

CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Exploration

Three Main Challenges in Robotics

1. Where am I? (**Localization**)

- Sense
- relate sensor readings to a world model
- compute location relative to model
- assumes a perfect world model

2. What the world looks like? (**Mapping**)

- sense from various positions
- integrate measurements to produce map
- assumes perfect knowledge of position

- Together 1 and 2 form the problem of *Simultaneous Localization and Mapping* (**SLAM**)

3. How do I go from **A** to **B**? (**Path Planning**)

- More general: Which action should I pick next?



Mapping

- What the world looks like
- Improve the accuracy of the map
- Ensure that all the important parts of the environment are mapped – Exploration!

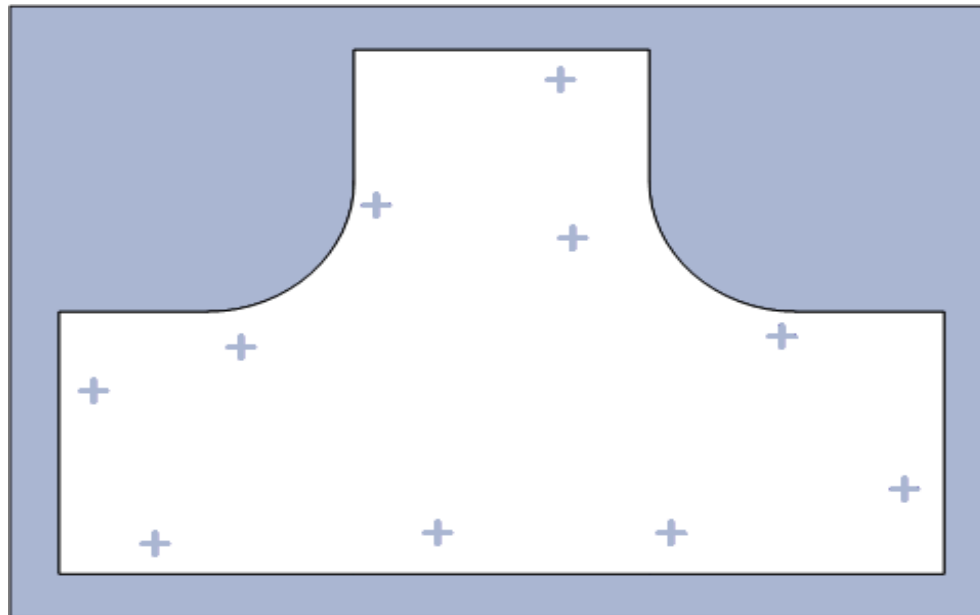


Environment Representation (Map)

- Grid Based Maps
- Feature Based Maps
- Topological Maps
- Hybrid Maps



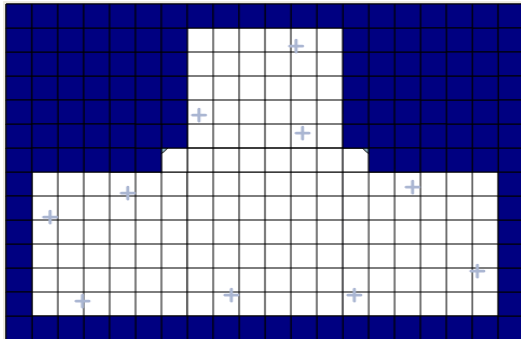
Consider this Environment:



Three Basic Map Types

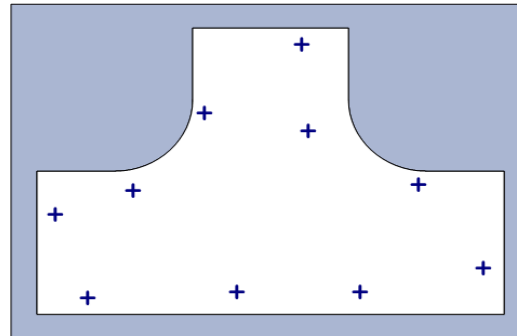
Grid-Based:

Collection of discretized obstacle/free-space pixels



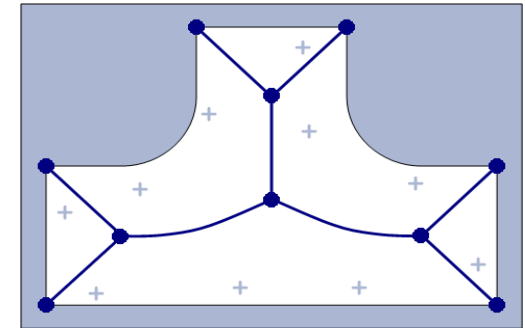
Feature-Based:

Collection of landmark locations and correlated uncertainty

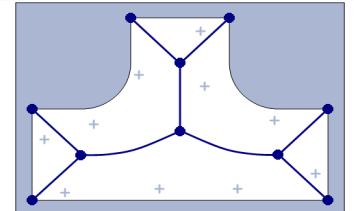
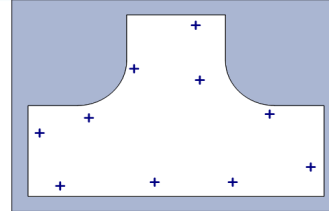
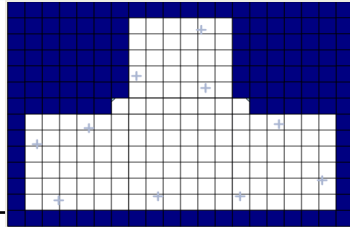


Topological:

Collection of nodes and their interconnections



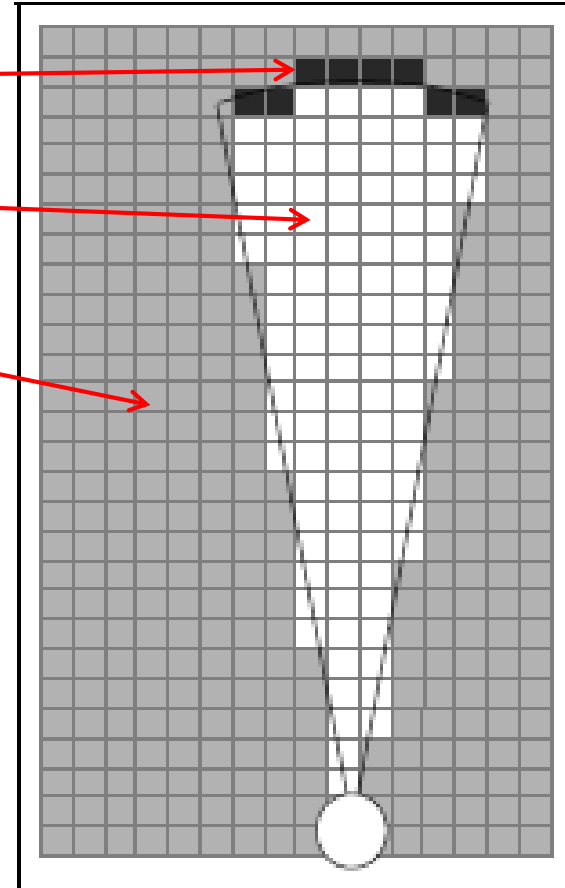
Three Basic Map Types



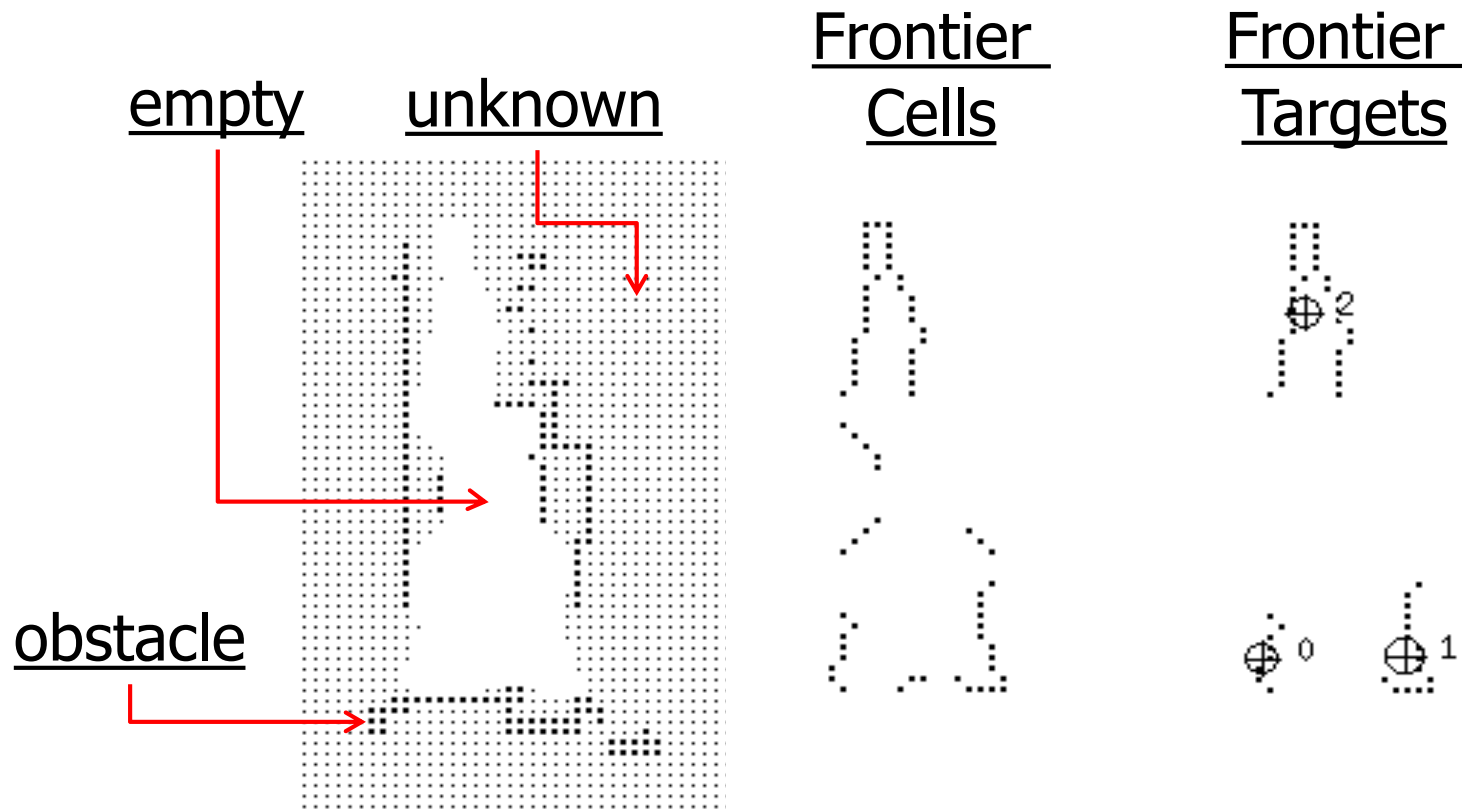
	Grid-Based	Feature-Based	Topological
Construction	Occupancy grids	Kalman Filter	Navigation control laws
Complexity	Grid size and resolution	Landmark covariance (N^3)	Minimal complexity
Obstacles	Discretized obstacles	Only structured obstacles	GVG defined by the safest path
Localization	Discrete localization	Arbitrary localization	Localize to nodes
Exploration	Frontier-based exploration	No inherent exploration	Graph exploration

Grid Based Maps

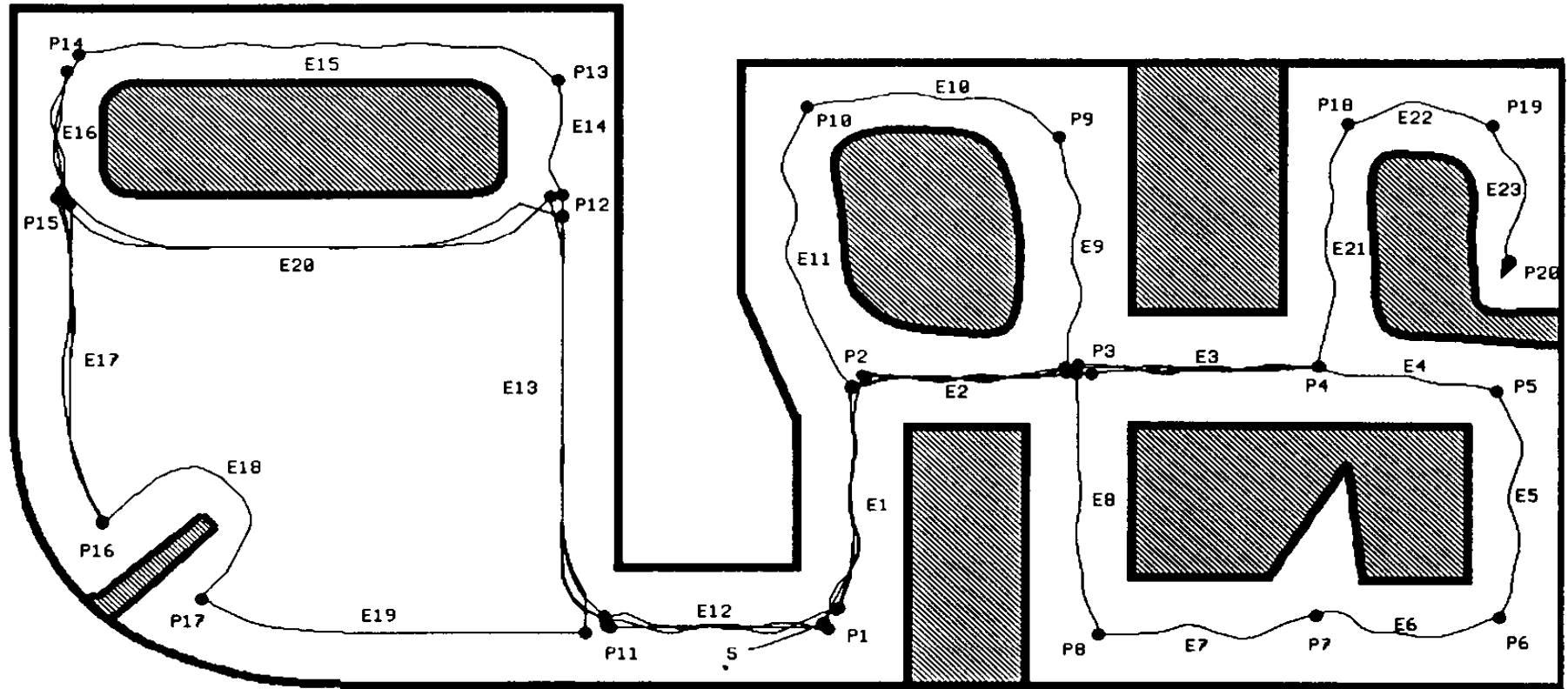
- Occupied cells
- Free cells
- Unknown cells



Frontier based Exploration (Grid Maps)



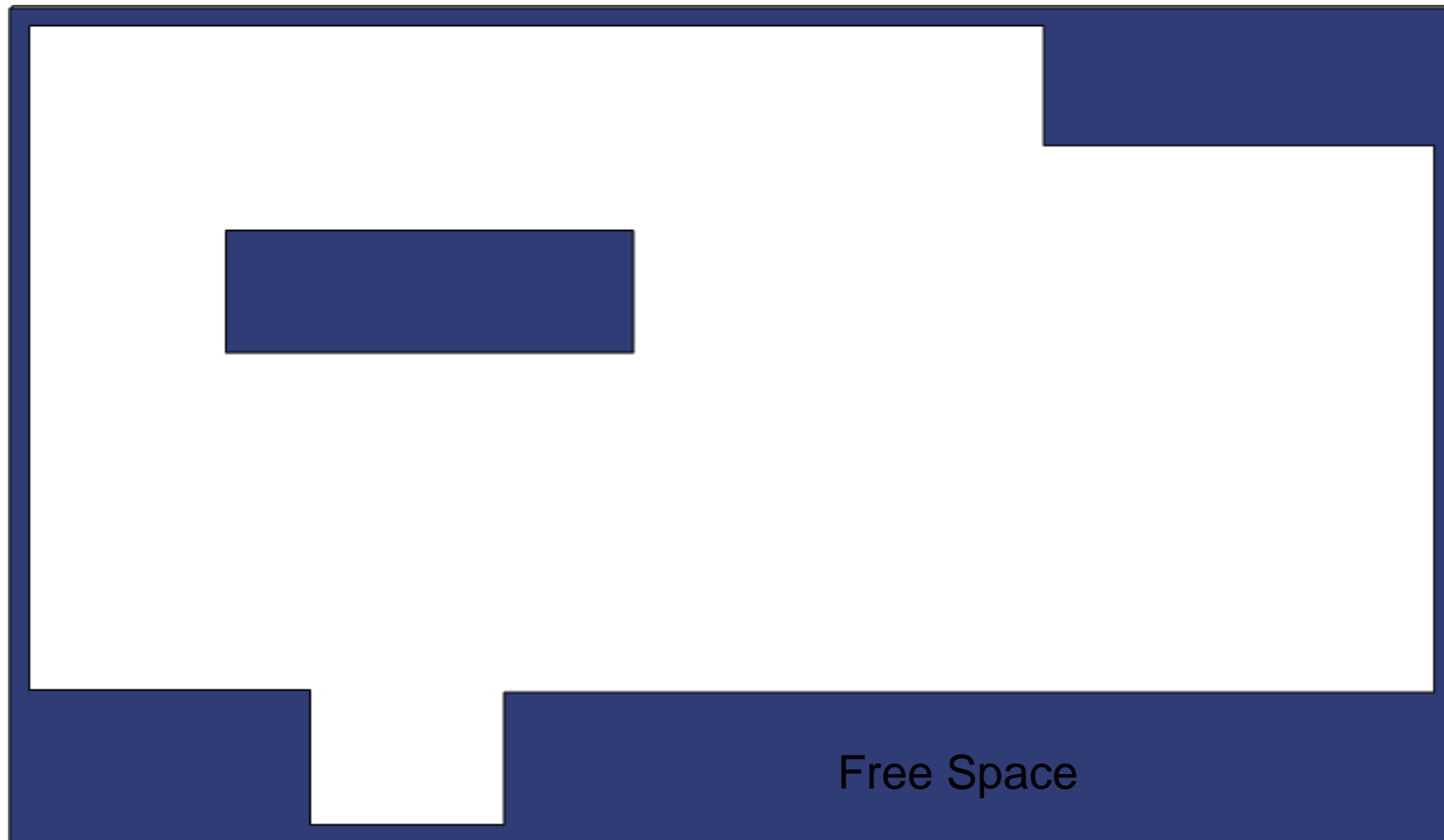
Topological Representations



- 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.



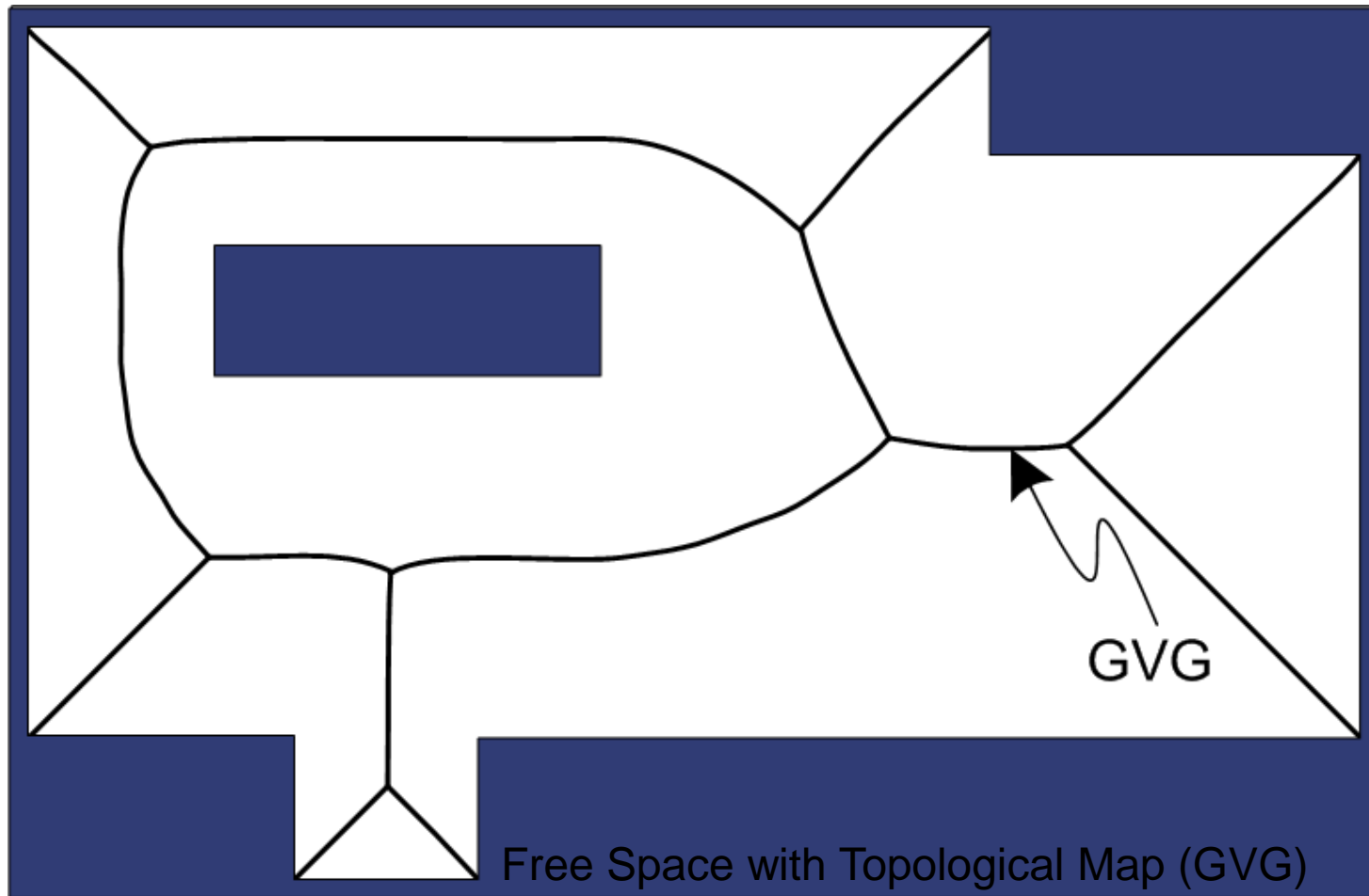
Generalized Voronoi Graph (GVG)



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.

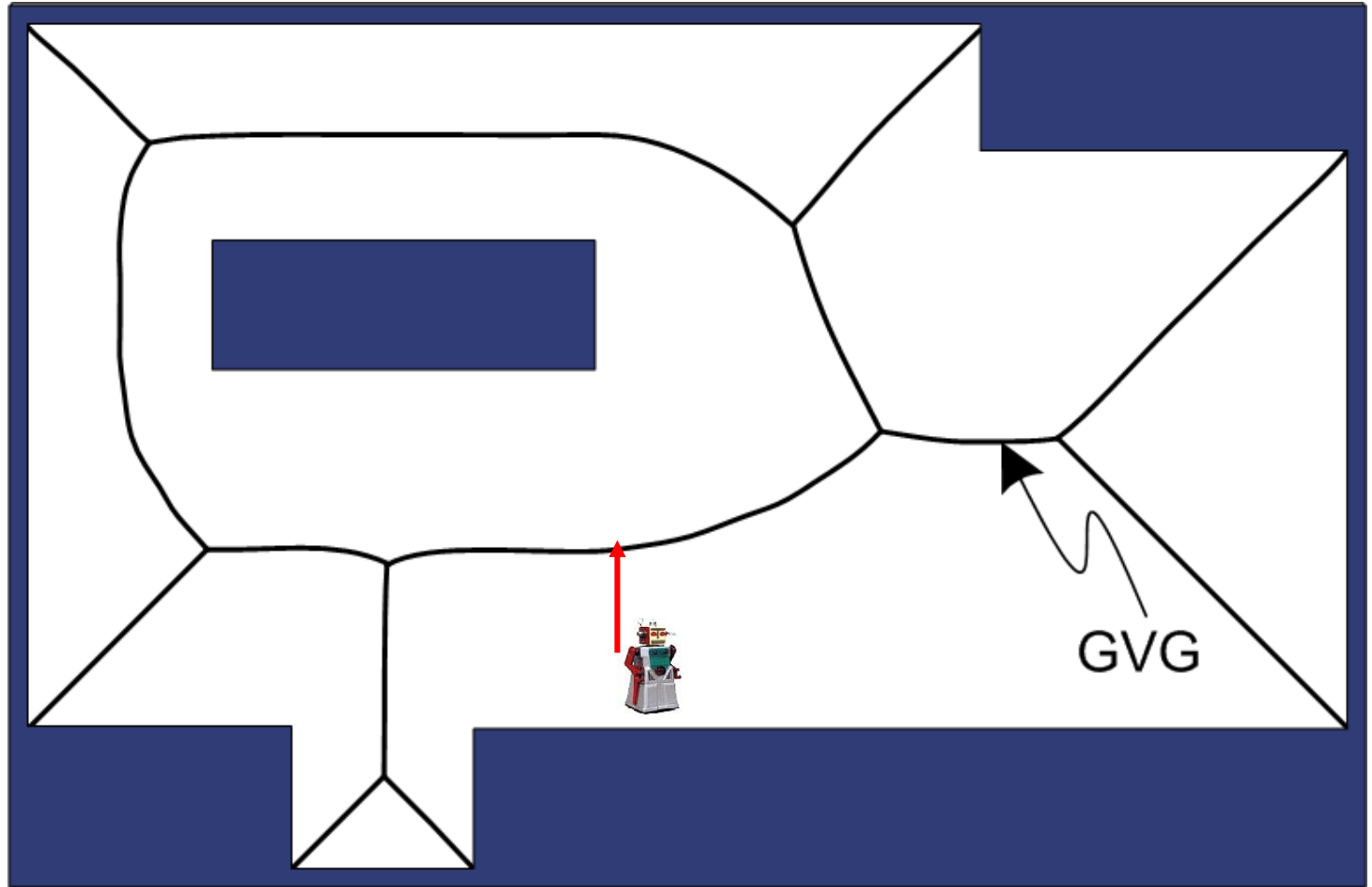


Generalized Voronoi Graph (GVG)



Generalized Voronoi Graph (GVG)

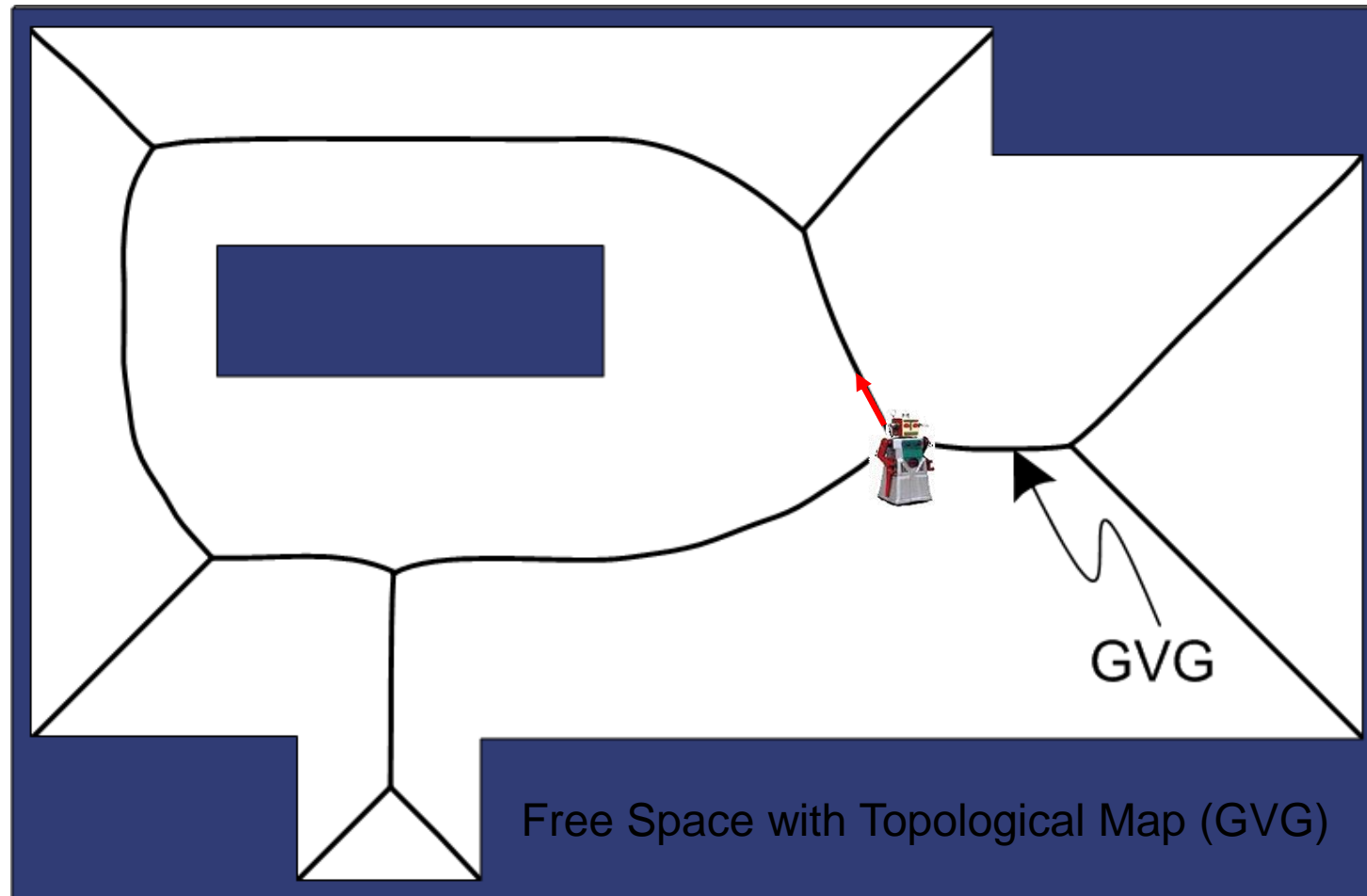
- Access GVG



Free Space with Topological Map (GVG)

Generalized Voronoi Graph (GVG)

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



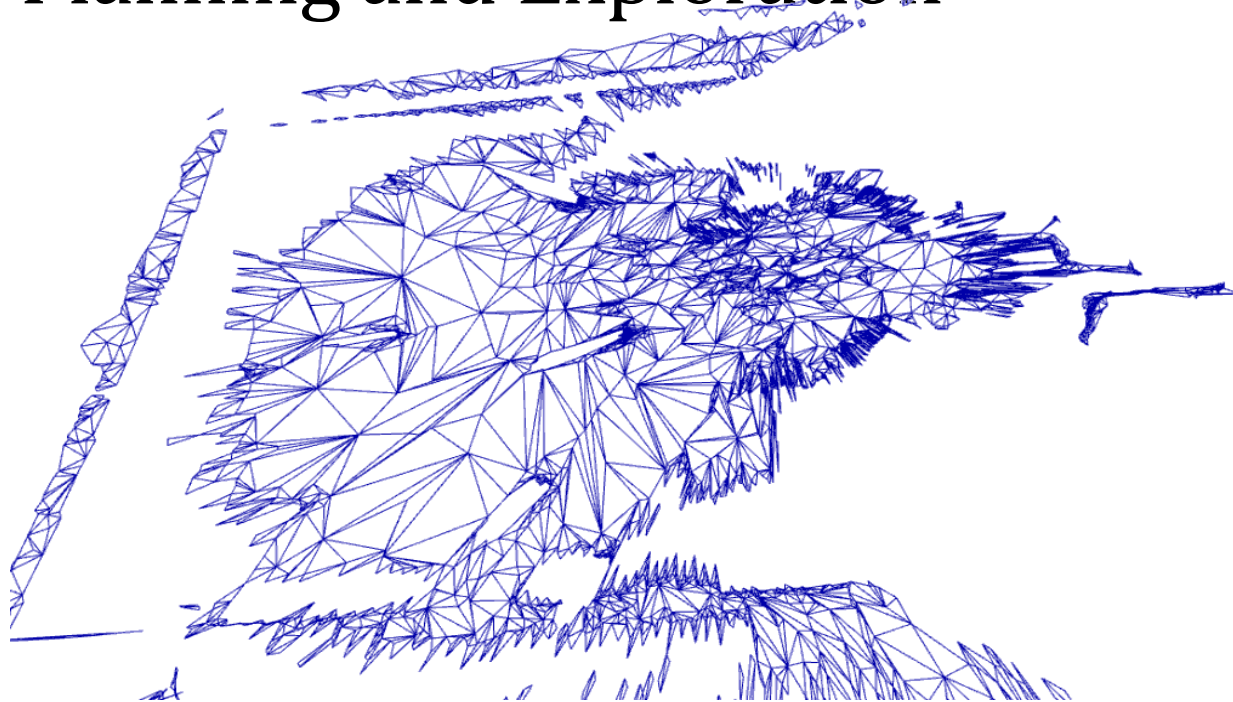
Exploration via Graph Search

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



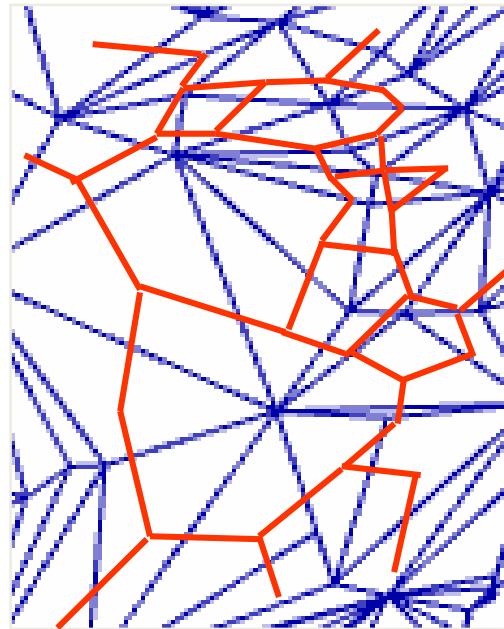
Irregular Triangular Mesh (ITM)

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



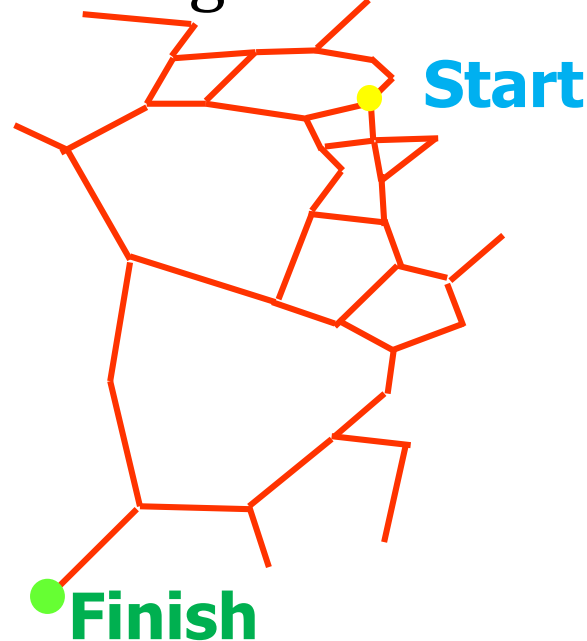
From 2.5D Representation to Topological

- Convert ITM into Connected Graph



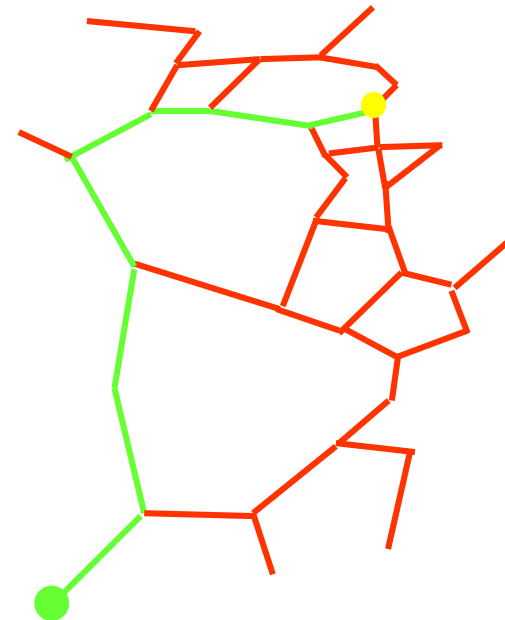
Planning

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



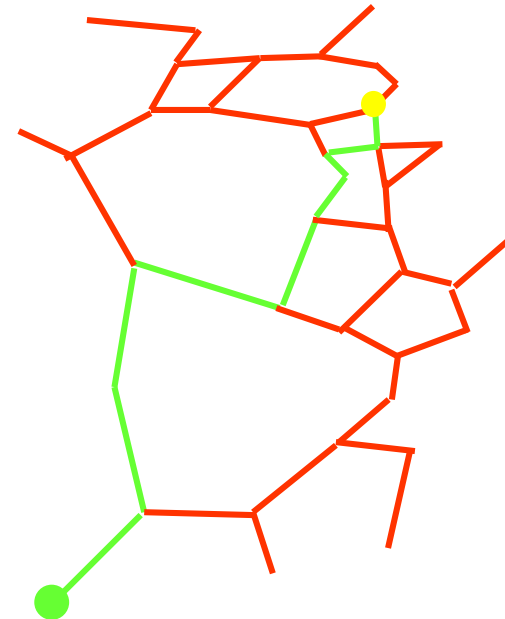
Planning

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



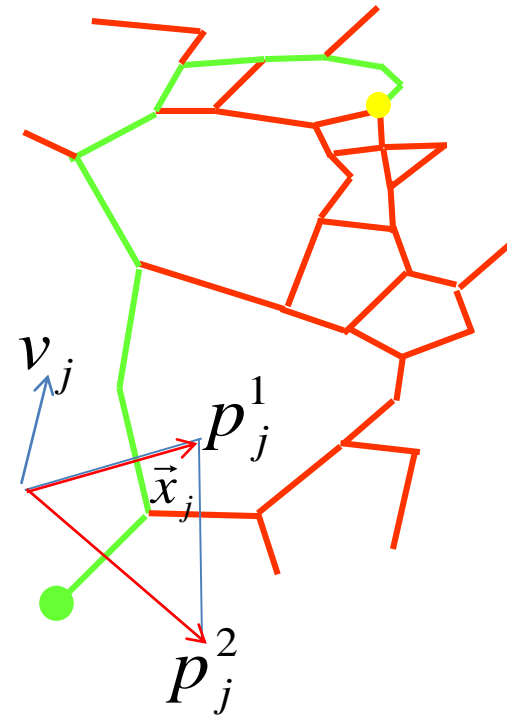
Planning

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



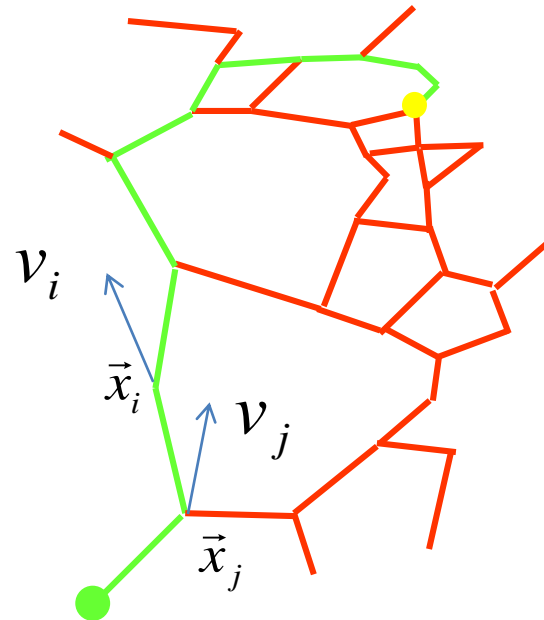
Planning

- 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 $v_j = \frac{p_j^1 \times p_j^2}{\|p_j^1\| \|p_j^2\|}$



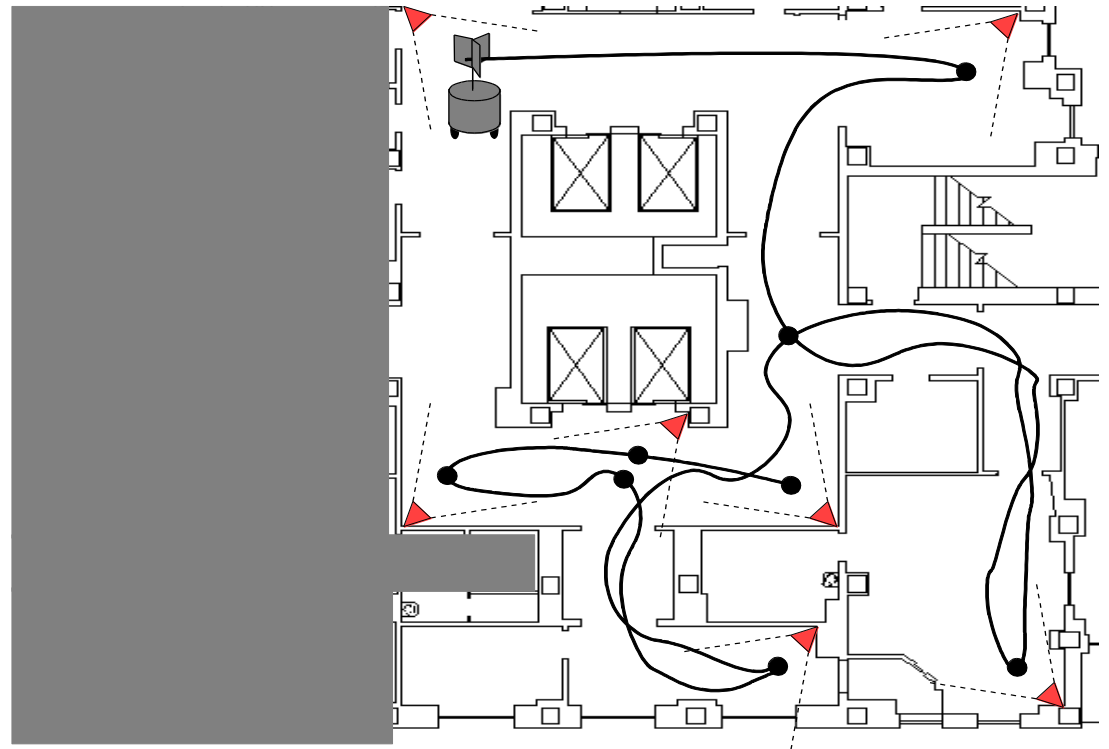
Planning

- 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 Planning Problem

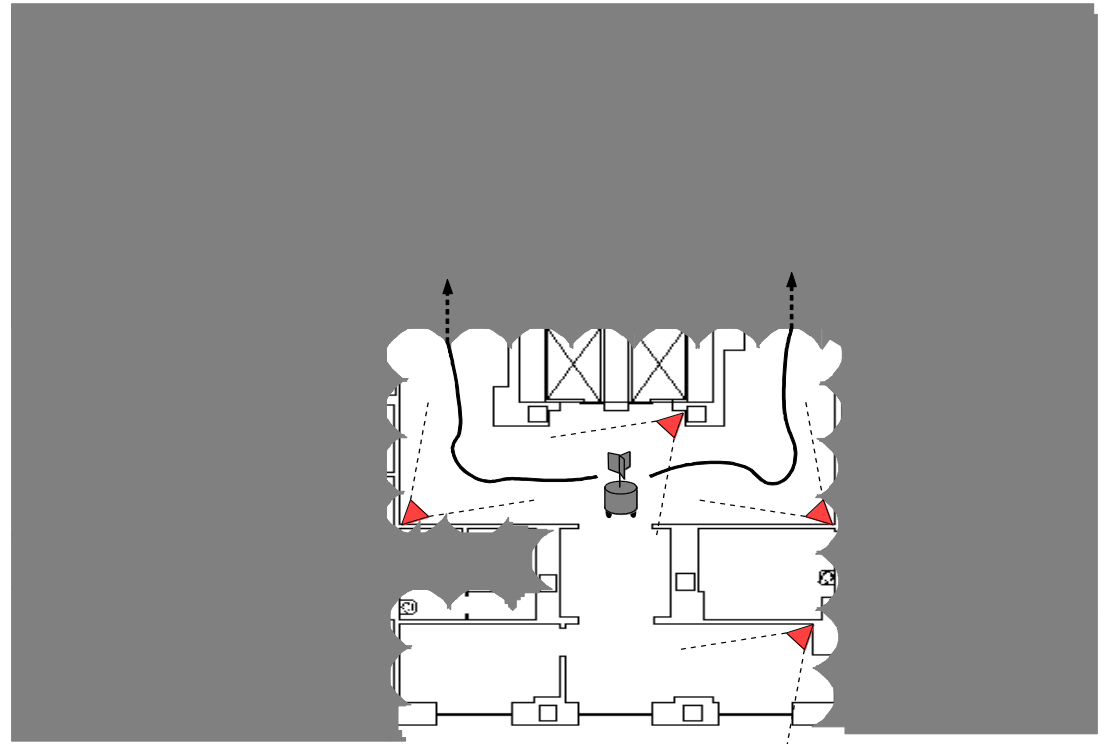
Two fundamental problems for path planning during exploration and mapping:



Exploration Planning Problem

Two fundamental problems for path planning during exploration and mapping:

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



Previous Localization Planning

- Reduce measure of map or position entropy
- Variety of graph search planning algorithms (breadth first, A*-search, RRT)
- Evaluate paths with simulation, or Cramer-Rao bounds for expected uncertainty
- e.g. [Fox et al RAS 1998], [Sim and Roy ICRA 2005], [He et al ICRA 2008], [Censi et al ICRA 2008]

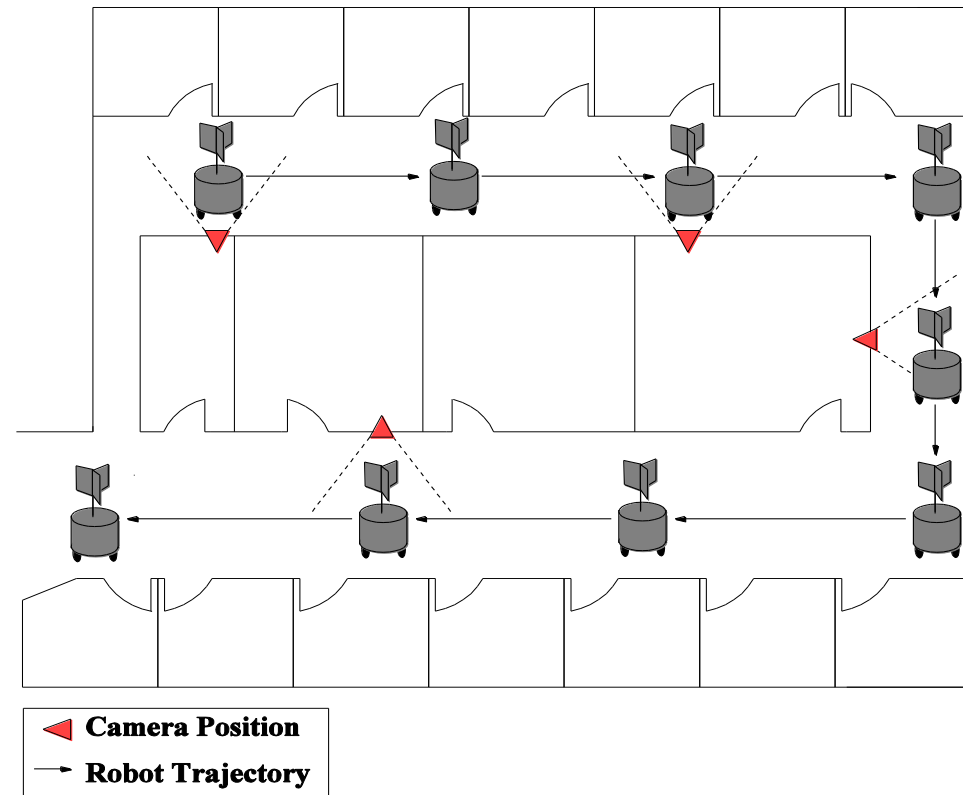
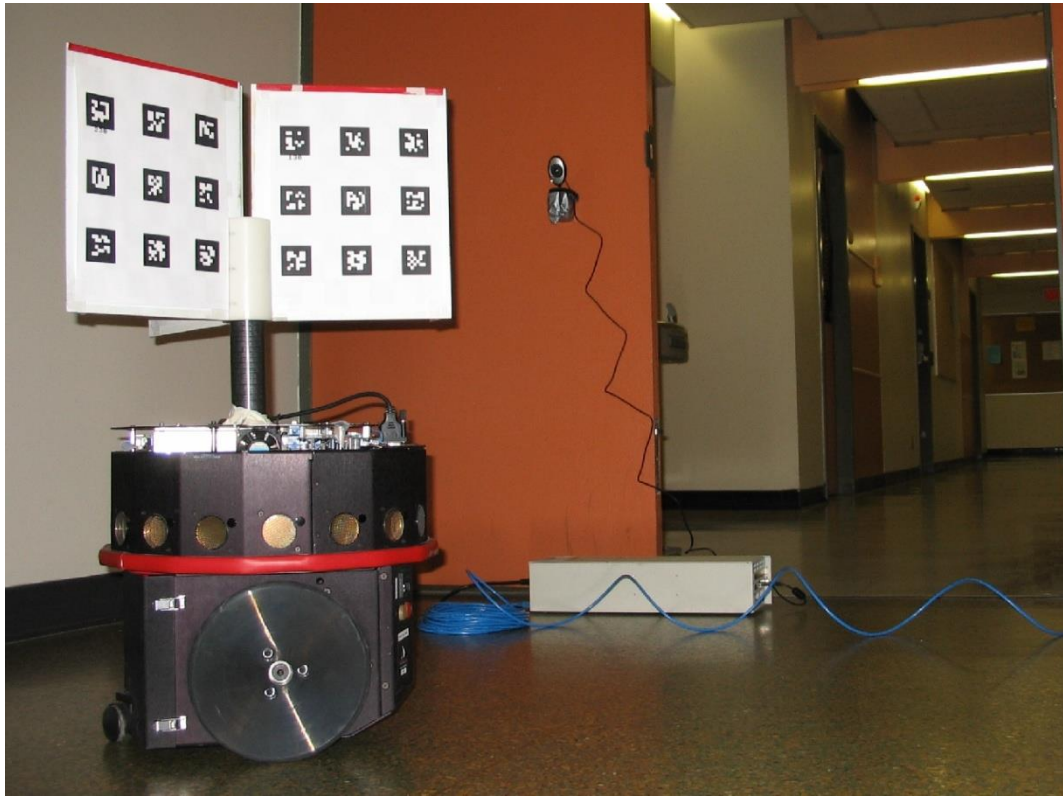


Previous Exploration Planning

- Includes motion into unexplored regions
- Typically requires prior knowledge of environment properties or rough layout
- Computation of exploration effects is a challenge
- e.g. [Bourque and Dudek IROS 1999], [Bourgault et al IROS 2002], [Kollar and Roy IJRR 2008]



Exploring a Camera Sensor Network



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



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: $C(p) = \omega_d \text{length}(p) + \omega_u \text{trace}(P(p))$
 - Distance-based “cost-to-go” heuristic function h used to compute estimated cost

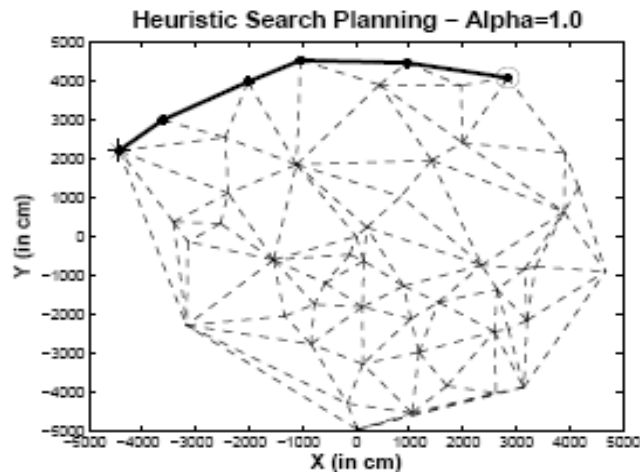
$$C(n) = f(n) + h(n)$$

Estimated cost through n Cost so far Estimated cost to go

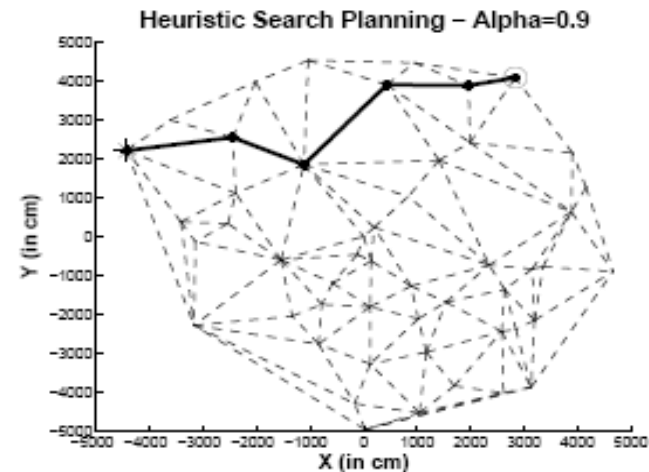
- Exploration Strategies



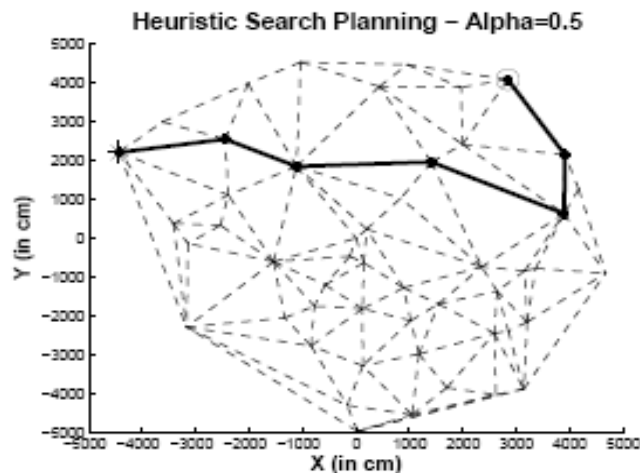
Effect of α Parameter for Relocalization



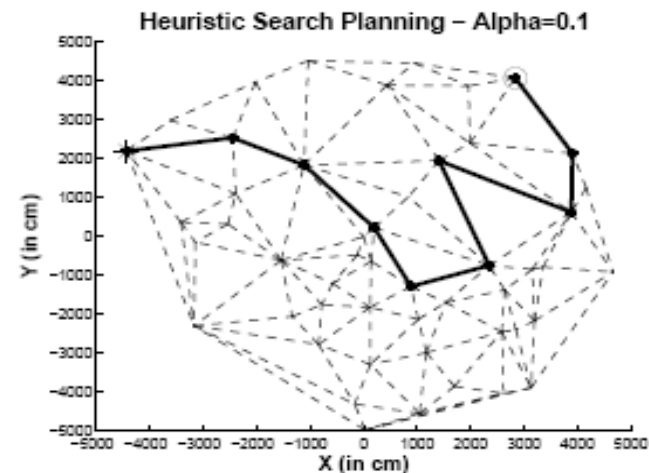
(a)



(b)



(c)



(d)



Heuristic Search

- Graph search to optimize cost function

$$C(p) = \omega_d \text{length}(p) + \omega_u \text{trace}(\Sigma(p))$$

- Heuristic search allows considering only a fraction of the paths, ordered by expected cost
- 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



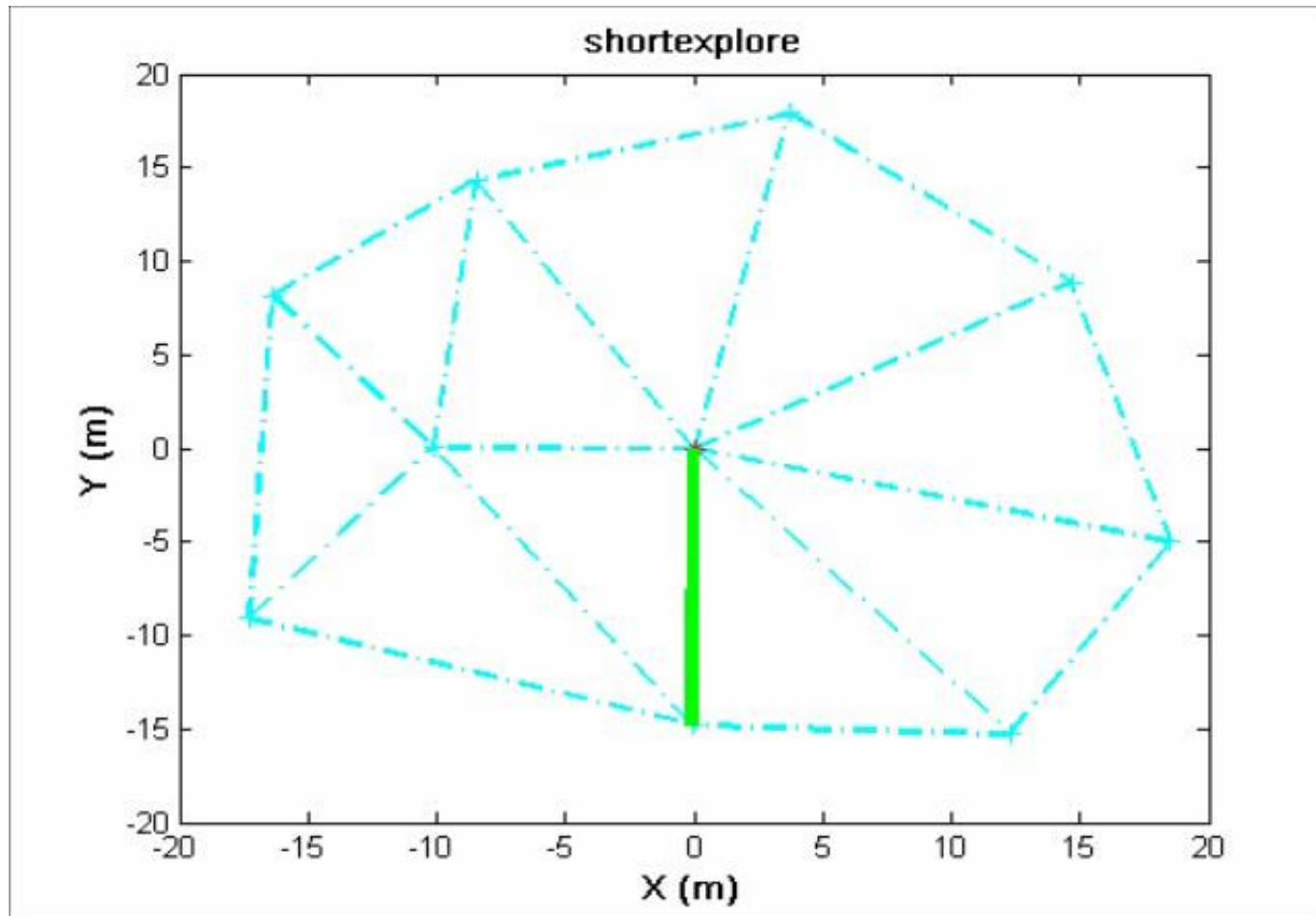
Exploration and Uncertainty Reduction

- Decision (exploration vs. exploitation)
- Target Node
- Path Planning through the known graph
- **Exploration Strategies**
 - One Step Exploration
 - Ear based exploration (submitted to IROS 2012)



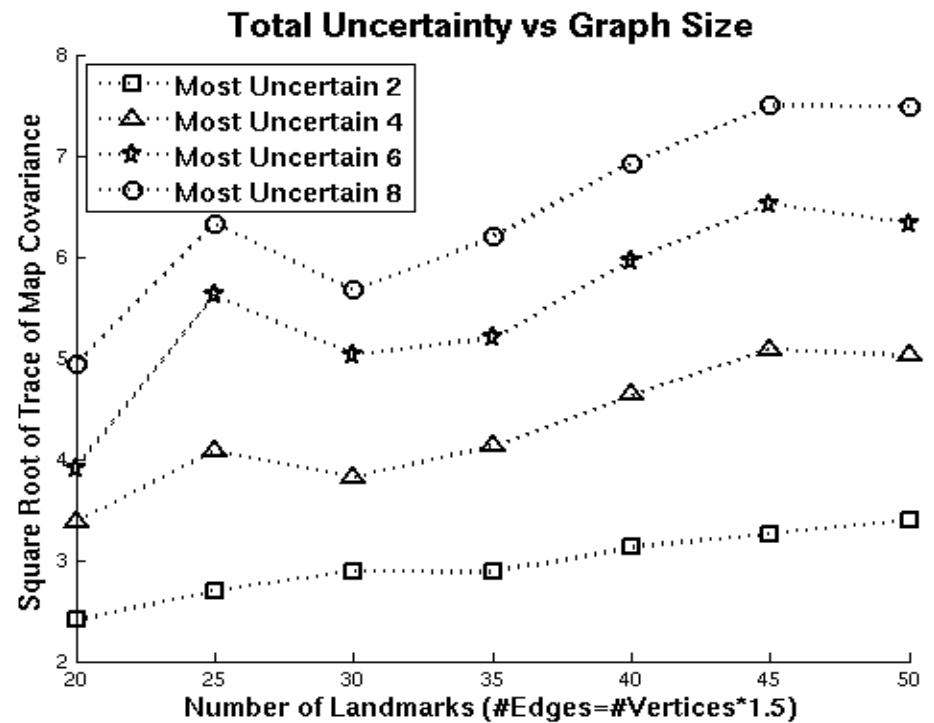
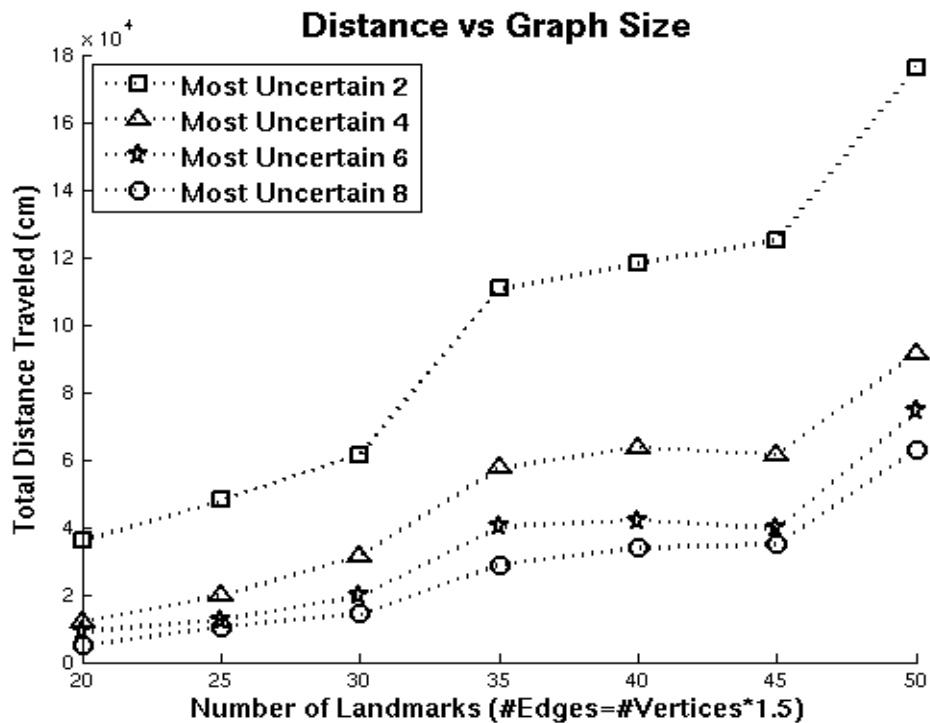
Shortest Node

$P(\text{exploit})=0.3$



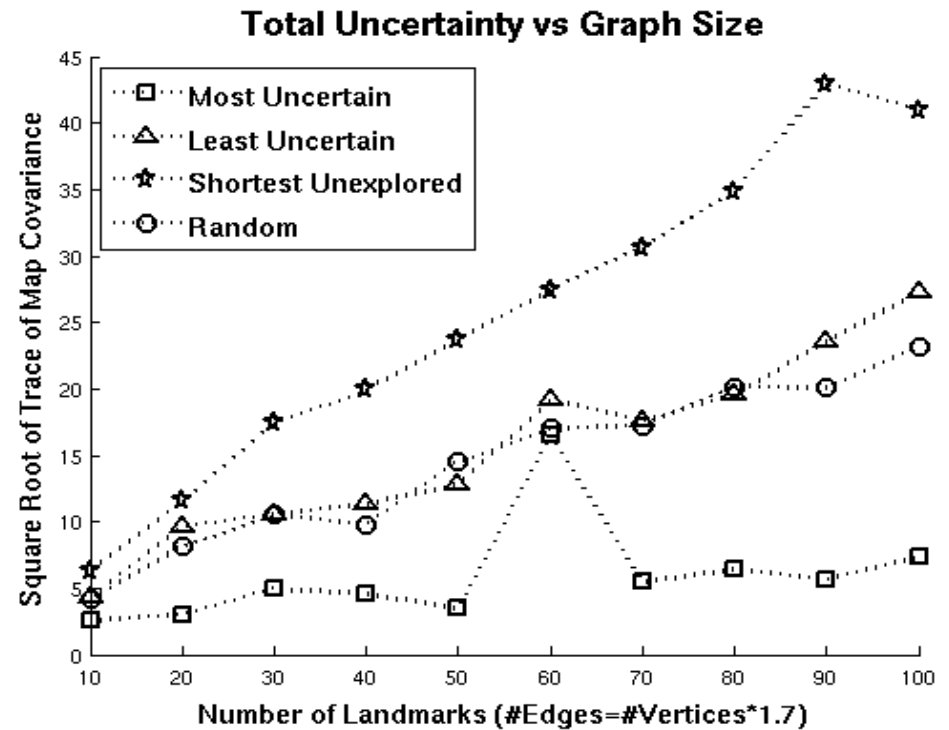
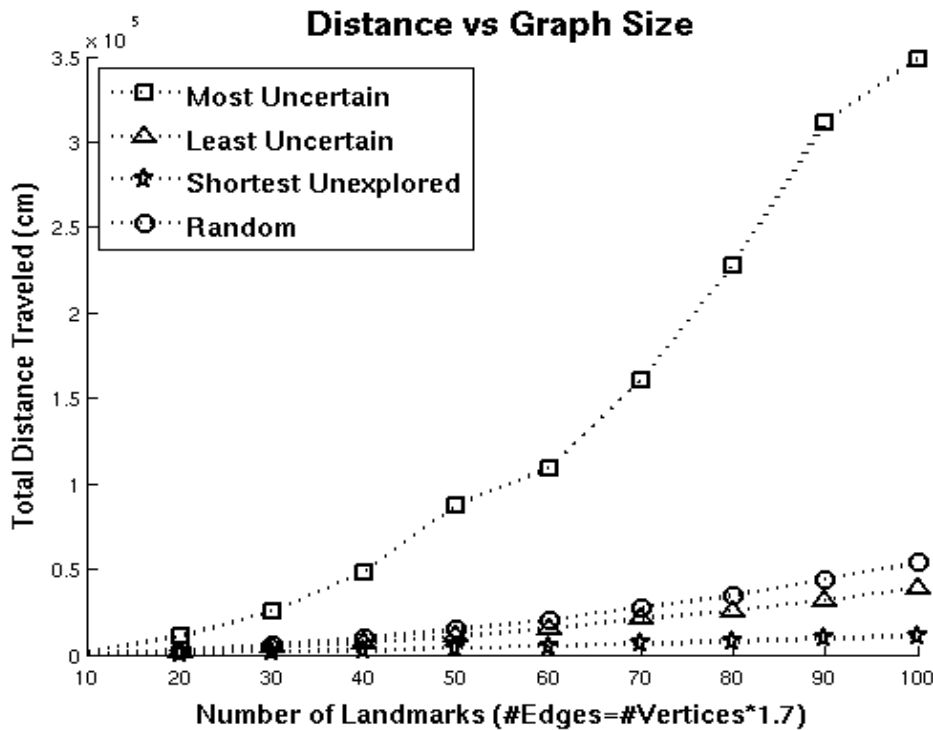
Experimental Results

Bounded Uncertainty



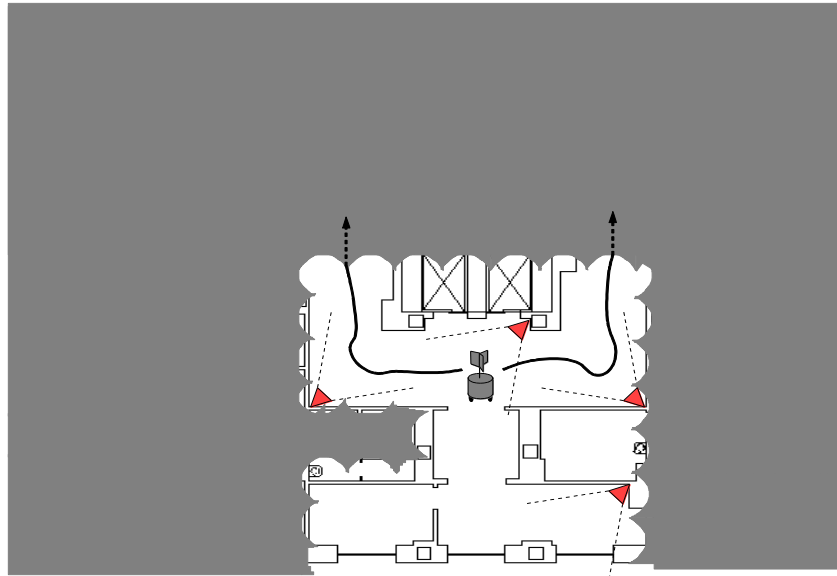
Experimental Results

Different Strategies



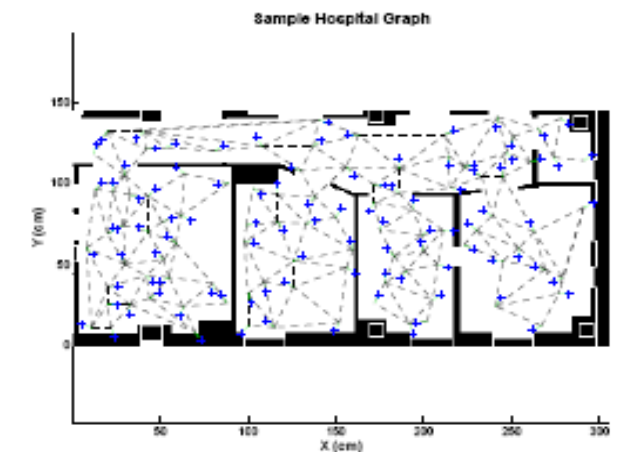
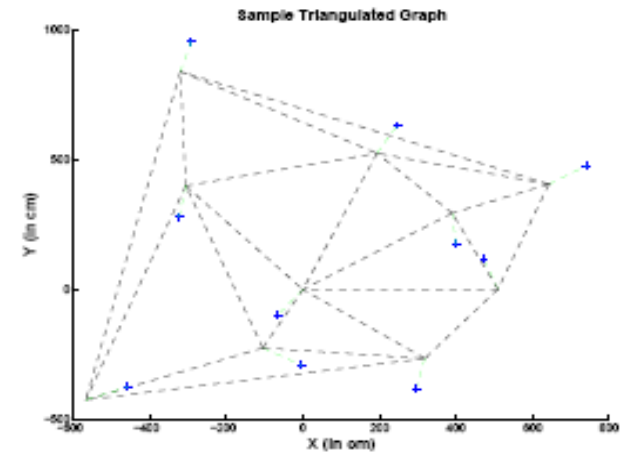
Planning Exploratory Steps

- 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

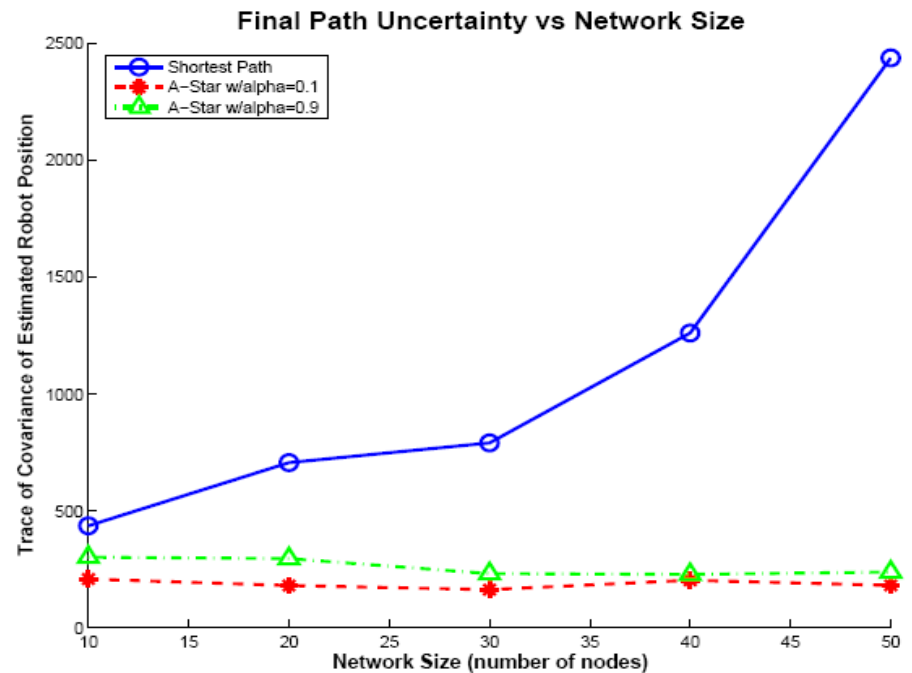
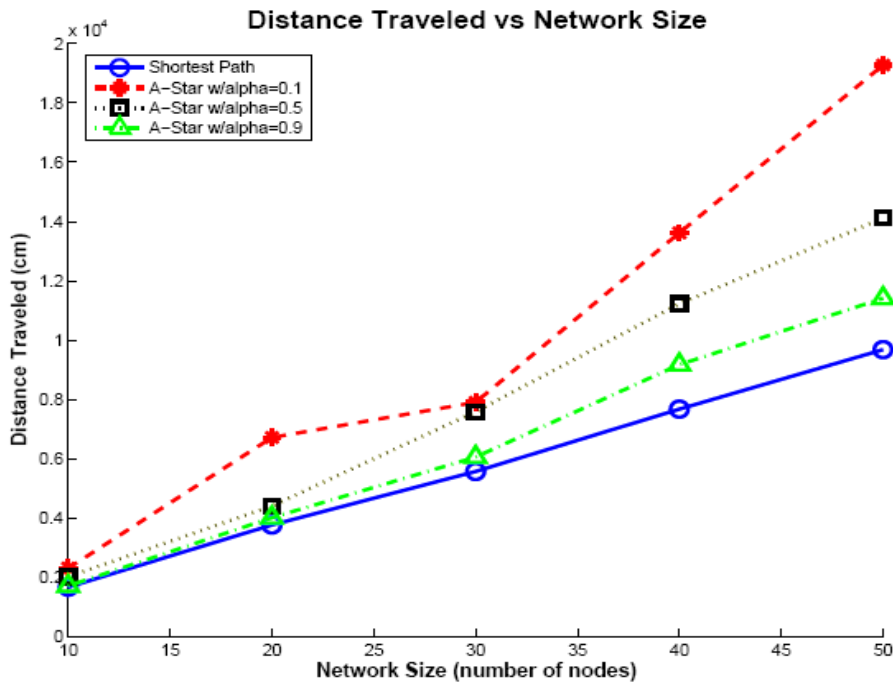


Simulation Results

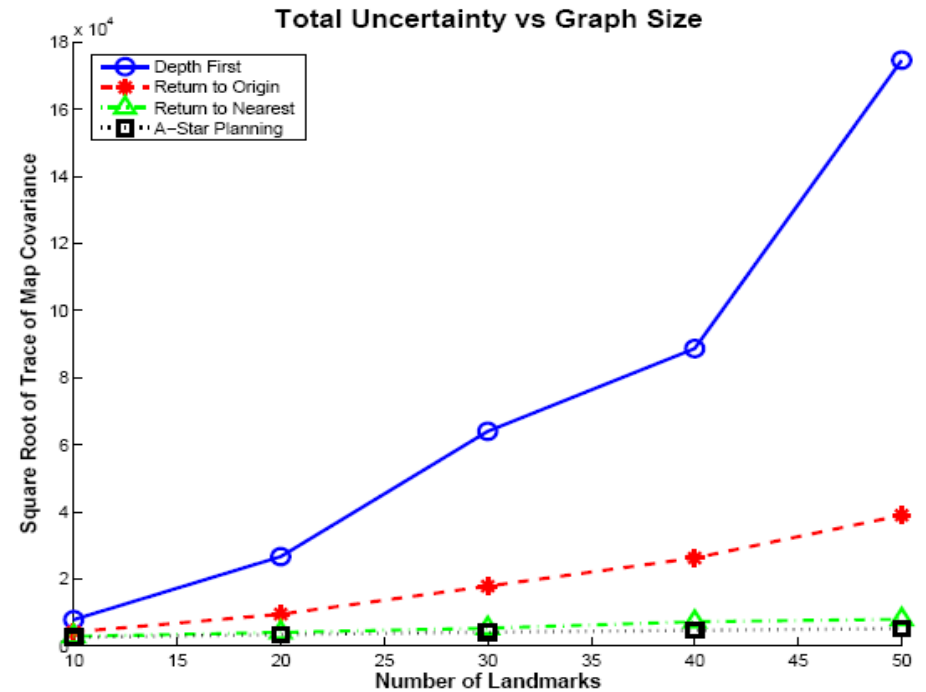
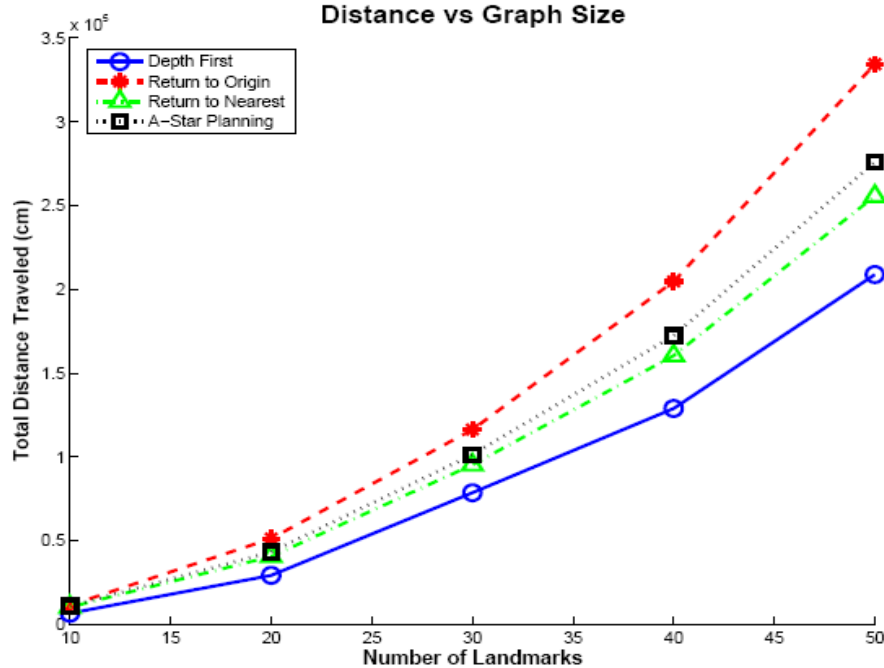
- Compared planners over many trials
- 3 realistic network types (2 shown)
- 3 methods for comparison:
 - Depth-first
 - Return to origin
 - Return to nearest explored



Simulated Relocalization Results



Simulated Exploration Results



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



References

- 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.
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- Stachniss, C. Hahnel, D. Burgard, W. , “Exploration with active loop-closing for FastSLAM”. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*. vol.2, pp 1505-1510, 2004.
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- T. Kollar and N. Roy, “Using reinforcement learning to improve exploration trajectories for error minimization”. In *of the IEEE International Conference on Robotics and Automation*, 2006.
- R. Martinez-Cantin, N. de Freitas, A. Doucet, and J. Castellanos, “Active policy learning for robot planning and exploration under Uncertainty”. In *Robotics: Science and Systems*, 2007.
- D. Meger, I. Rekleitis, and G. Dudek. “Heuristic Search Planning to Reduce Exploration Uncertainty”. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp 3382-3399, 2008.

• QUESTIONS?

