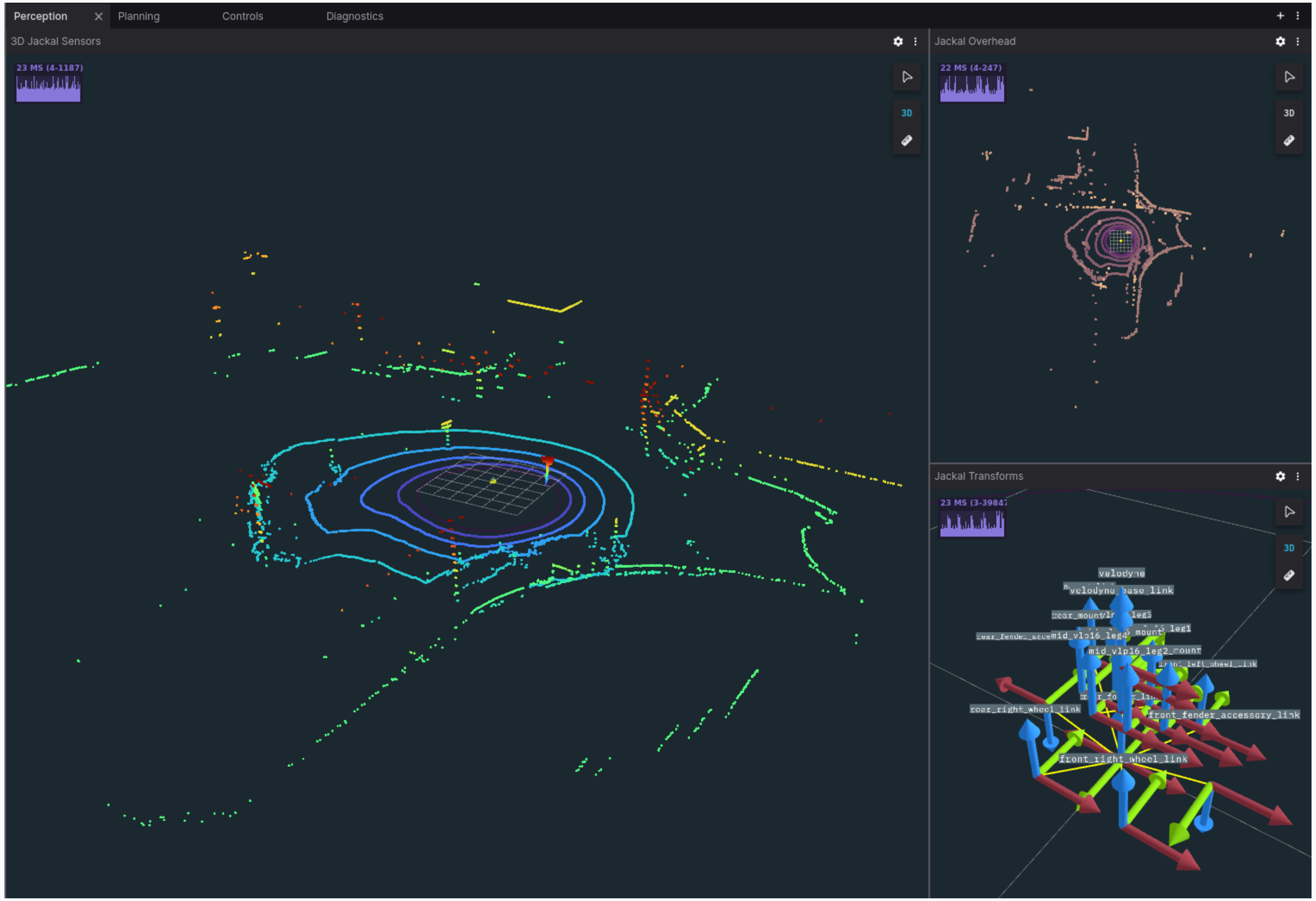
- Simulated tools are necessary to achieve comprehensive, repeatable results proving the efficacy of an implementation
- For multi-robot systems, this is particularly critical for high-fidelity wireless communication emulation



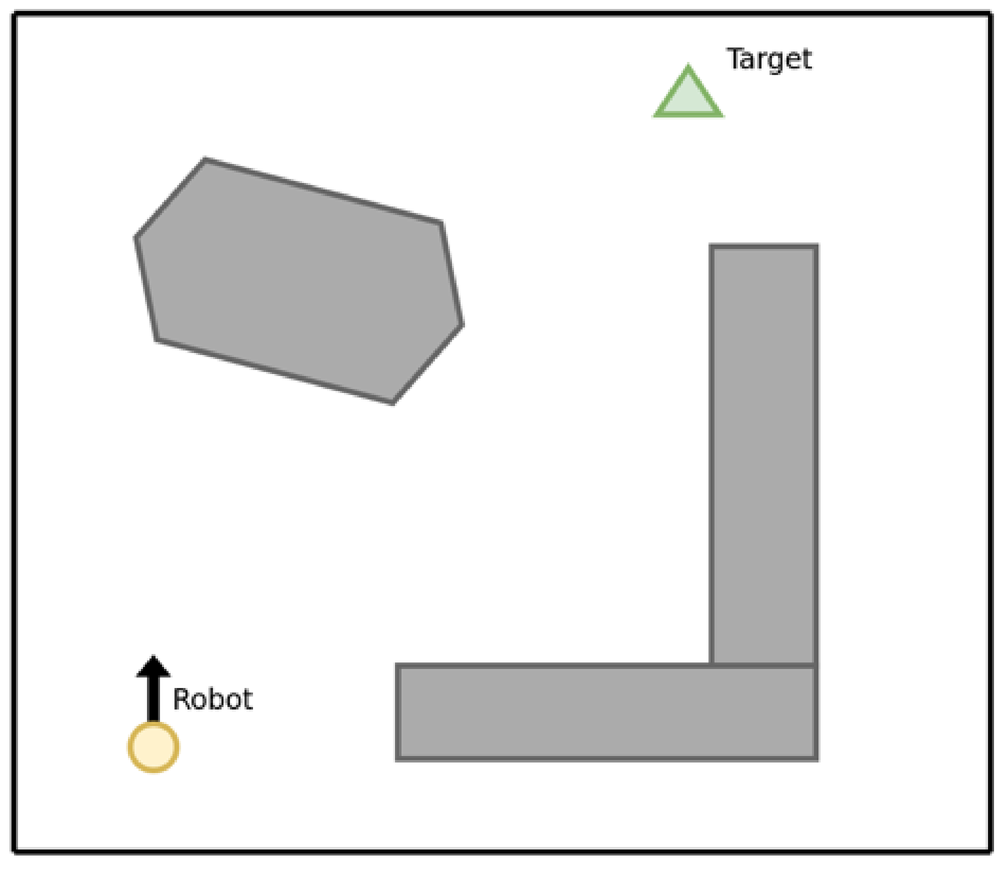
Towards Multi-Robot Validation: Network-Stack Virtualization

Fully Virtualized Robot Networking

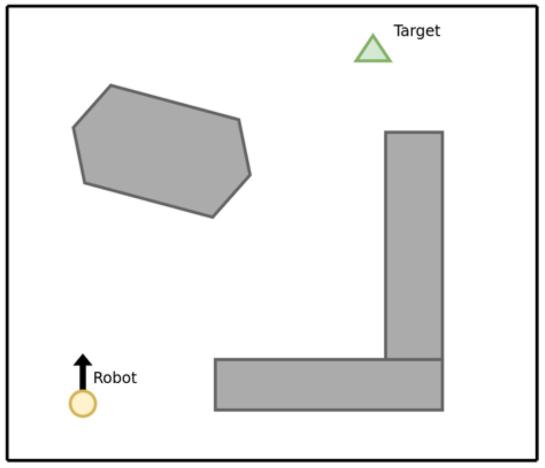
- We leverage existing tools from the field of computer hardware virtualization and emulation to implement a high-fidelity proxy for robot integration testing

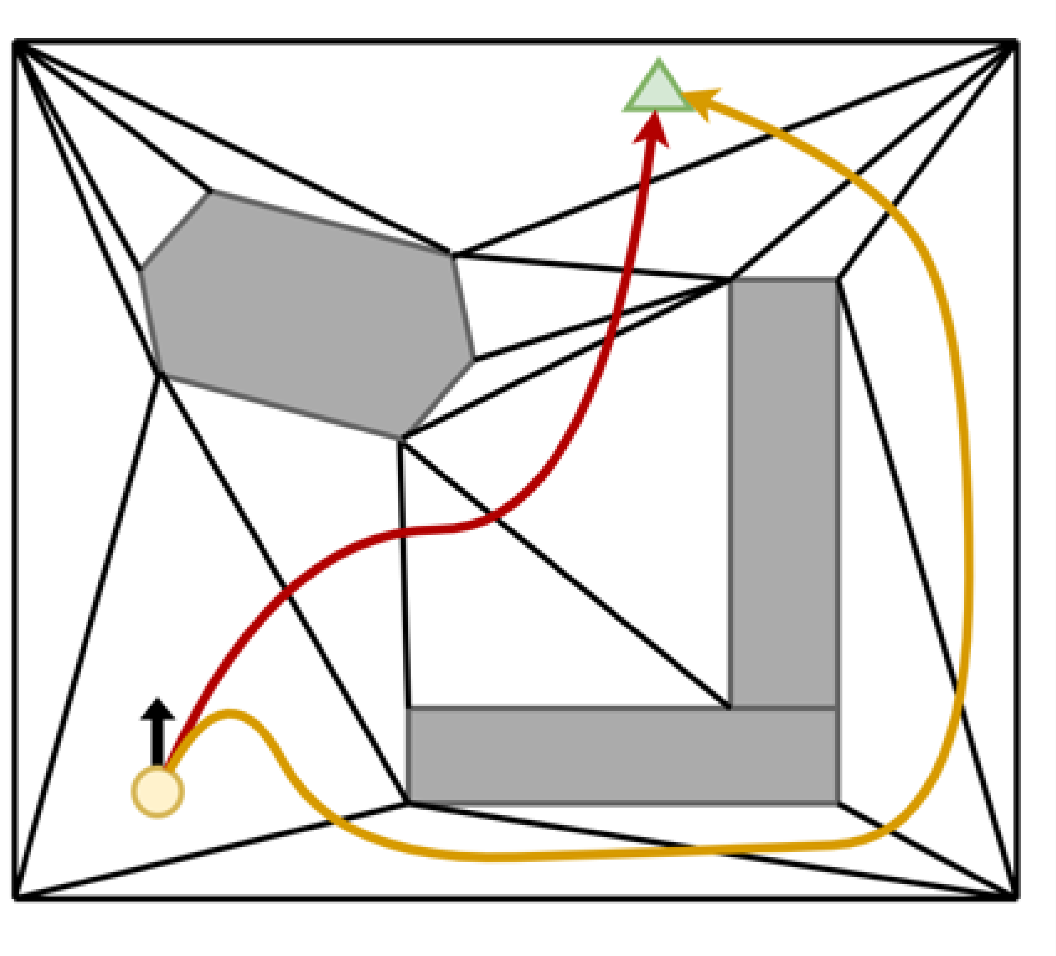


Topological Motion Planning for Persistent Monitoring



Topological Motion Planning





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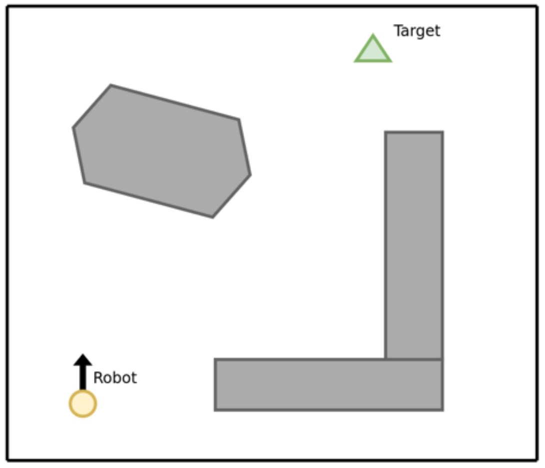

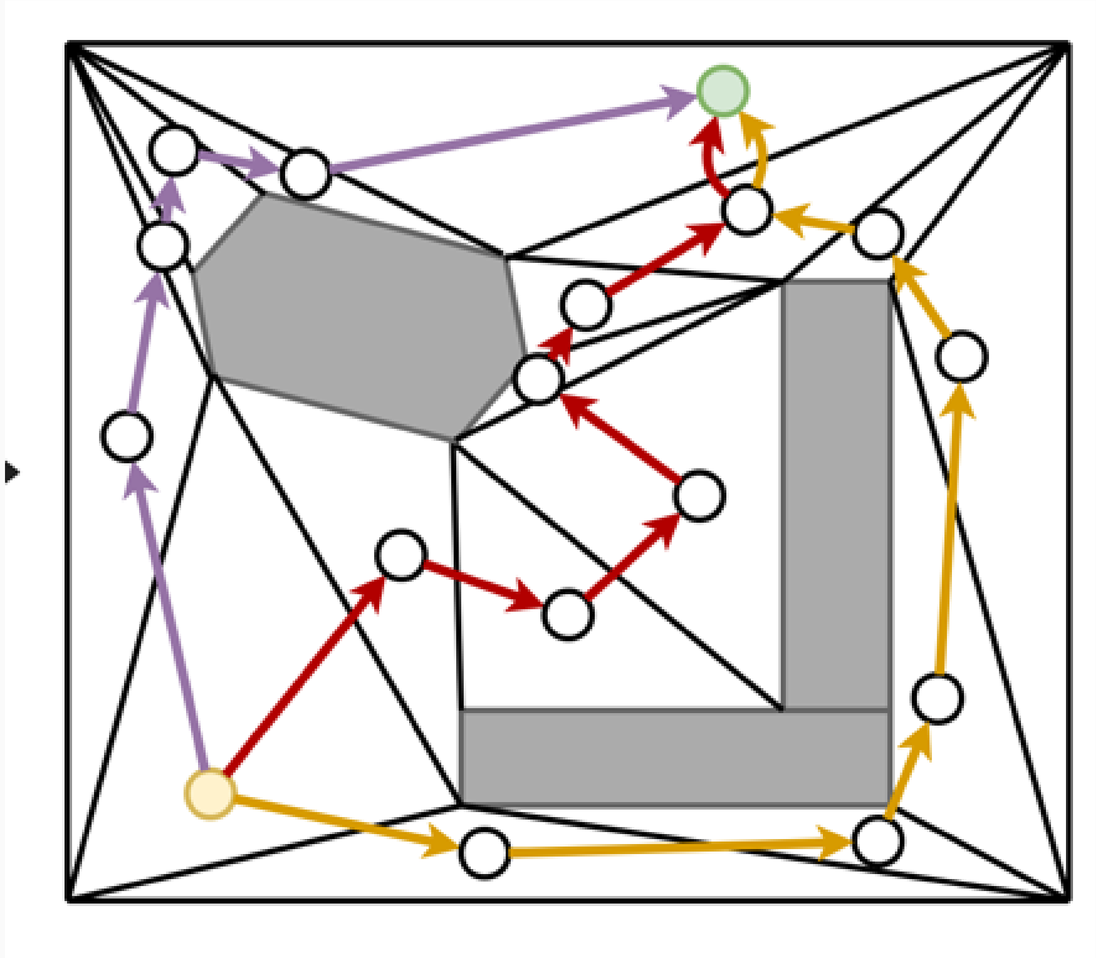

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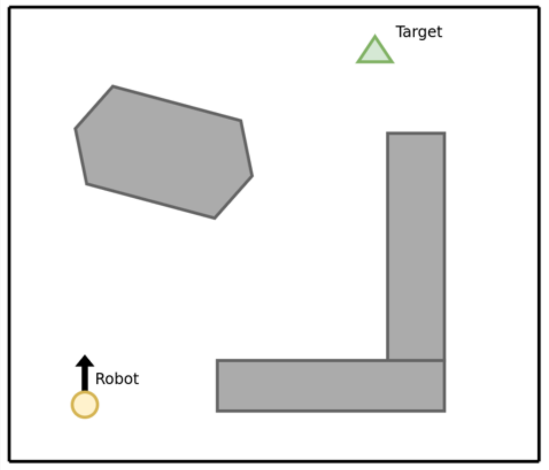

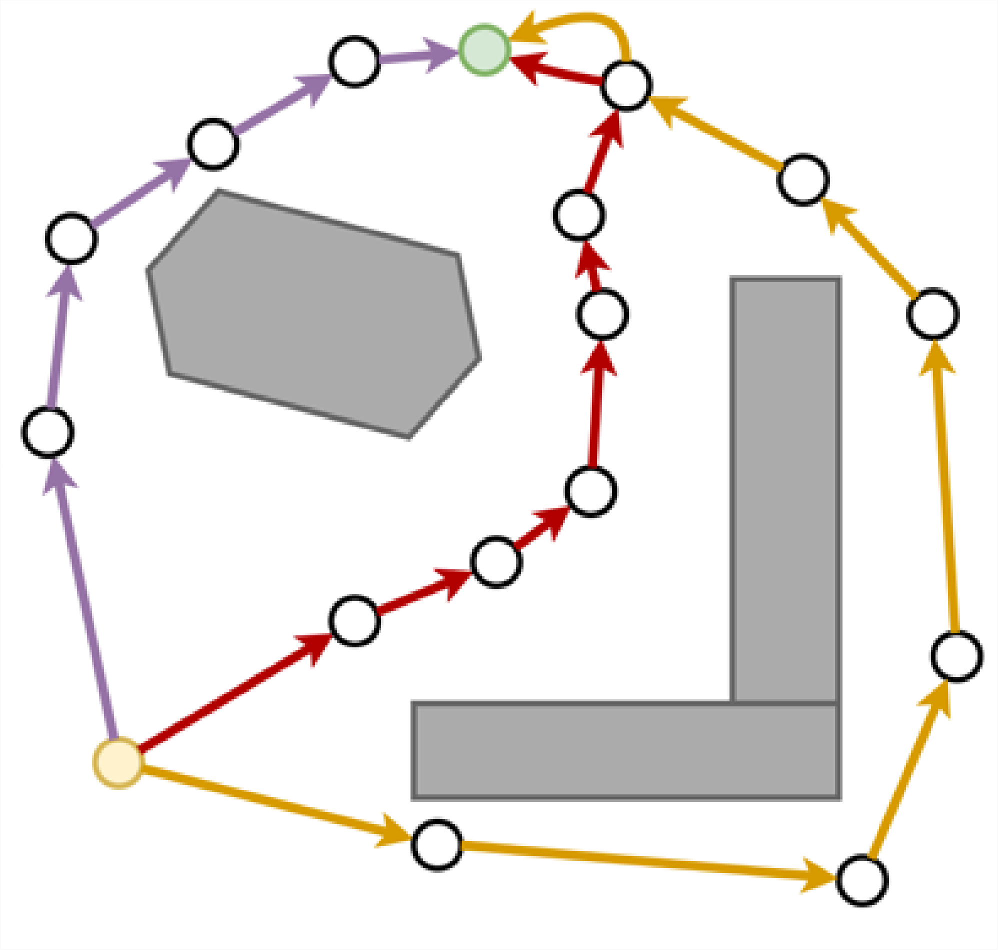

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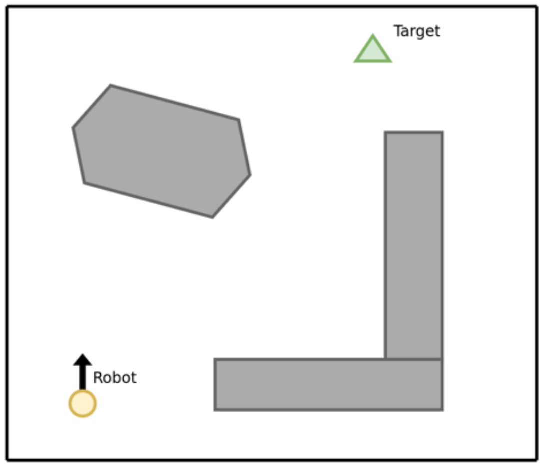

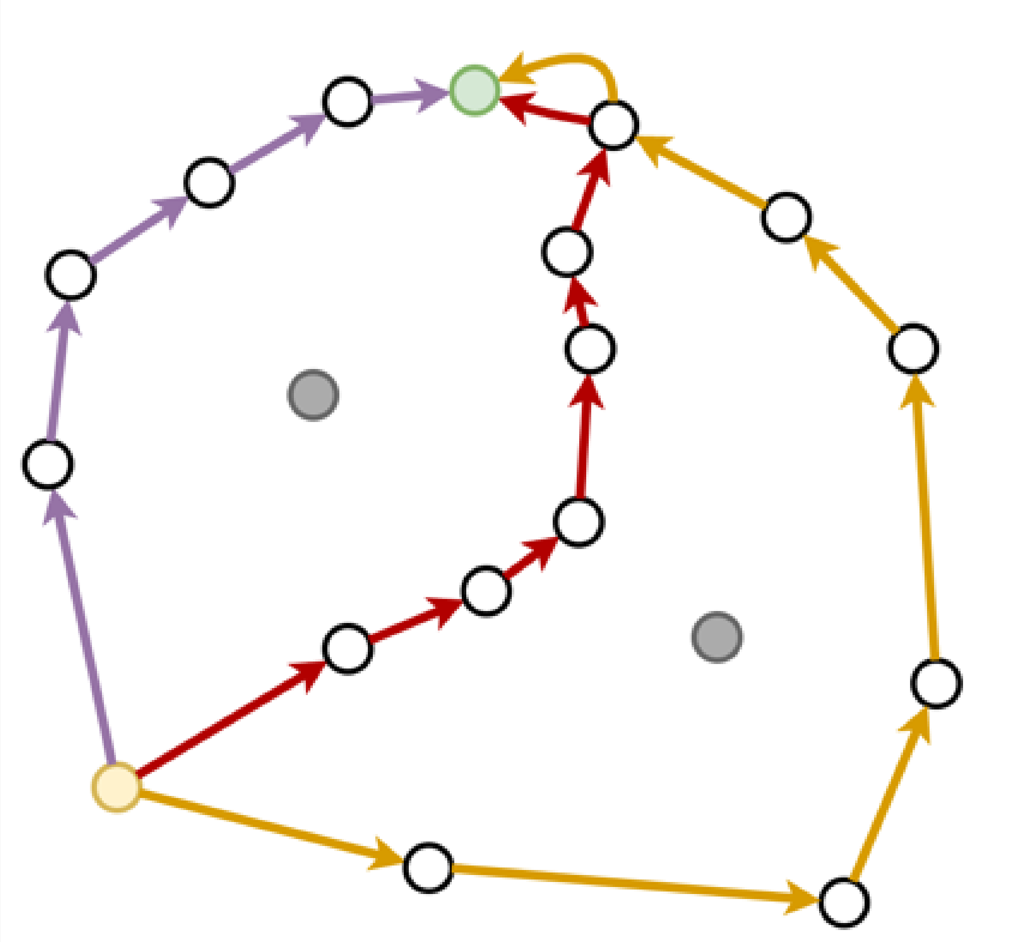

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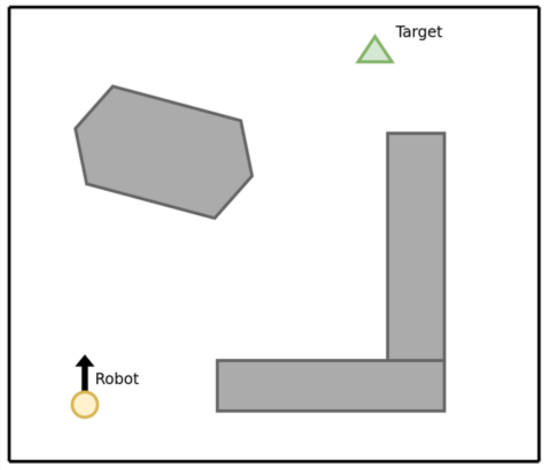

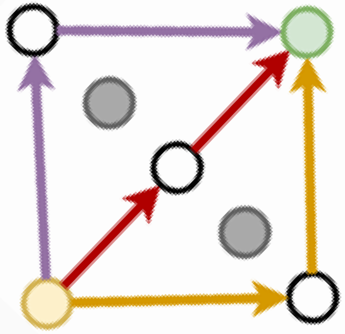

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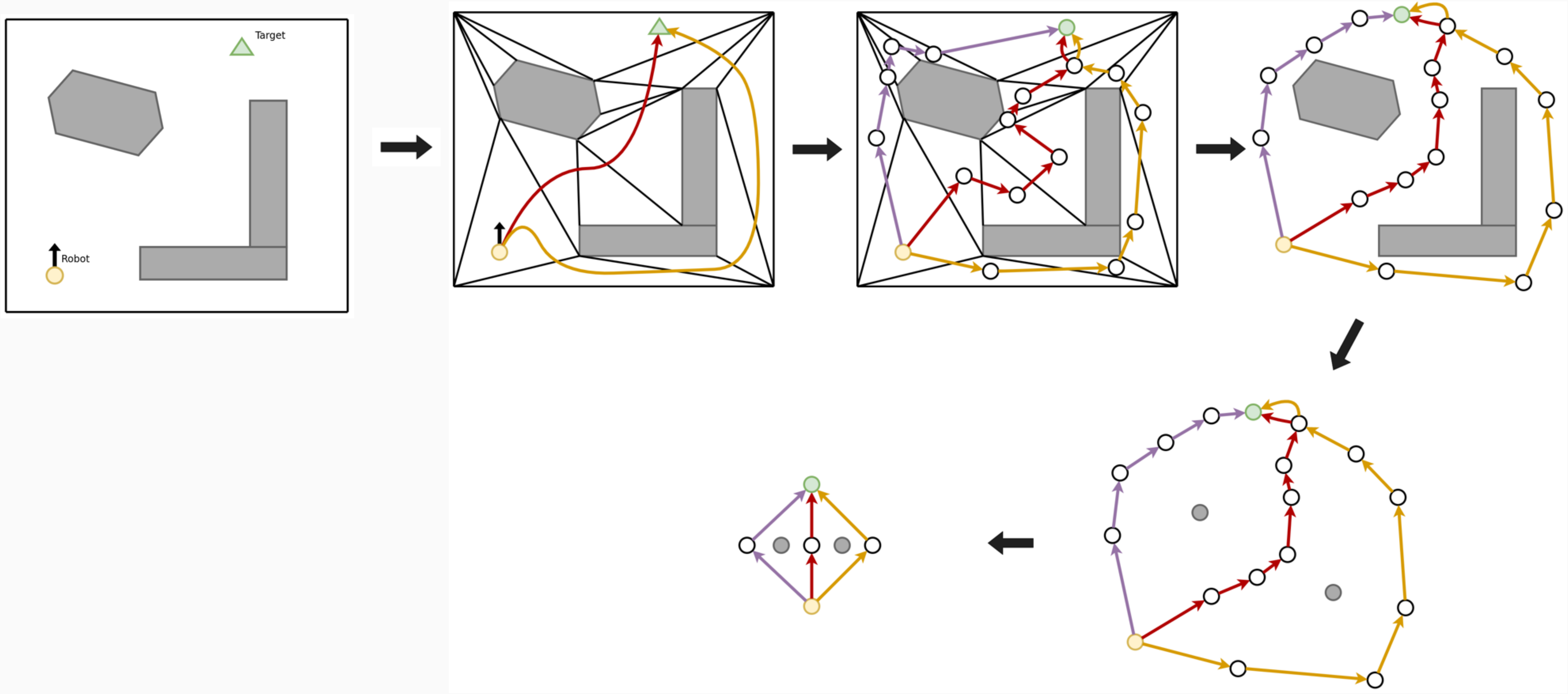

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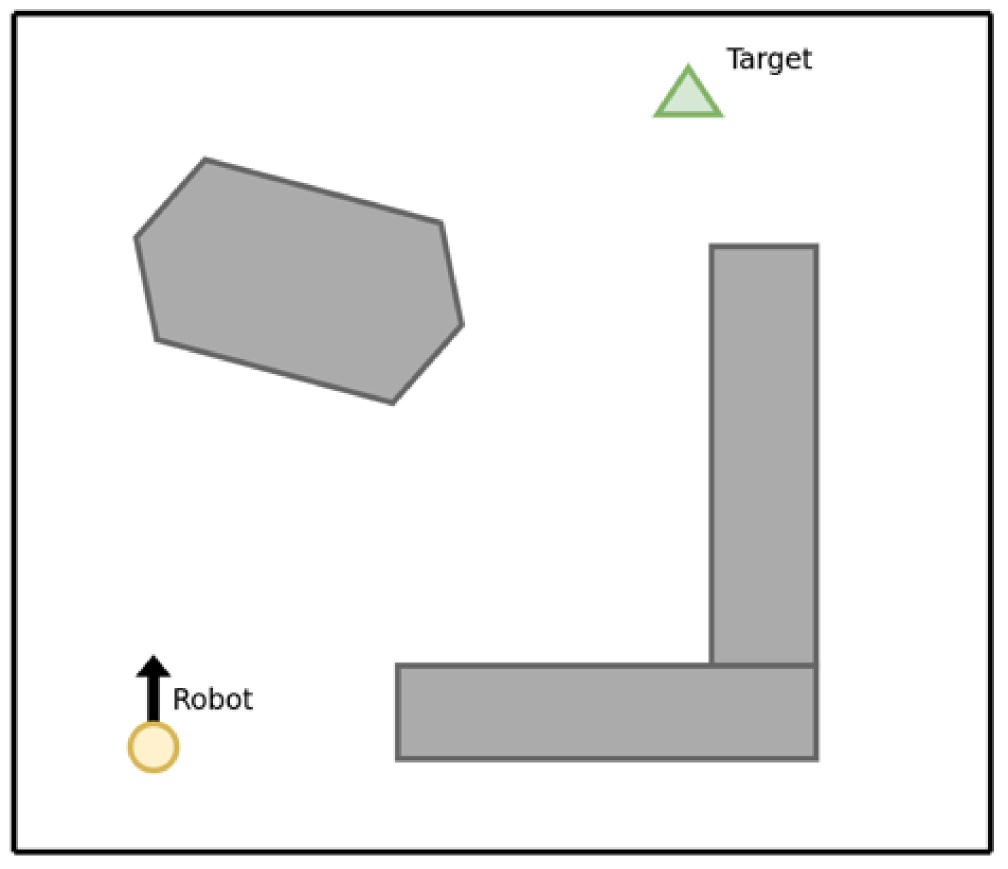

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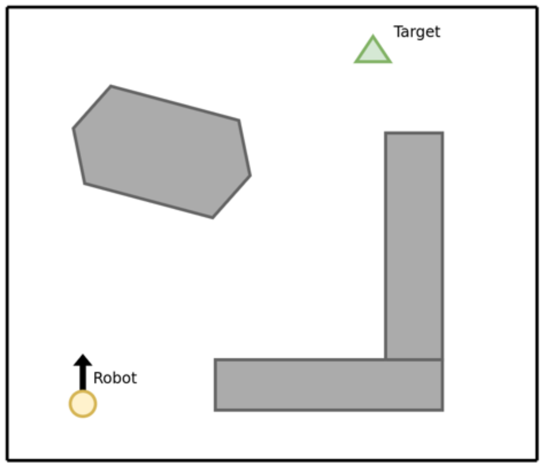

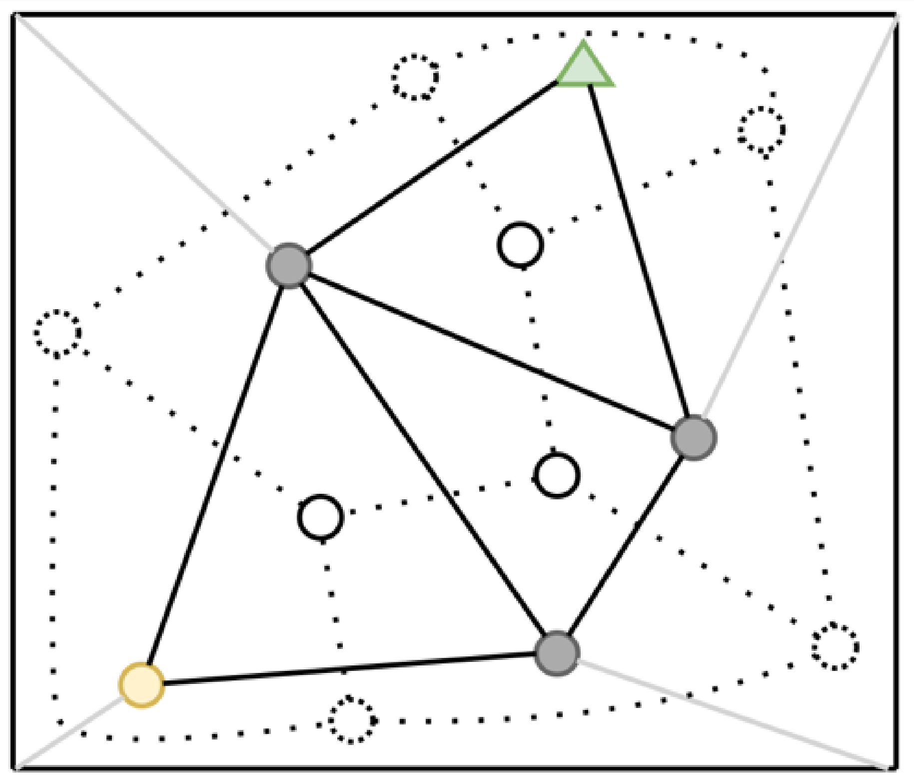

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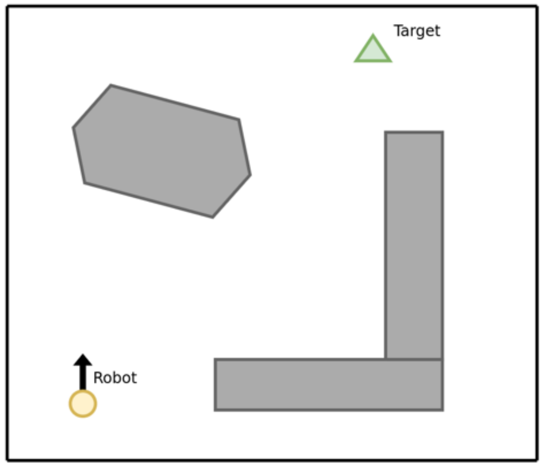

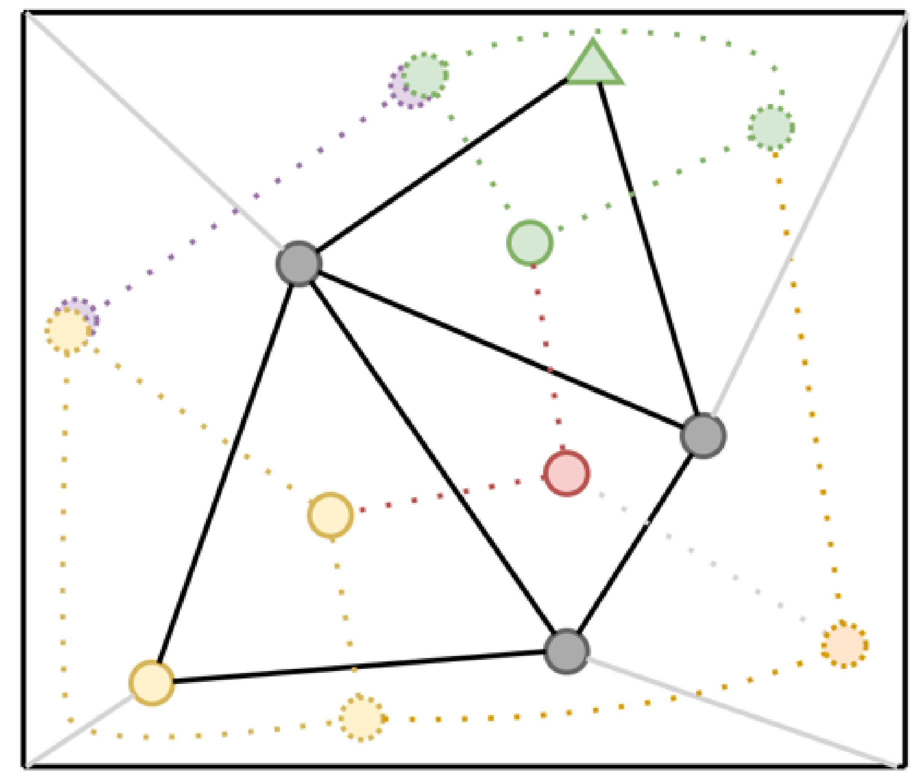

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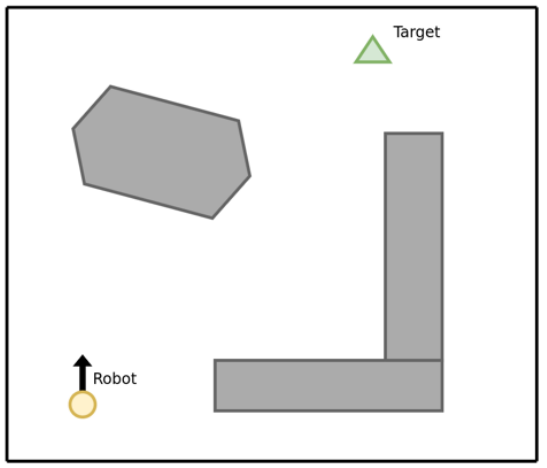

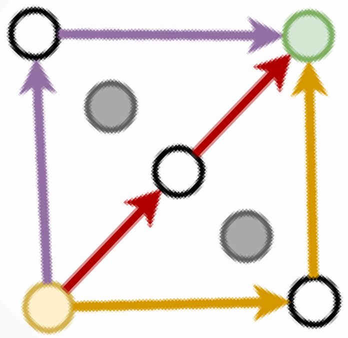

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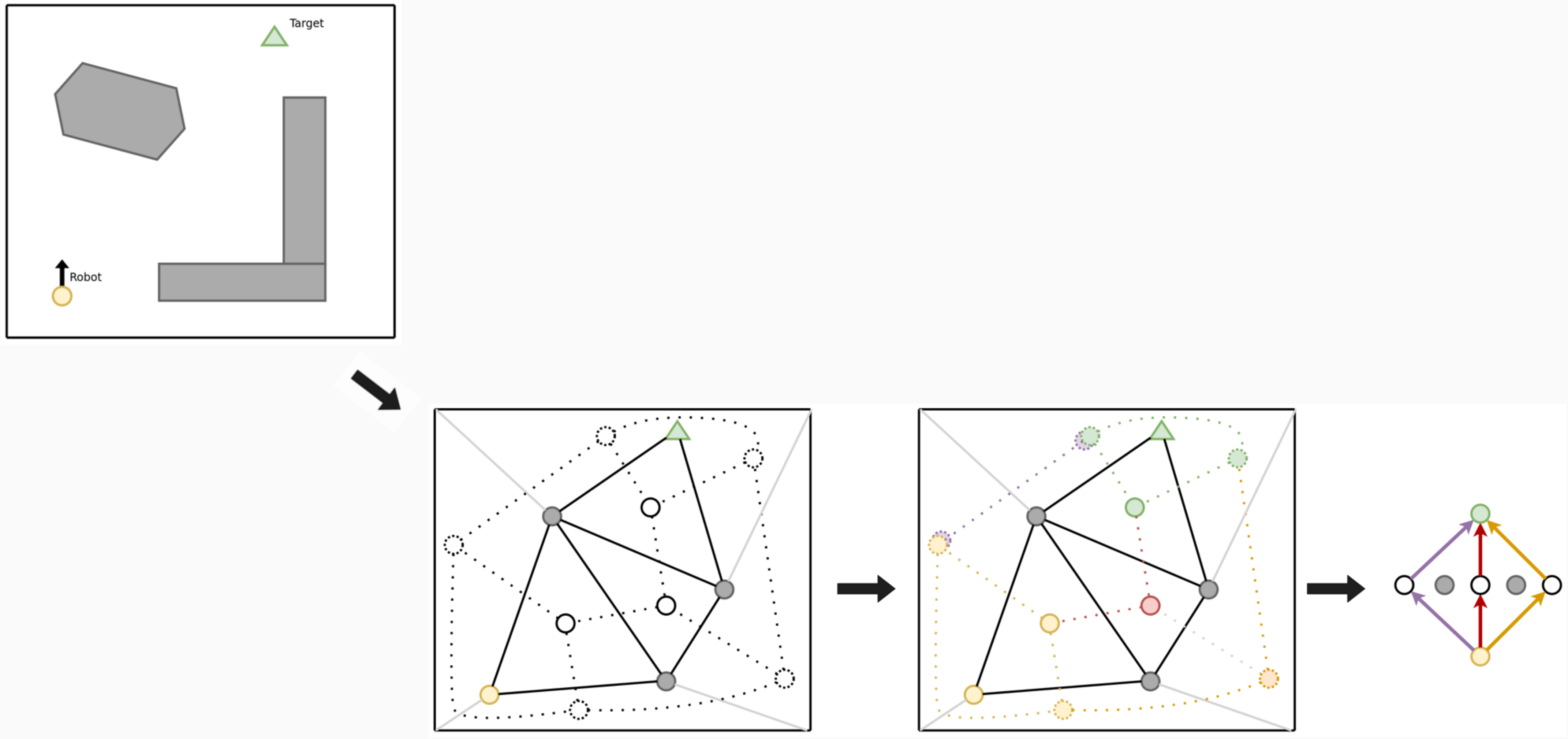
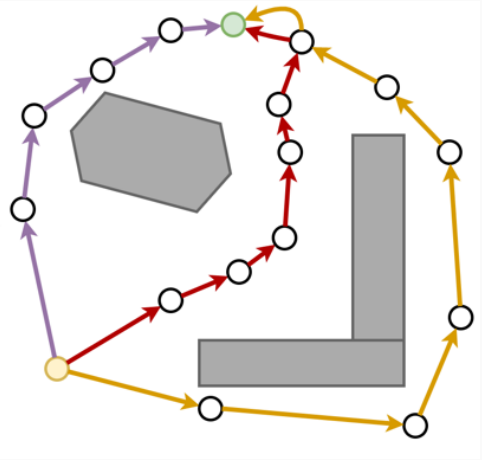
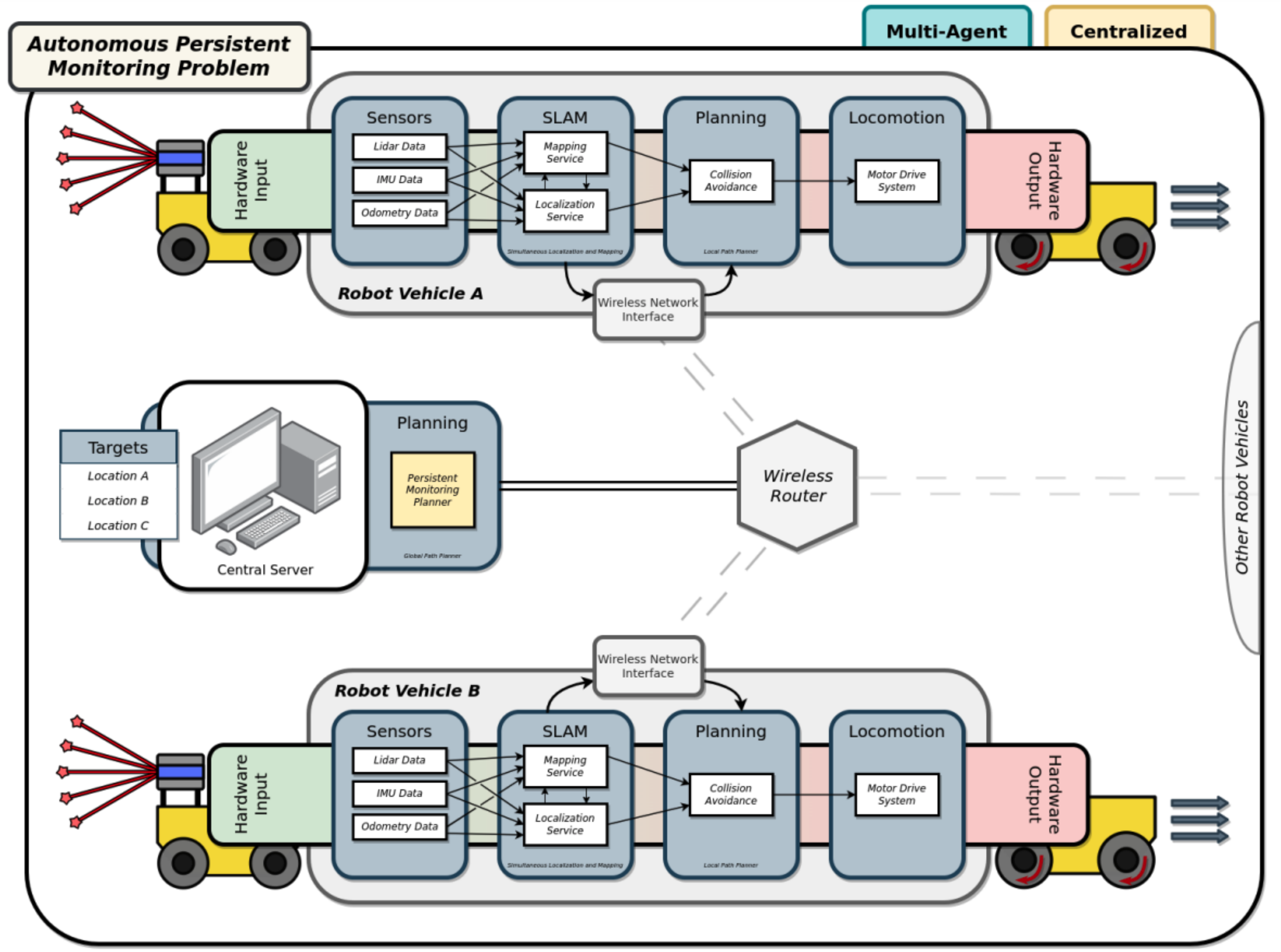


Next Steps: Topological Planning and Physical Realization

- Currently extending previous simulation system implementations to support high-level, tractable topological motion planning
- Remaining year of project will target goal of implementation and testing of the persistent monitoring planner in real-world environment





Thank you

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