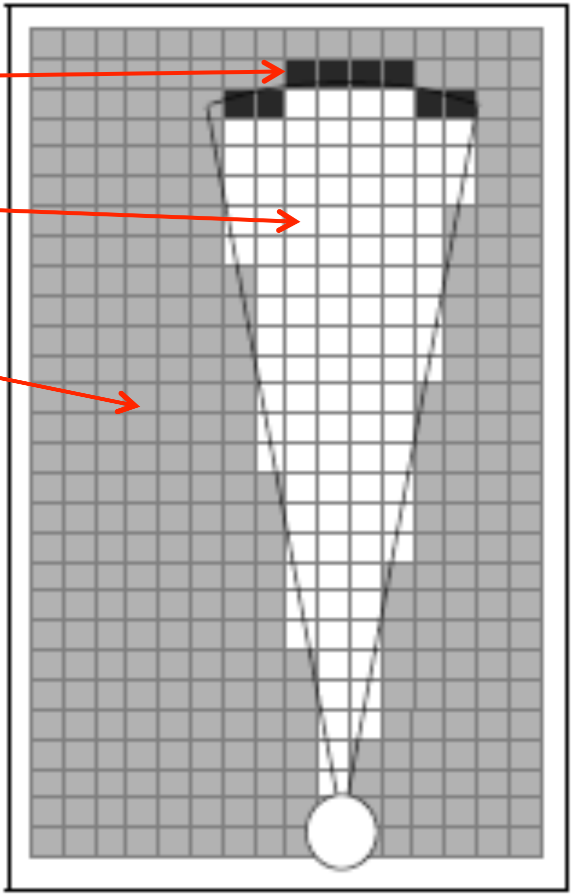
UNIVERSITY OF
SOUTH CAROLINA

CSCE 574 ROBOTICS

Exploration

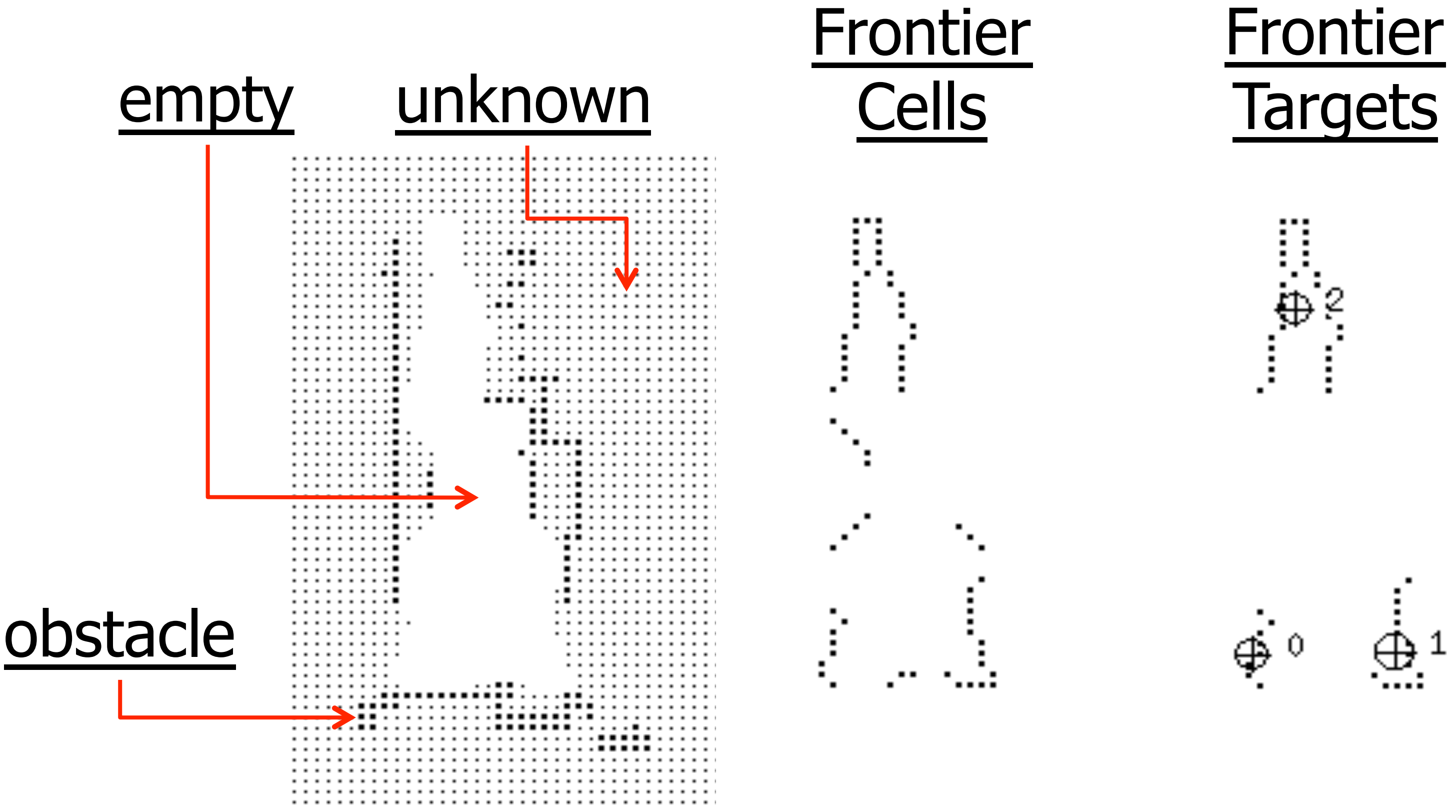
Ioannis Rekleitis

Grid Based Maps



- Occupied cells
- Free cells
- Unknown cells

Frontier based Exploration (Grid Maps)



empty

unknown

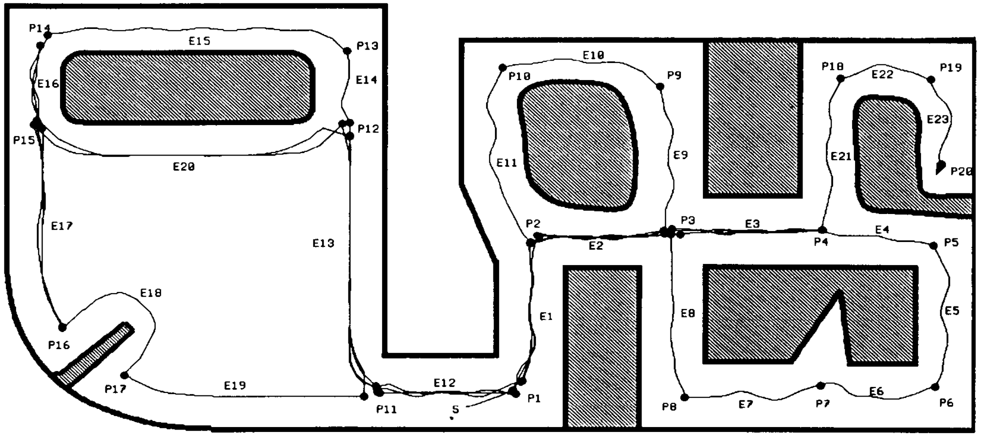
obstacle

Frontier Cells

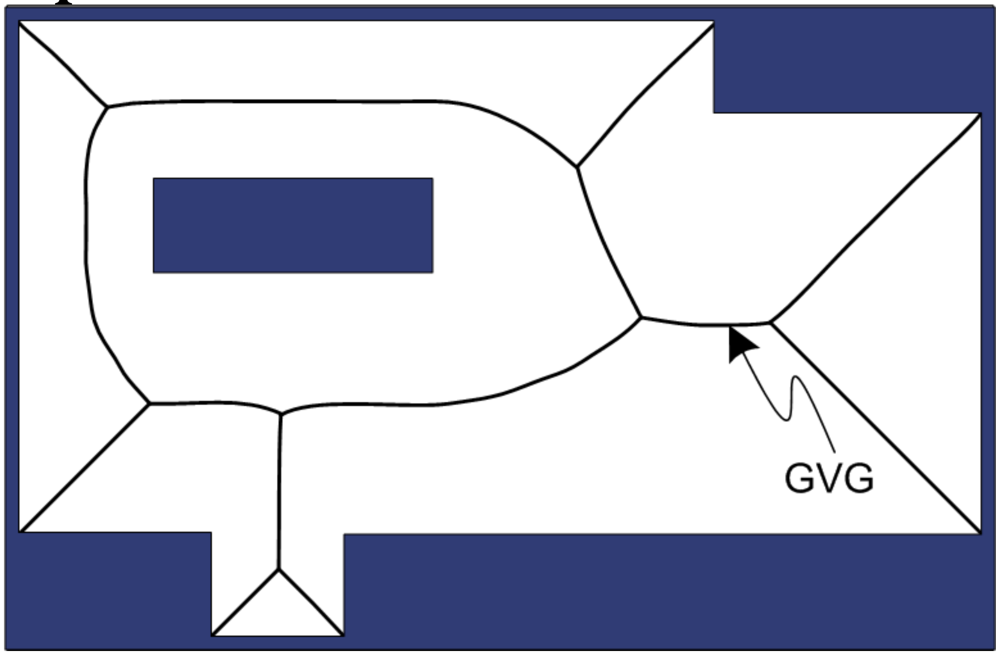
Frontier Targets

Topological Representations

- Apply on a topological map

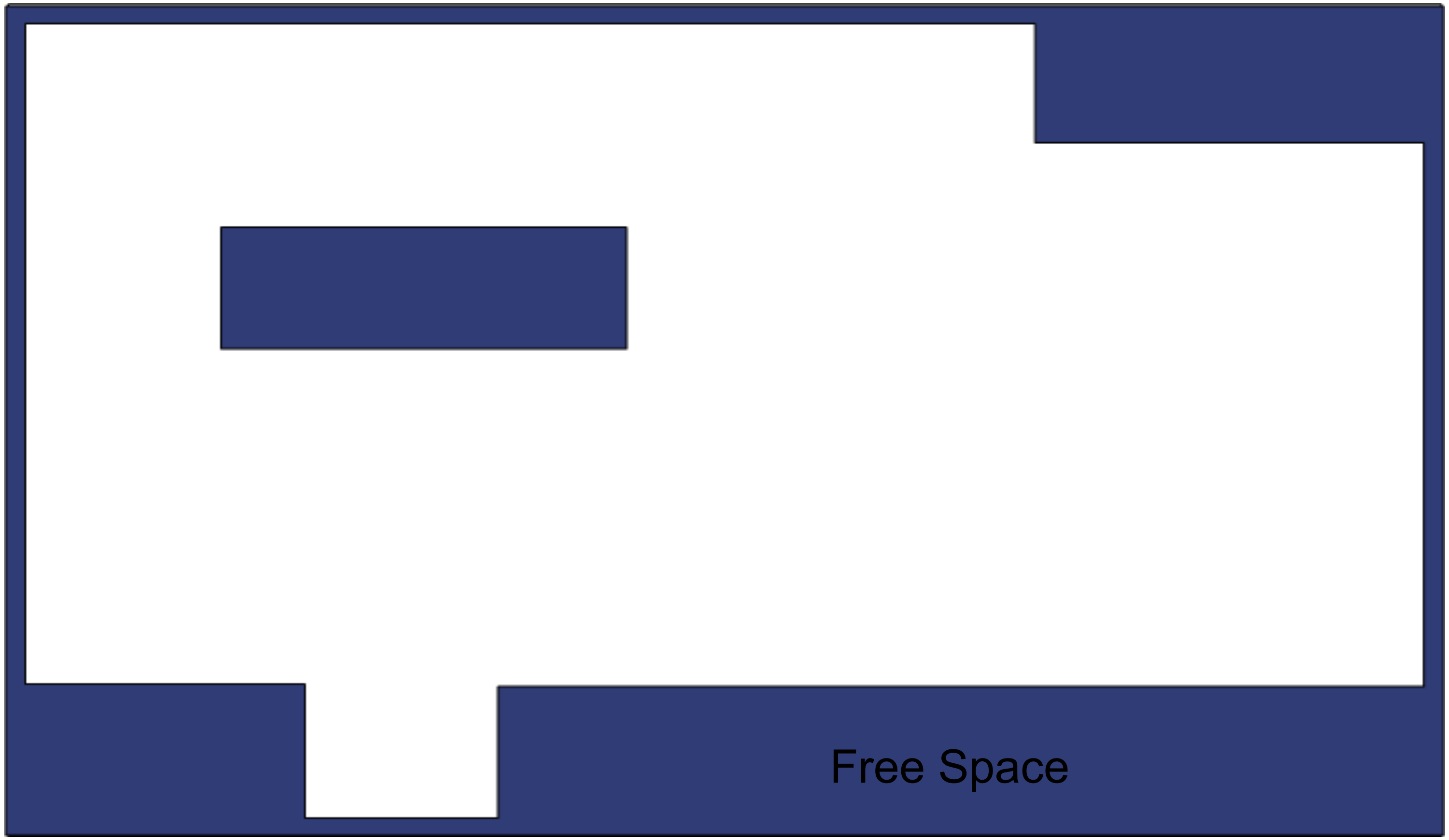


- B. J. Kuipers and Y.-T. Byun. "A robot exploration and mapping strategy based on a semantic hierarchy of spatial representations". In *Journal of Robotics and Autonomous Systems,* 8: 47-63, 1991.



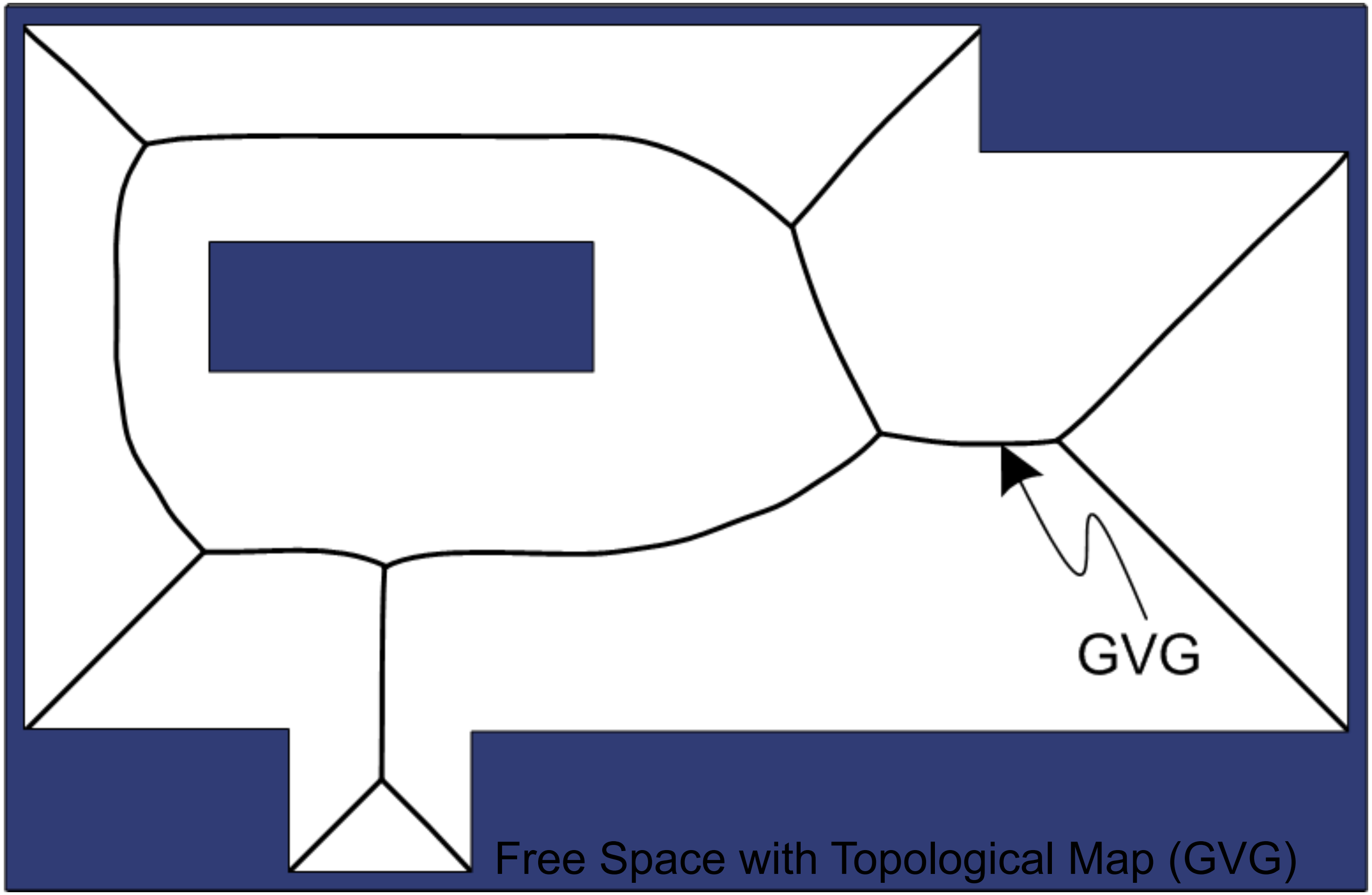
H. Choset, J. Burdick, "Sensor based planning, part ii: Incremental construction of the generalized Voronoi graph". In IEEE Conference on Robotics and Automation, pp. 1643 – 1648, 1995.

Generalized Voronoi Graph (GVG)



H. Choset, J. Burdick, “Sensor based planning, part ii: Incremental construction of the generalized voronoi graph”. In IEEE Conference on Robotics and Automation, pp. 1643 – 1648, 1995.

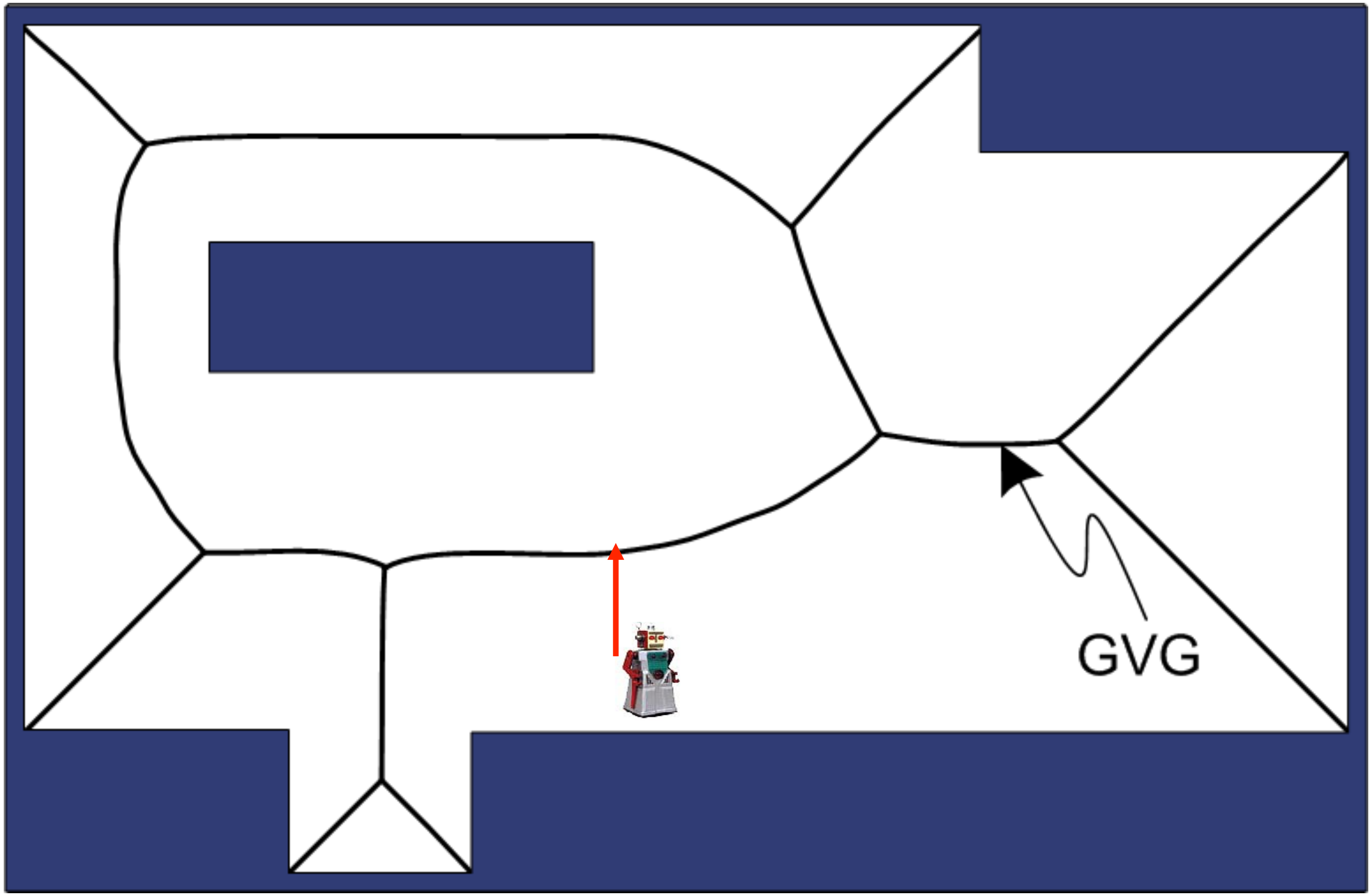
Generalized Voronoi Graph (GVG)



Free Space with Topological Map (GVG)

Generalized Voronoi Graph (GVG)

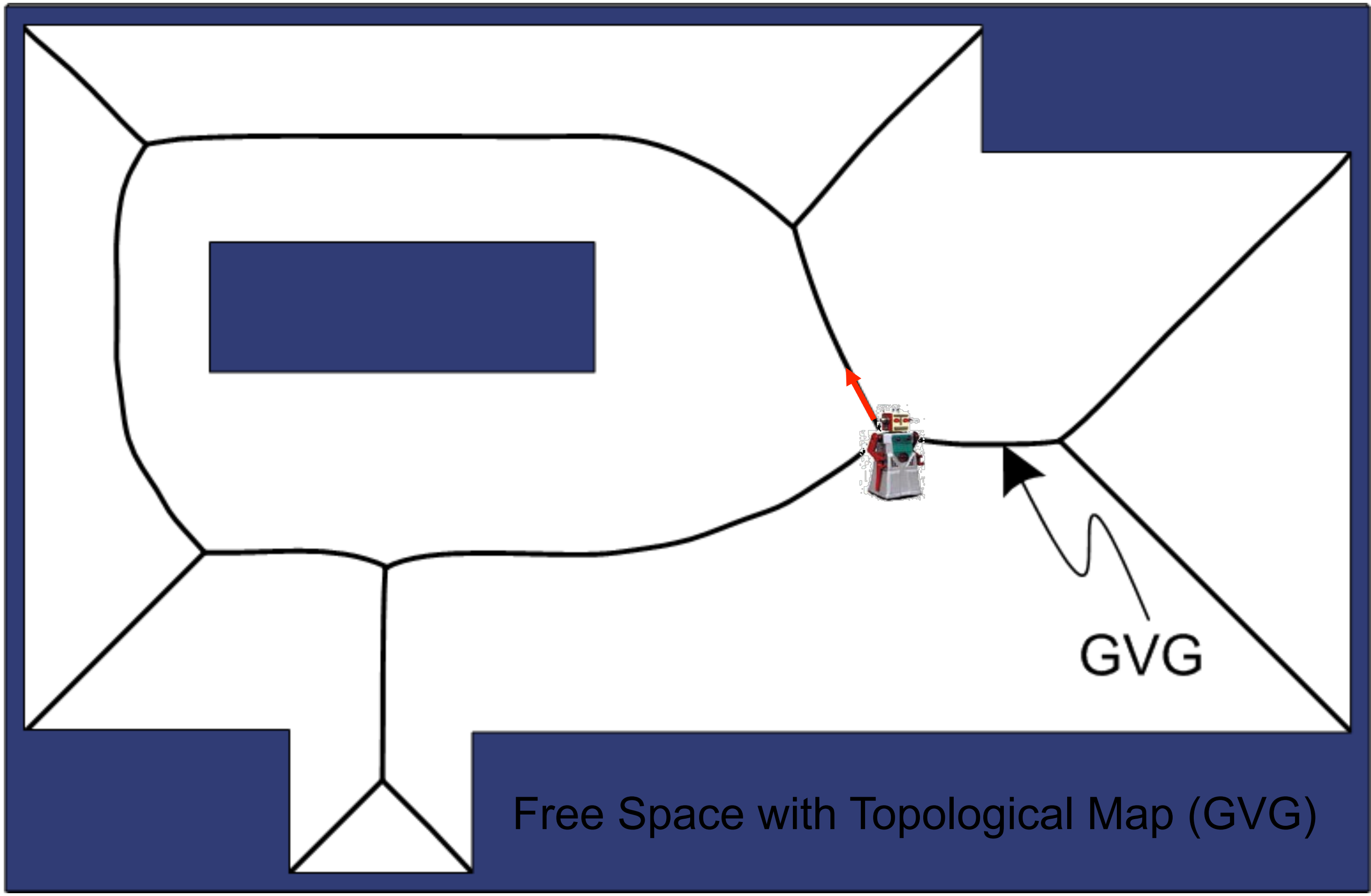
- Access GVG



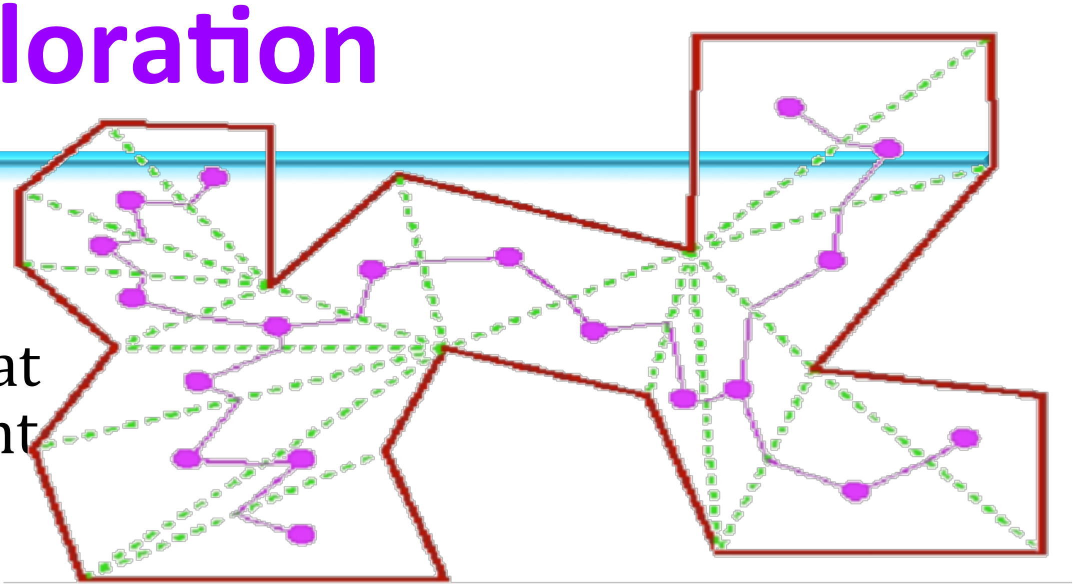
Free Space with Topological Map (GVG)

Generalized Voronoi Graph (GVG)

- Access GVG
- Follow Edge
- Home to the MeetPoint
- Select Edge



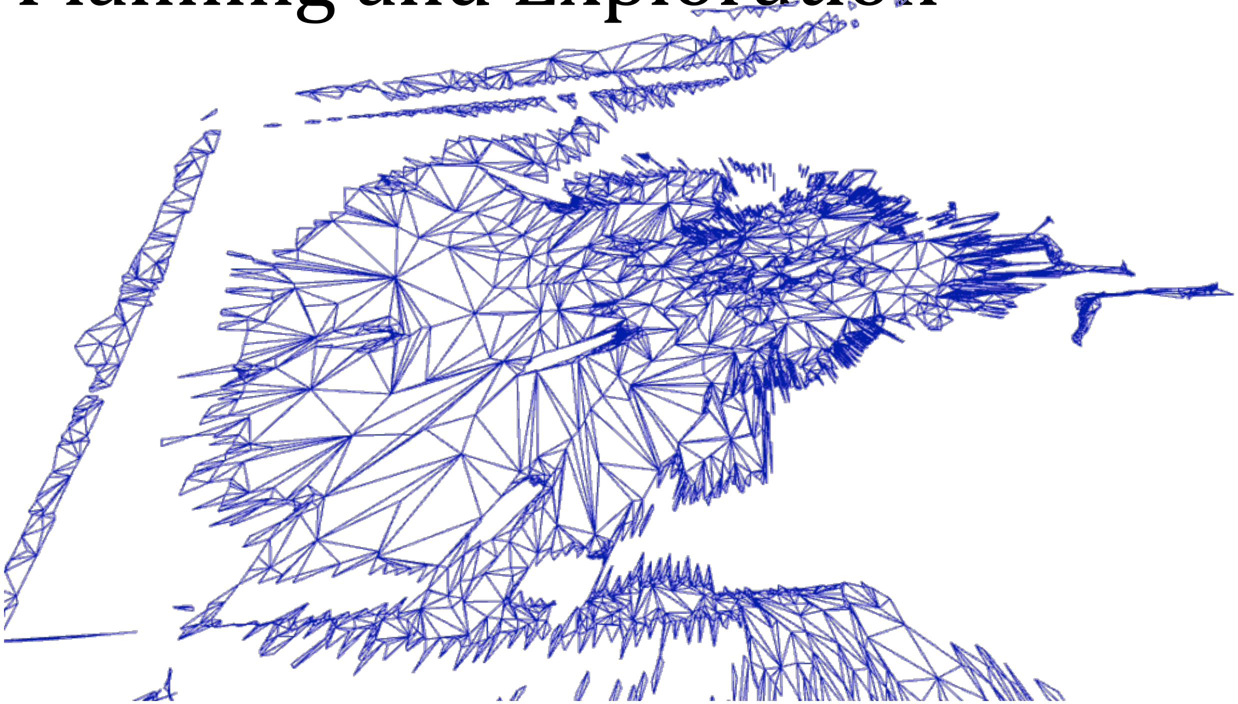
Cooperative Exploration



- **Robot Position:**
  - Stationary Robot: Positioned at the corners of the environment
  - Moving Robot: Follows the walls.
- **Exploration order:**
  - The two robots explore the free space by following the Dual Graph of the Triangulation.
- **Decision points:**
  - Reflex vertices.

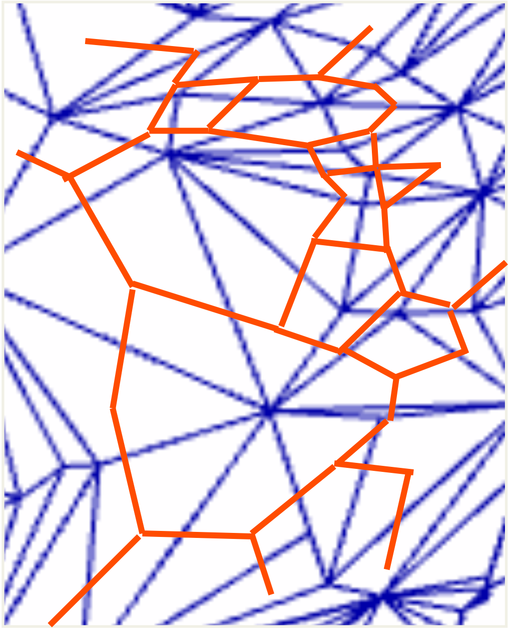
Irregular Triangular Mesh (ITM)

- Terrain Representation
- Underlying Topological Structure
- Path Planning and Exploration



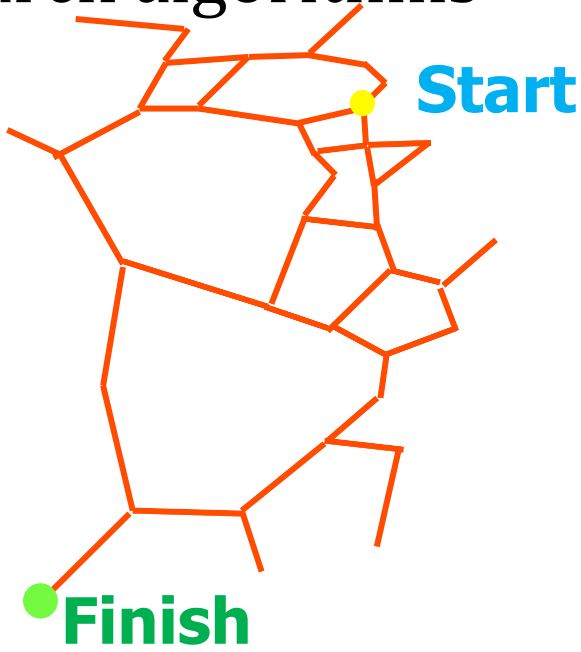
From 2.5D Representation to Topological

- Convert ITM into Connected Graph



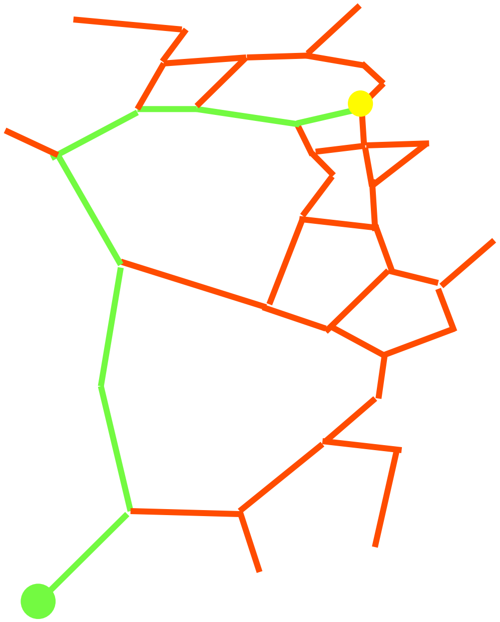
Planning

- Convert ITM into Connected Graph
- Planning using Graph Search Algorithms:
  - – Dijkstra, A* search algorithms



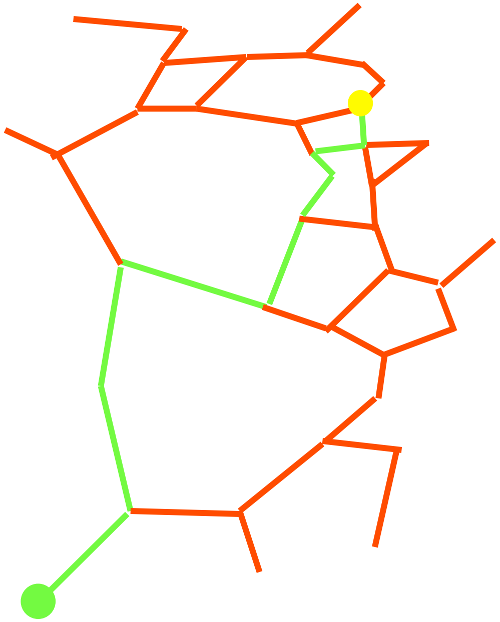
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A* search algorithms
- Different Cost Functions Q
  - Number of triangles $Q = 1$



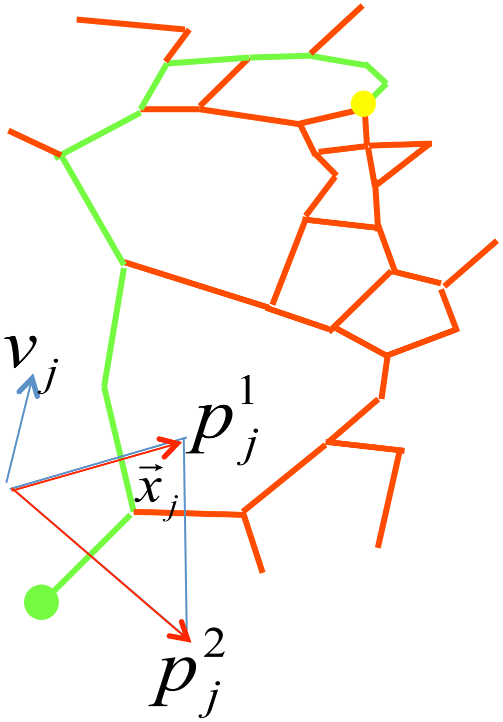
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance $Q = \left\| \vec{x}_i - \vec{x}_j \right\|$



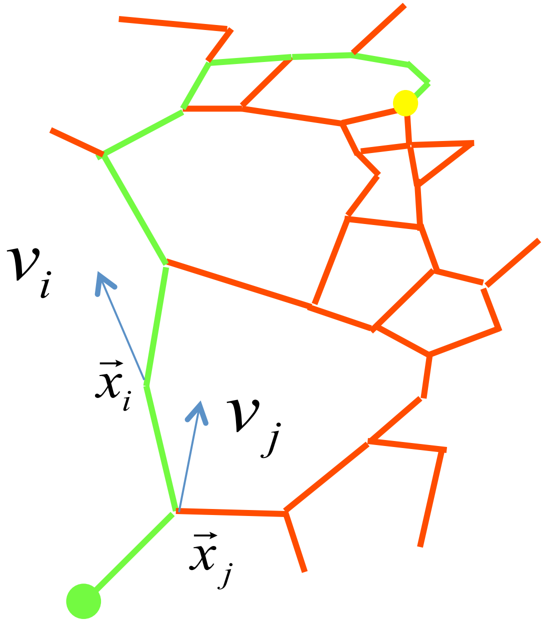
Planning

- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance
  - Slope of each triangle $v_j = \dfrac{p_j^1 \times p_i^2}{\left\|p_j^1\right\| \left\|p_j^2\right\|}$



Planning

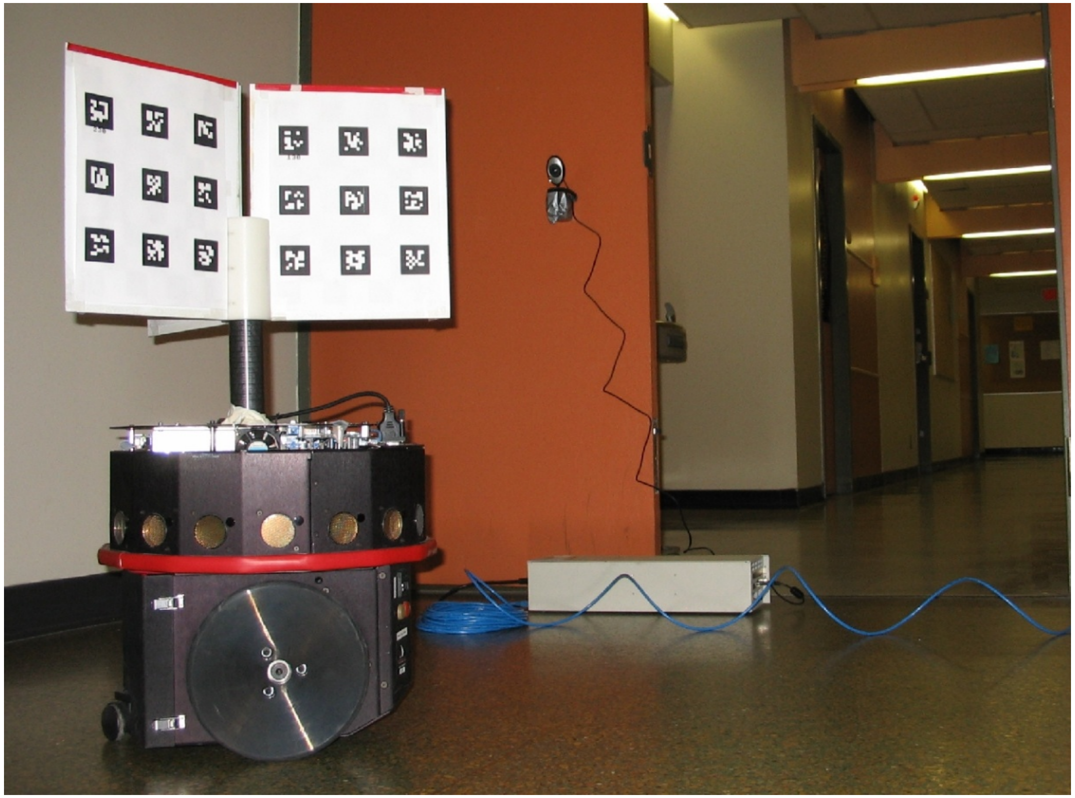
- Convert ITM into Connected Graph
- Path Planning using Graph Search Algorithms:
  - Dijkstra, A*
- Different Cost Functions Q
  - Number of triangles
  - Euclidian distance
  - Slope of each triangle
  - Cross triangle slope

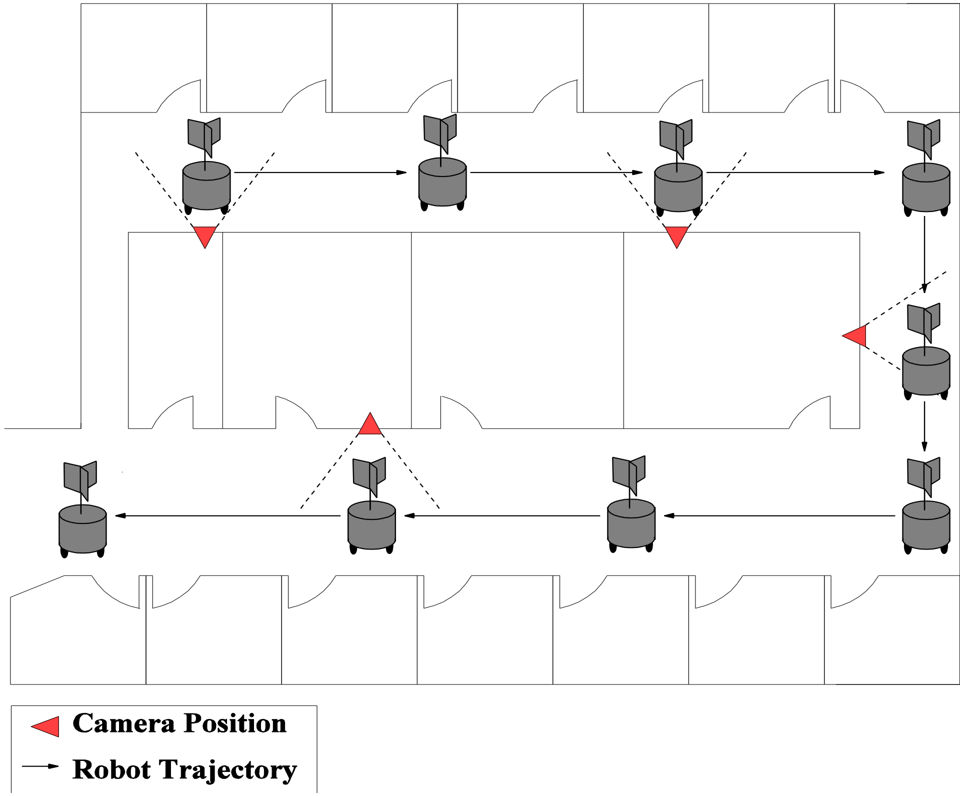


Exploration via Graph Search

- Exhaustive Depth First Search
- Breadth-First Search
- Heuristics

Exploring a Camera Sensor Network

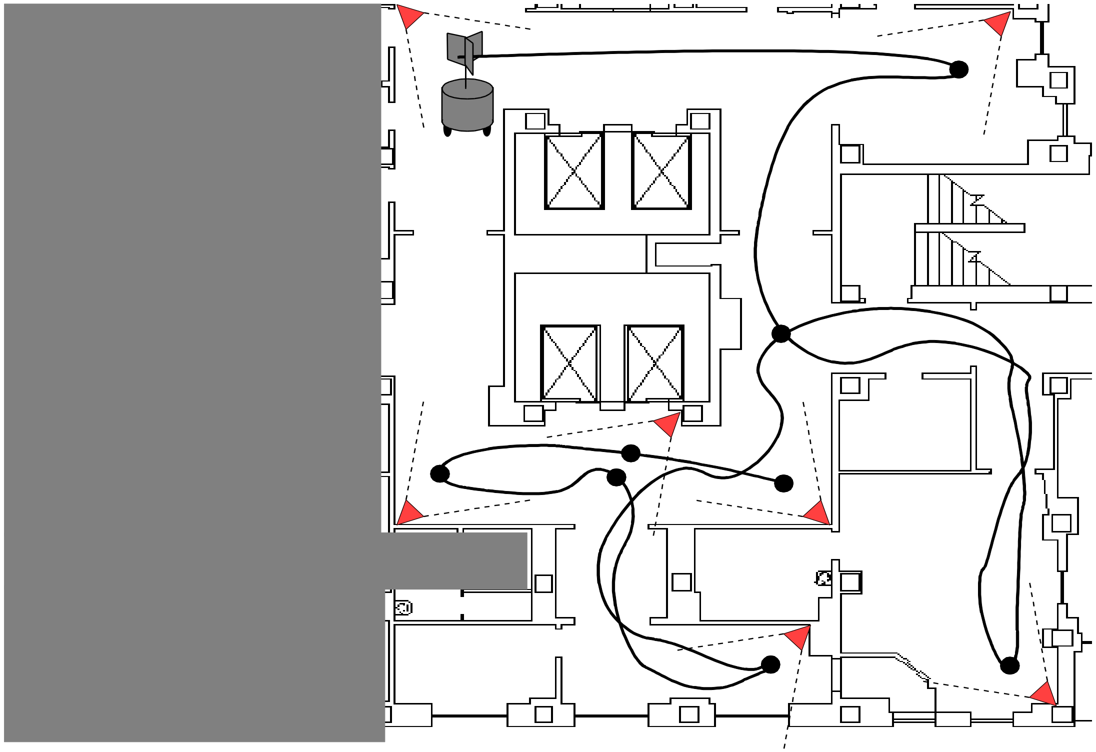




D. Meger, I. Rekleitis, and G. Dudek. "Heuristic Search Planning to Reduce Exploration Uncertainty", IROS 2008.

Exploration Planning Problem

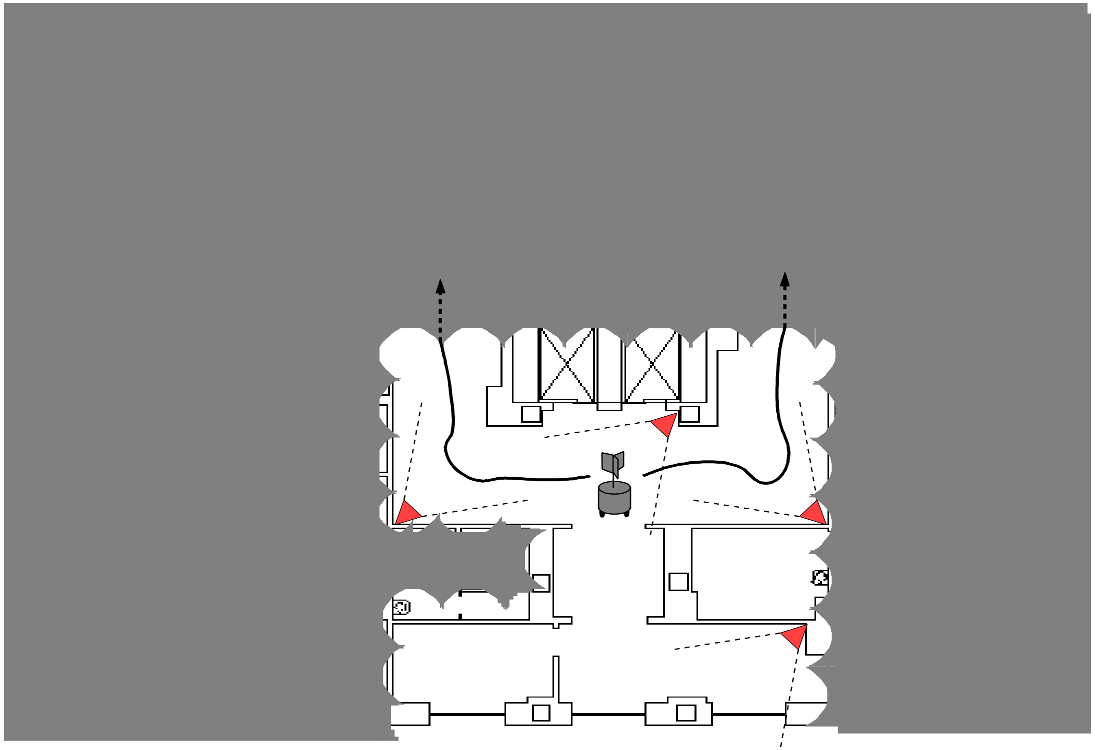
Two fundamental problems for path planning during exploration and mapping:



Exploration Planning Problem

Two fundamental problems for path planning during exploration and mapping:

- – Planning for re-localization
- – Planning the exploration of new territory



Heuristic Search Planning Method

- Solution to exploration planning for camera sensor networks
  - Composed of two alternated steps: exploration and re-localization
  - Combined distance and uncertainty cost function
  - Heuristic search for good paths

Exploration and Uncertainty Reduction

- Decision (exploration vs exploitation)
- Target Node
- Path Planning through the known graph
- Exploration Strategies

Exploration and Uncertainty Reduction

- Decision (exploration vs. exploitation)
  - **Epsilon-Greedy**
  - **Epsilon-First**
  - **Adaptive**
  - **Bounded Uncertainty**
- Target Node
- Path Planning through the known graph
- Exploration Strategies

Exploration and Uncertainty Reduction

- Decision (exploration vs. exploitation)
- Target Node (Exploration)
  - **Random**
  - **Shortest distance**
  - **Maximum Uncertainty**
  - **Minimum Uncertainty**
- Path Planning through the known graph
- Exploration Strategies

Exploration and Uncertainty Reduction

- Decision (exploration vs. exploitation)
- Target Node (Relocalization)
  - **Maximum Uncertainty**
- Path Planning through the known graph
- Exploration Strategies

Exploration and Uncertainty Reduction

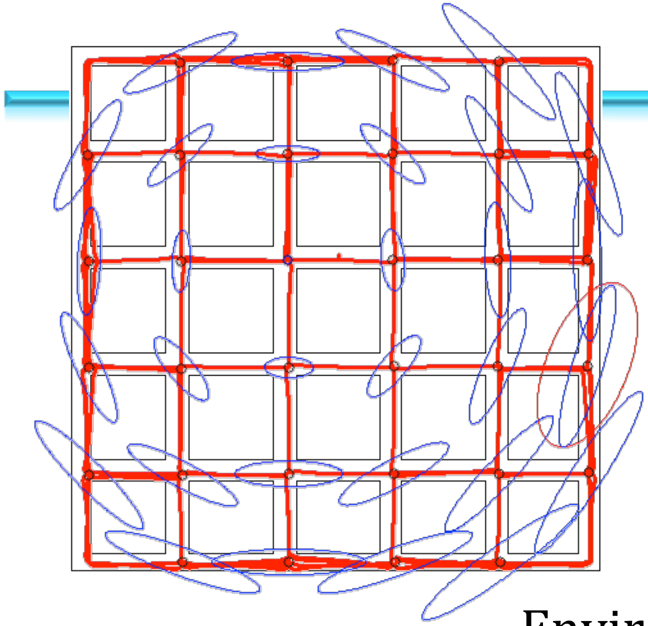
- Decision (exploration vs. exploitation)
- Target Node
- Path Planning through the known graph
  - Work with D. Meger and G. Dudek [IROS 2008]
  - A* based strategy
  - Cost: $C(p) = \omega_d length(p) + \omega_u trace(P(p))$
  - Distance-based "cost-to-go" heuristic function *h* used to compute estimated cost

$$C(n) = f(n) + h(n)$$

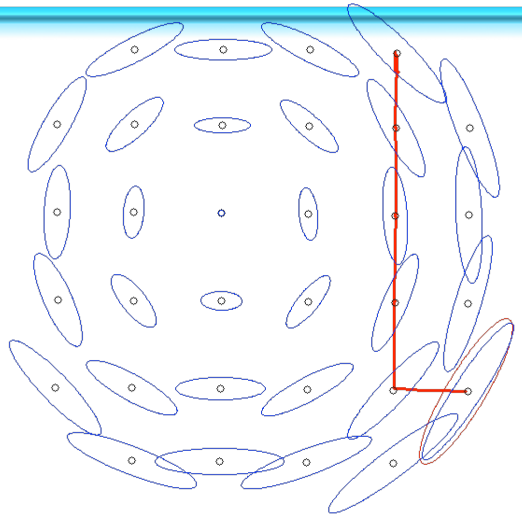
Estimated cost through n Cost so far Estimated cost to go

- Exploration Strategies

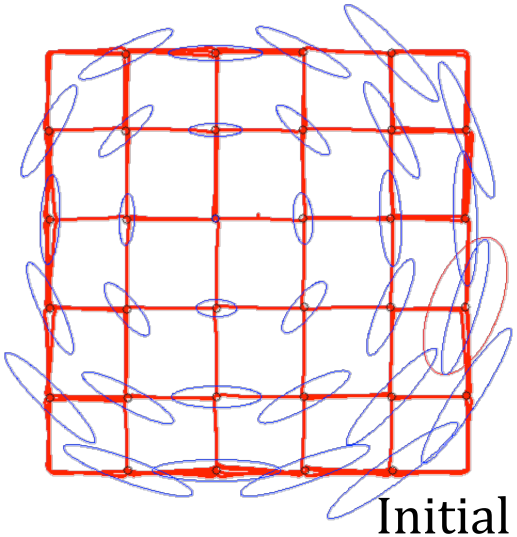
Effect of α Parameter for Relocalization



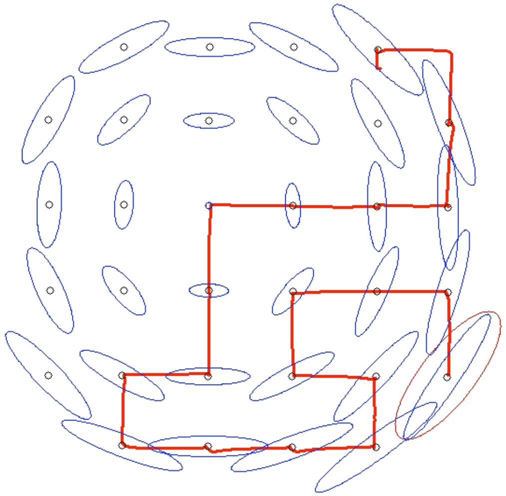
Environment with map



Shortest Path (alpha=1)

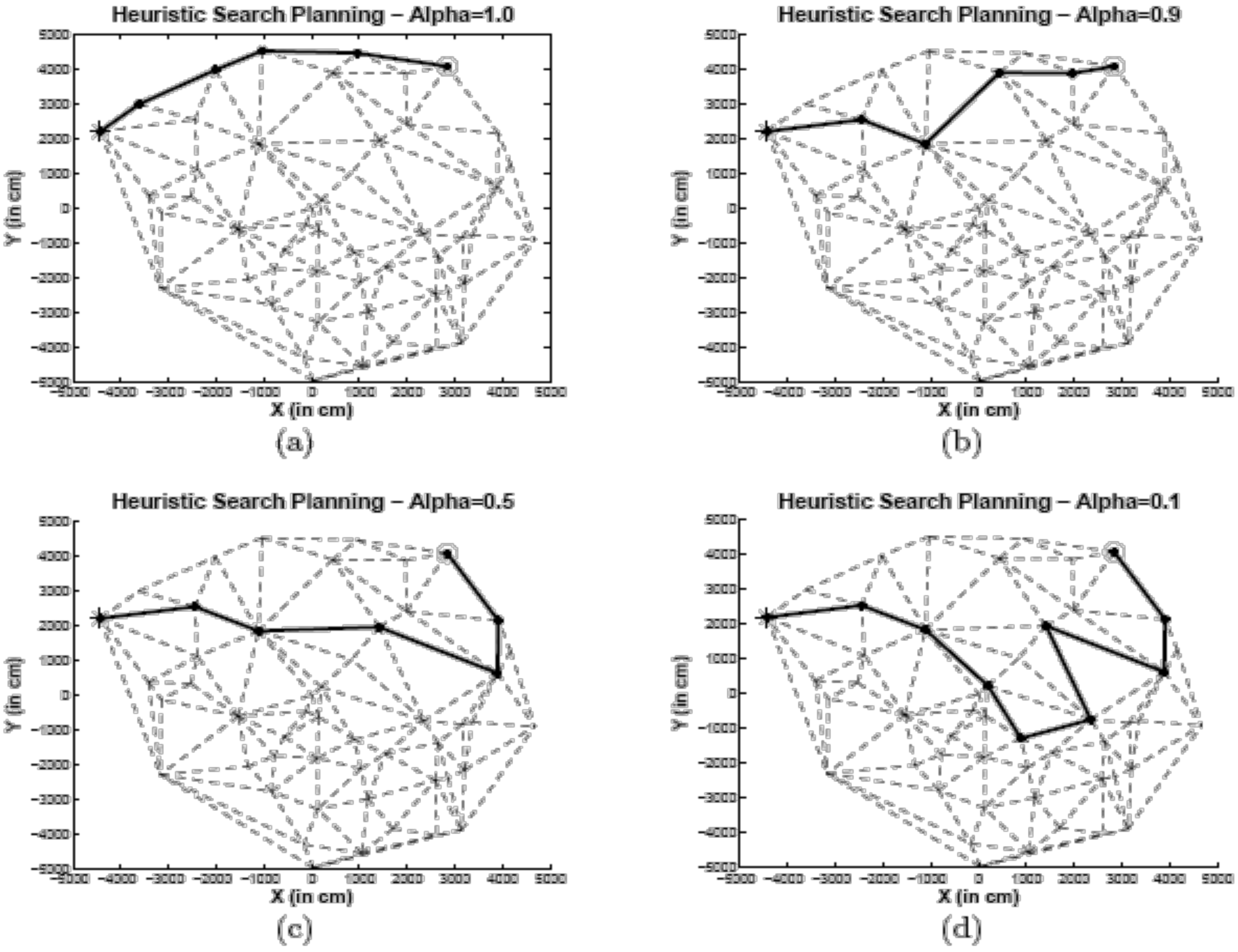


Initial map



Lower Uncertainty (alpha=0)

Effect of α Parameter for Relocalization



(a) (b)

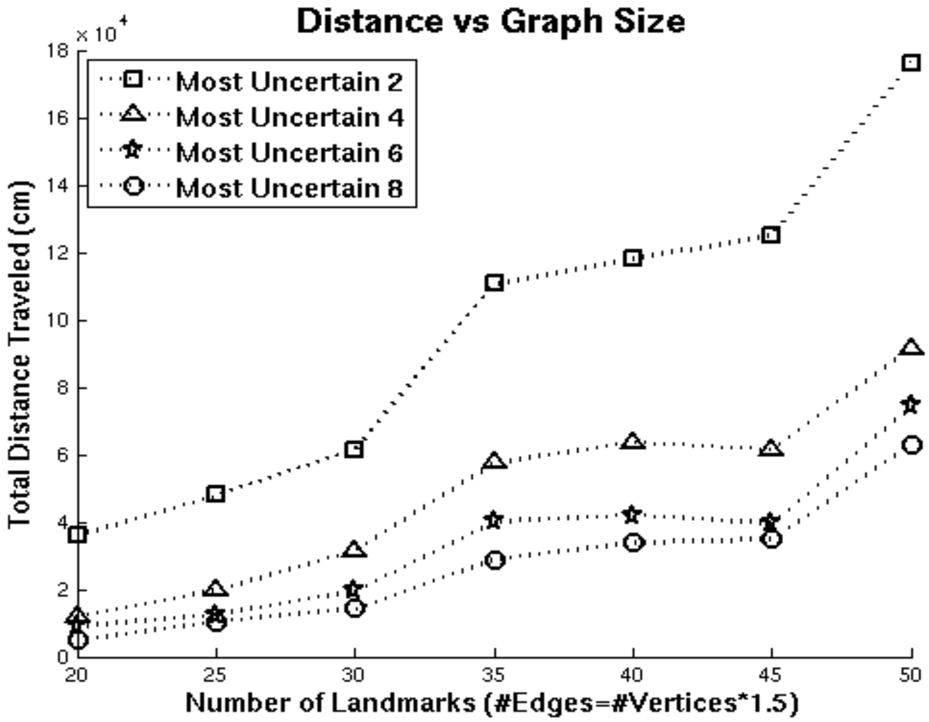
(c) (d)

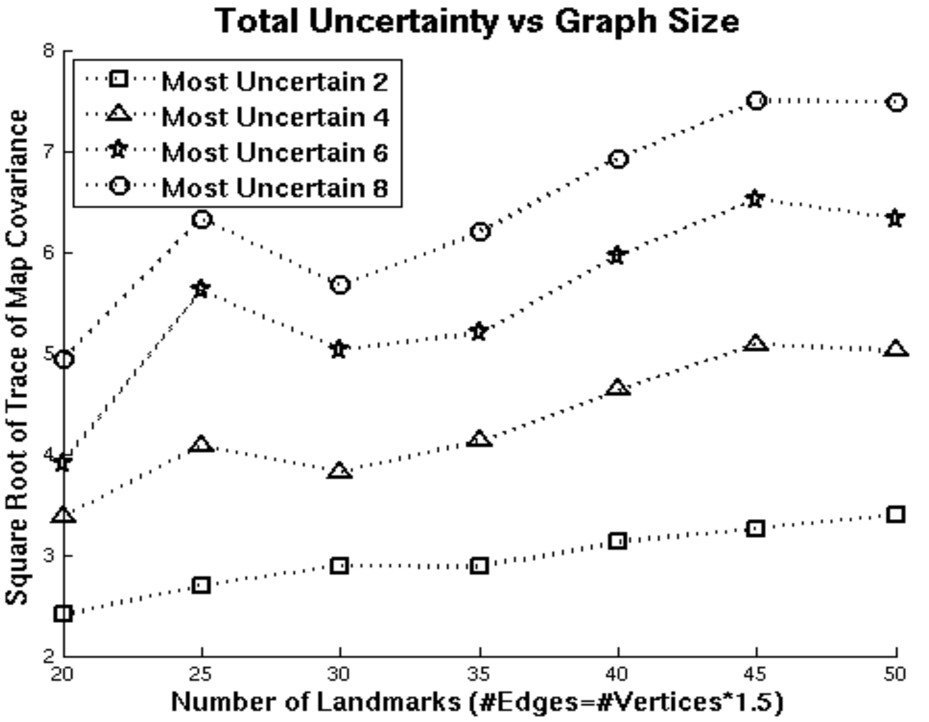
Exploration and Uncertainty Reduction

- Decision (exploration vs. exploitation)
- Target Node
- Path Planning through the known graph
- Exploration Strategies
  - One Step Exploration
  - Ear based exploration

Shortest Node
P(exploit)=0.3

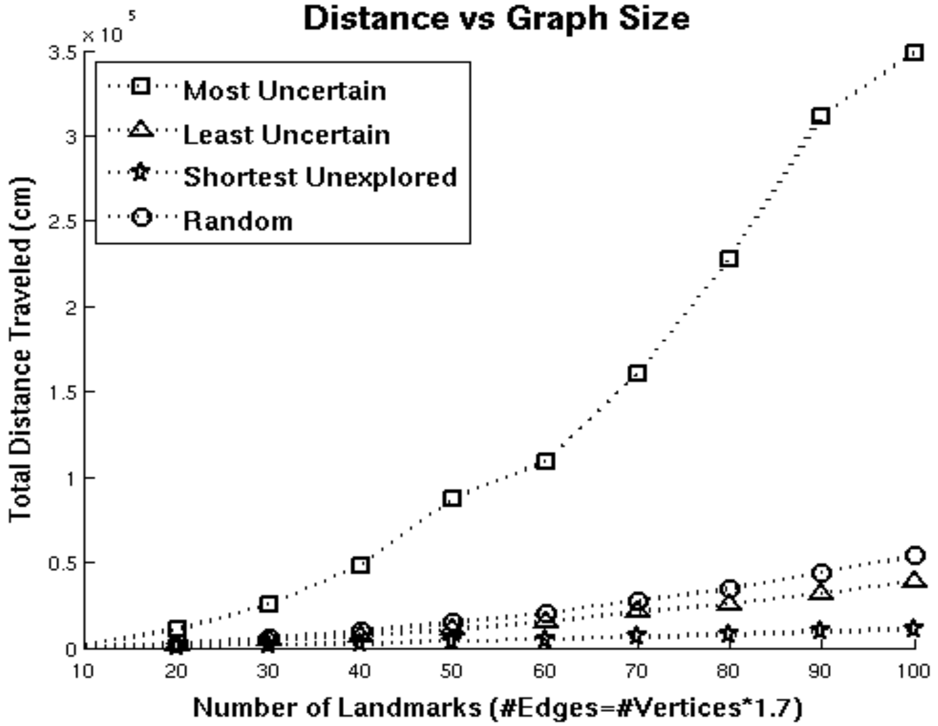
Experimental Results
Bounded Uncertainty

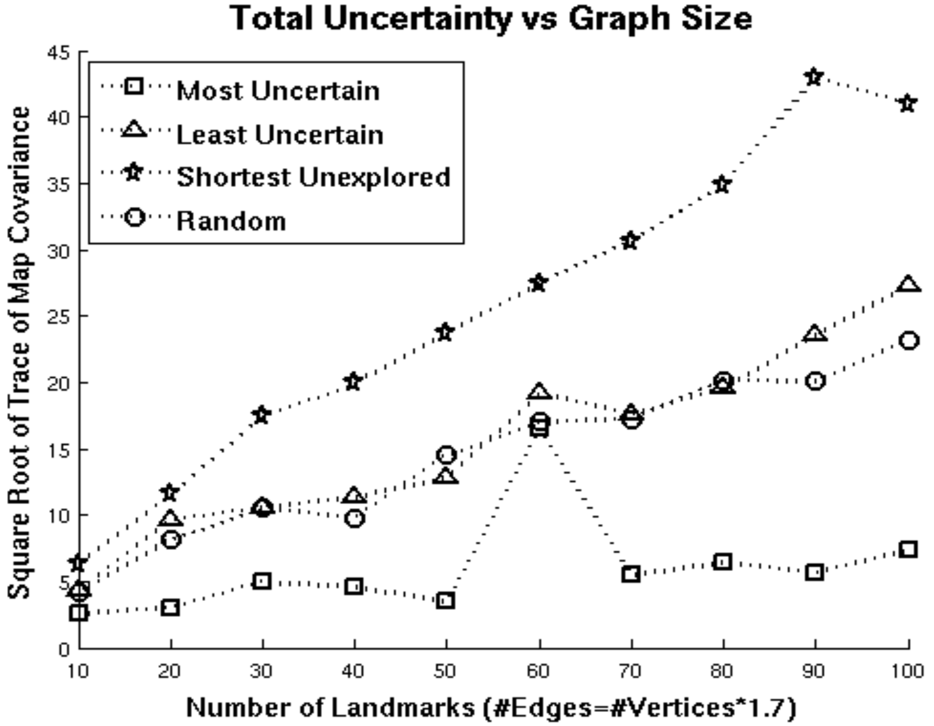




Experimental Results

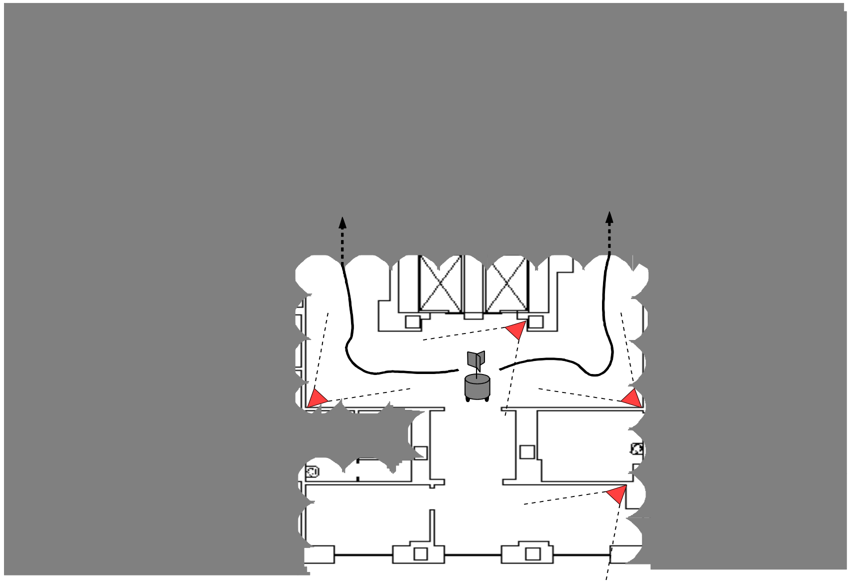
Different Strategies


Distance vs Graph Size


Total Uncertainty vs Graph Size

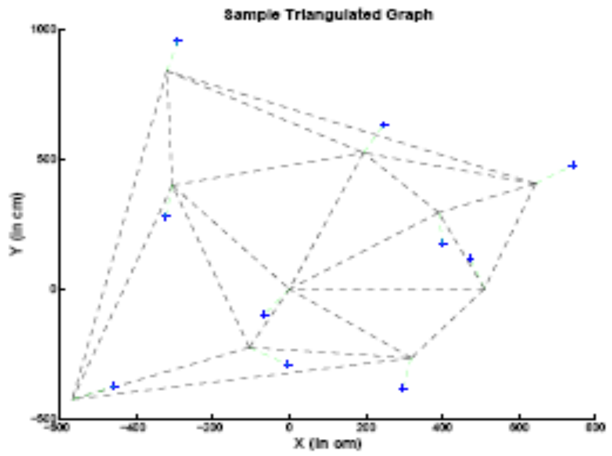
Planning Exploratory Steps

- Choose motion in unexplored space to locate additional camera nodes
- Planner cannot simulate these paths
- Evaluated 2 strategies: 1) nearest camera and 2) a randomly selected camera

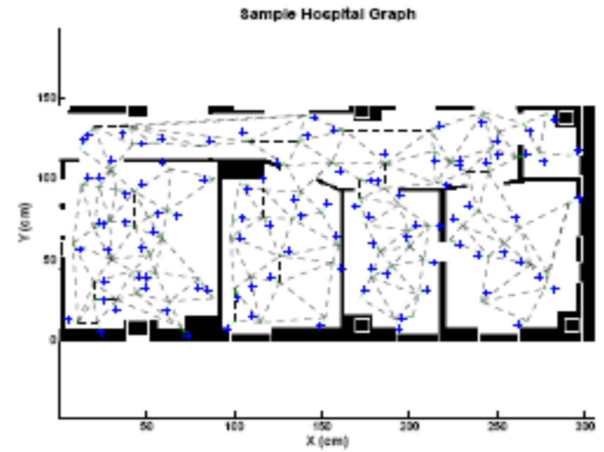


Simulation Results

- Compared planners over many trials
- 3 realistic network types (2 shown)
- 3 methods for comparison:
  - Depth-first
  - Return to origin
  - Return to nearest explored

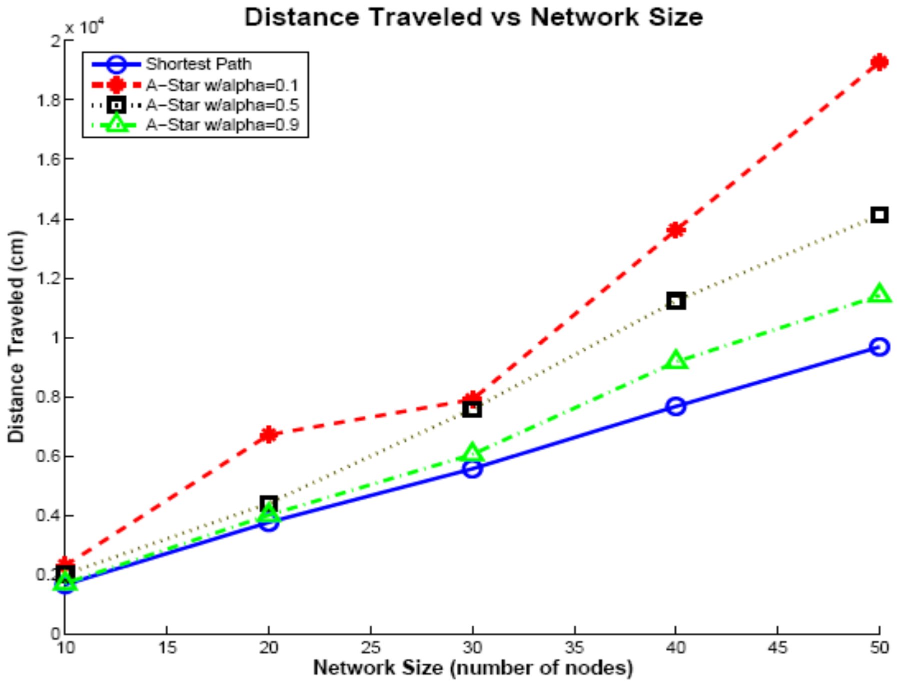


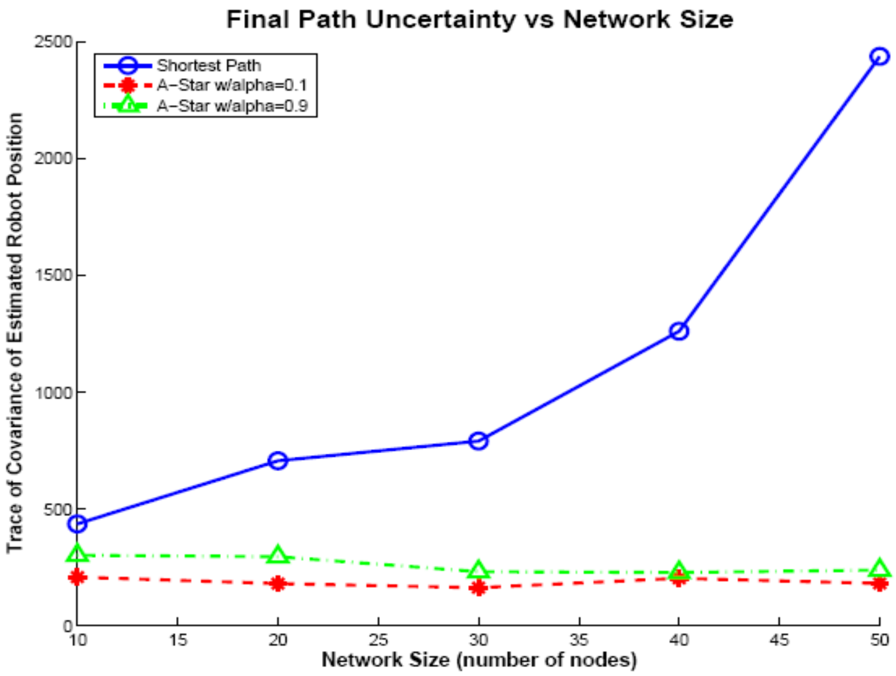
Sample Triangulated Graph



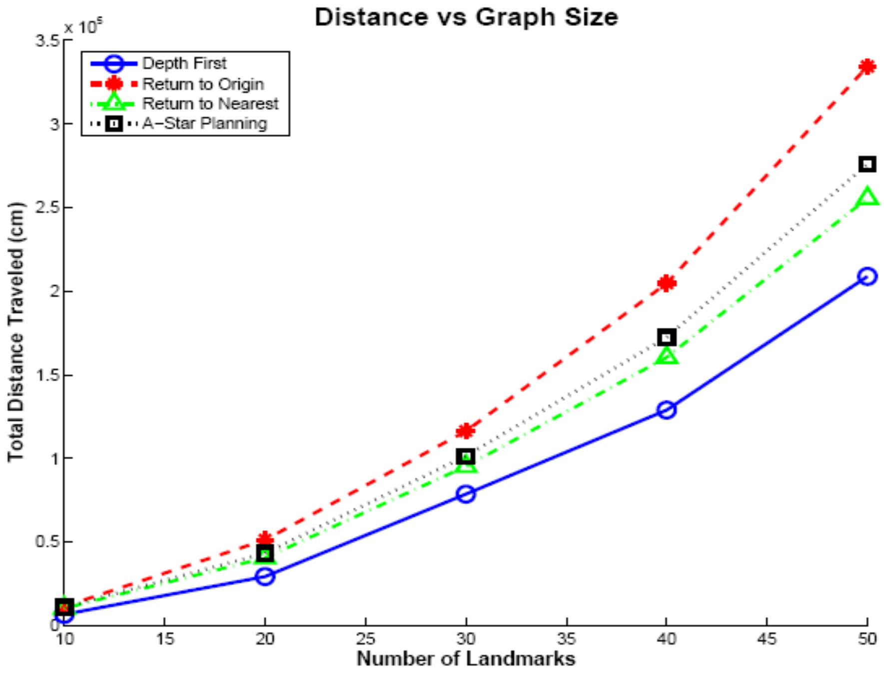
Sample Hospital Graph

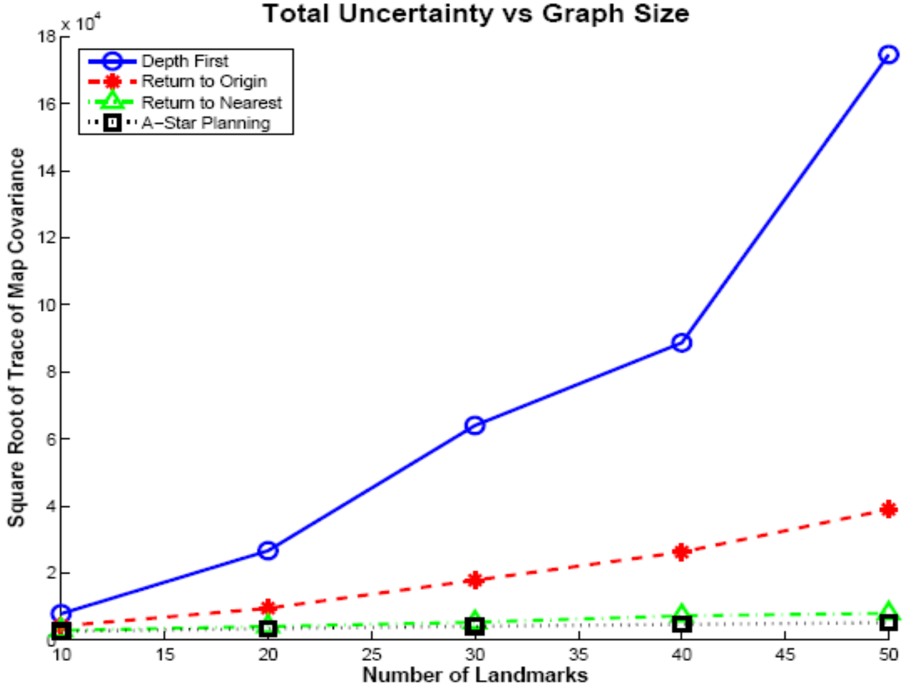
Simulated Relocalization Results



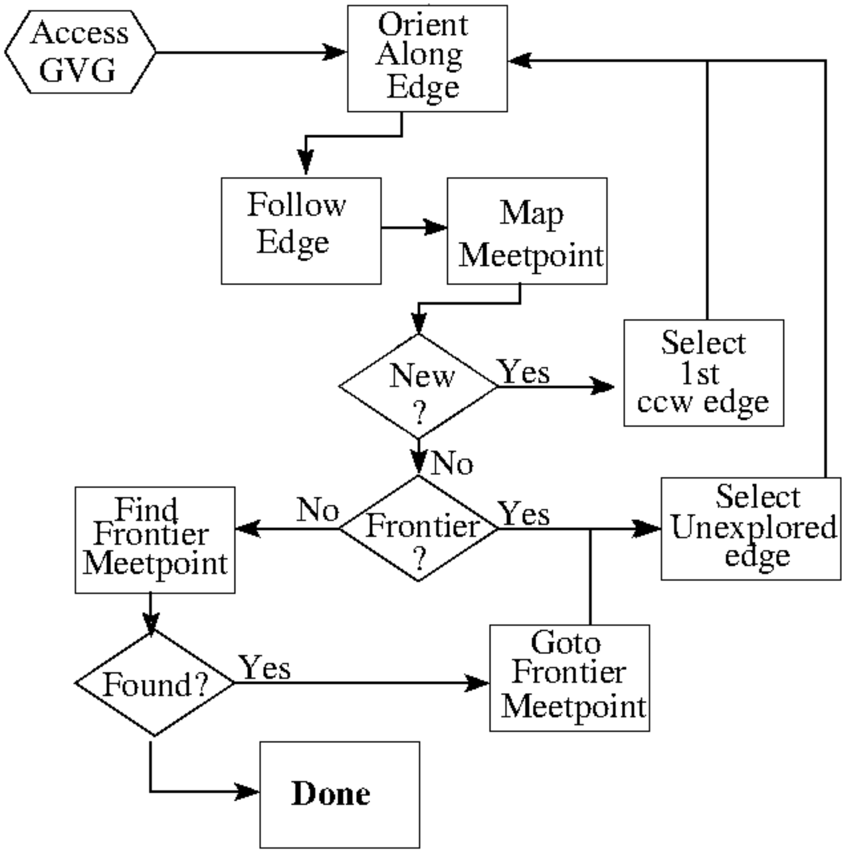


Simulated Exploration Results

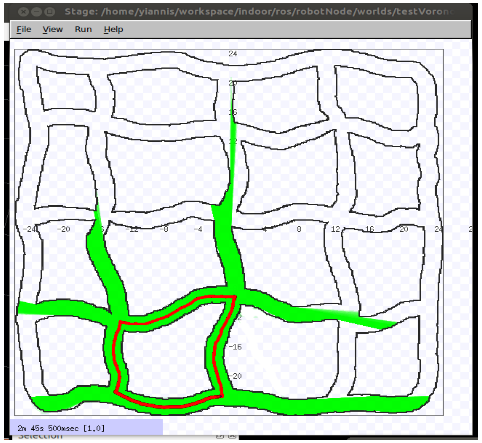


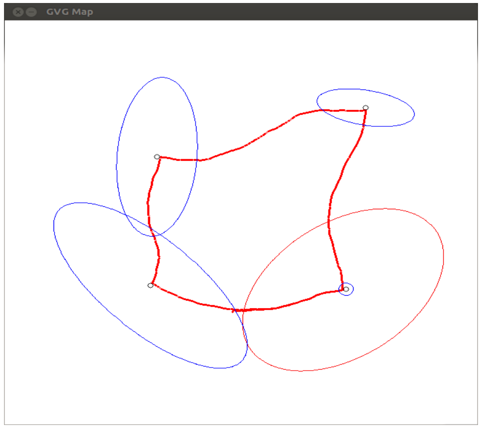


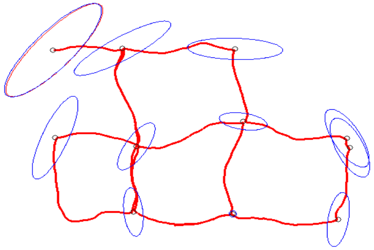
Ear-Based Exploration Algorithm

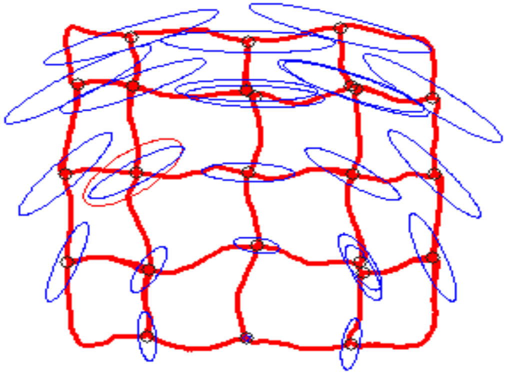


Exploration of the GVG





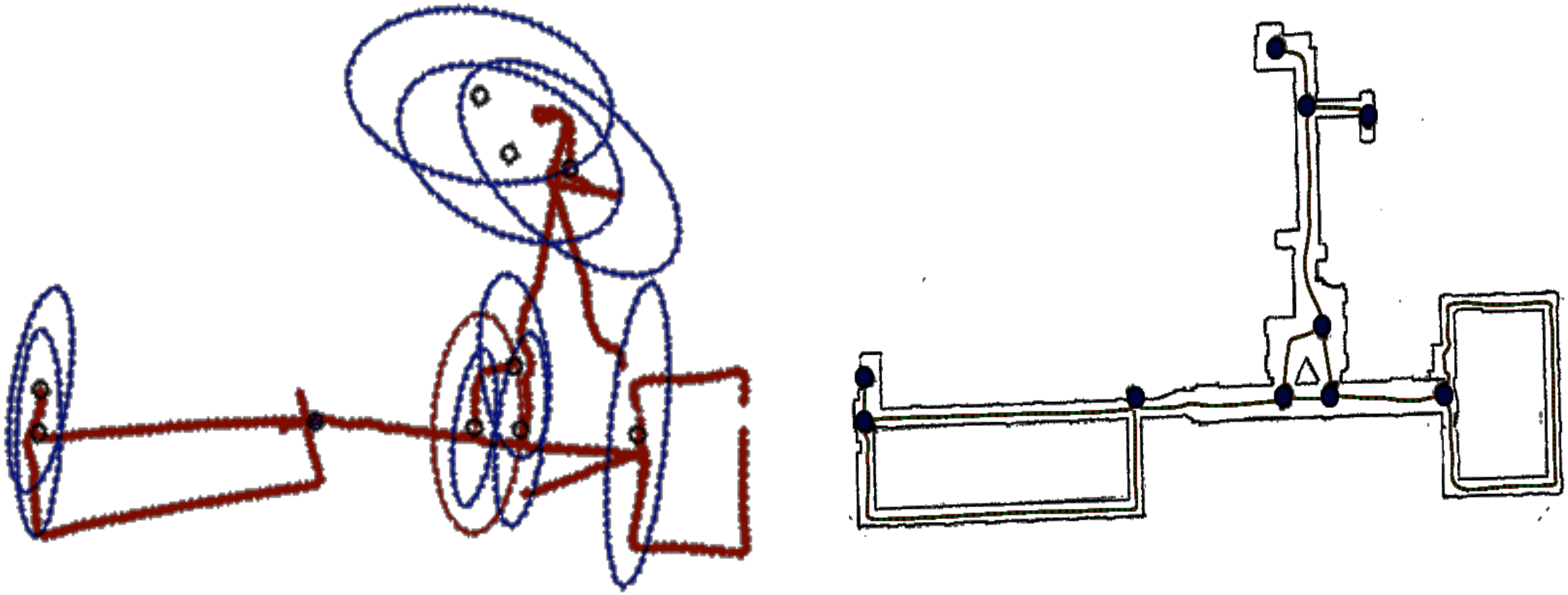




Simulation in StageRos

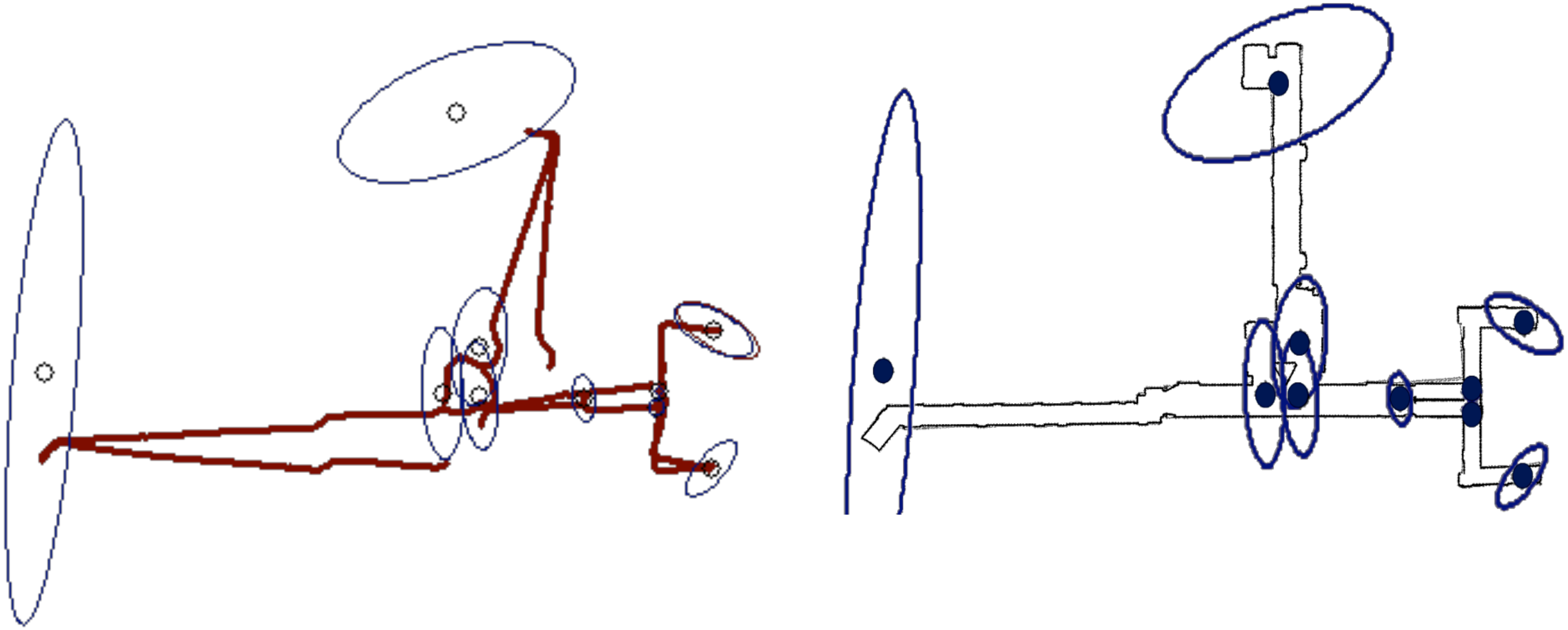
Ear based exploration

Exploration of the GVG



Real environment, McConnell 4th floor

Exploration of the GVG



Real environment, McConnell 3rd floor

Video of the Ear-based Exploration

Exploration Key Points

- Mapping requires exploration
- Exploration strategies depend on the representation
- Topological representations are the most convenient for exploration
- Two objectives:
  - Explore new territory
  - Improve the accuracy by relocalization