CS-417 INTRODUCTION TO ROBOTICS AND INTELLIGENT SYSTEMS

Exploration

Ioannis Rekleitis

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?

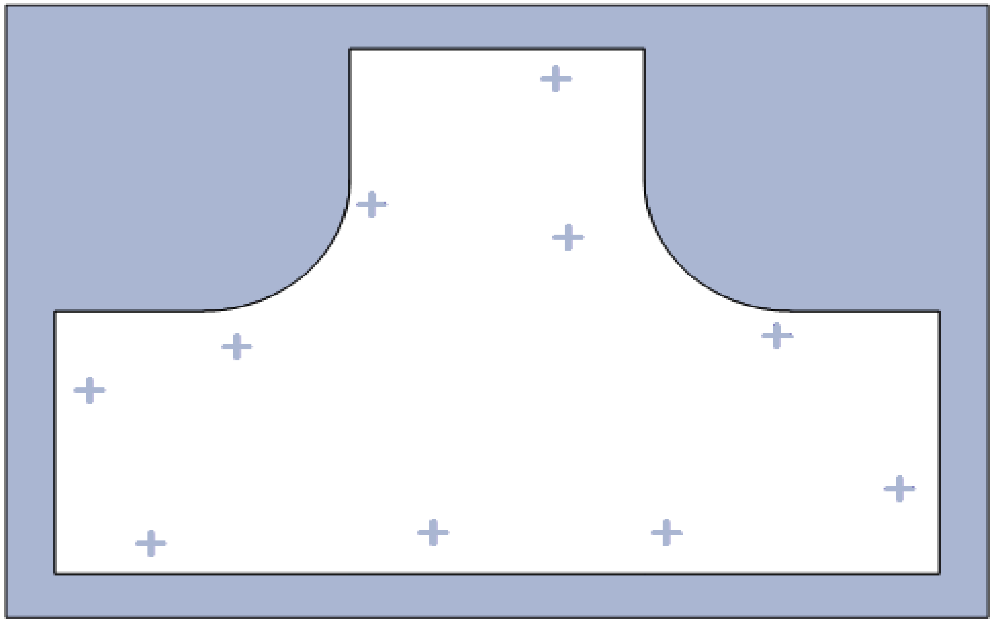
Mapping

- 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

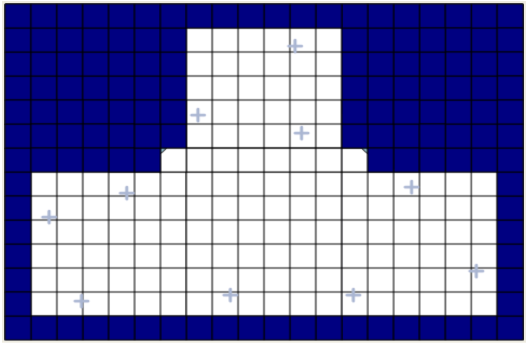
Consider this Environment:



Three Basic Map Types

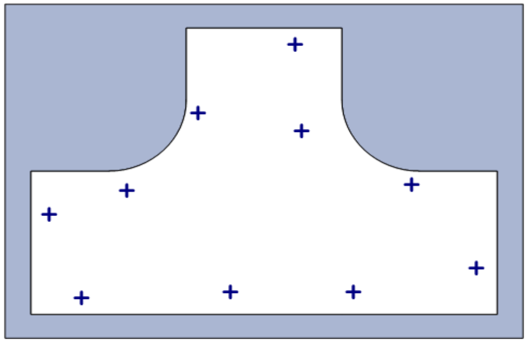
Grid-Based:

Collection of discretized obstacle/free-space pixels



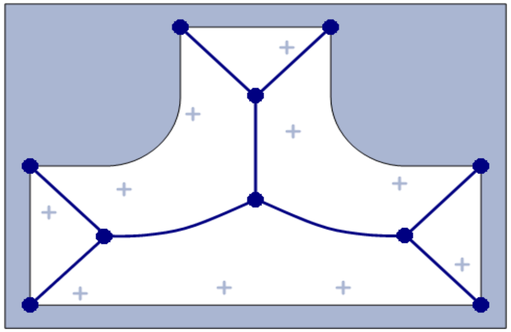
Feature-Based:

Collection of landmark locations and correlated uncertainty

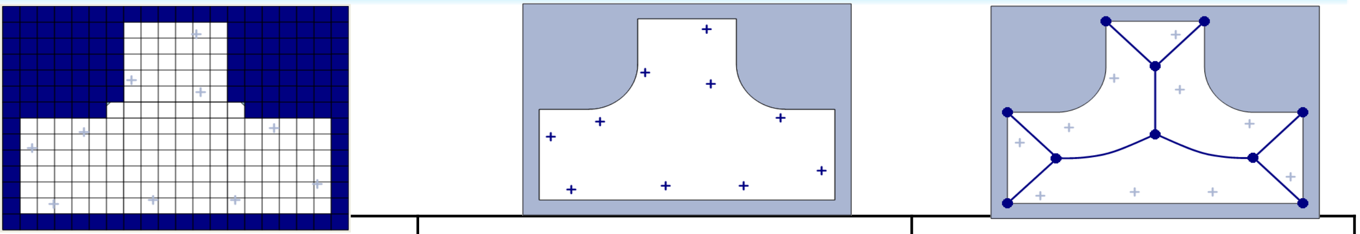


Topological:

Collection of nodes and their interconnections

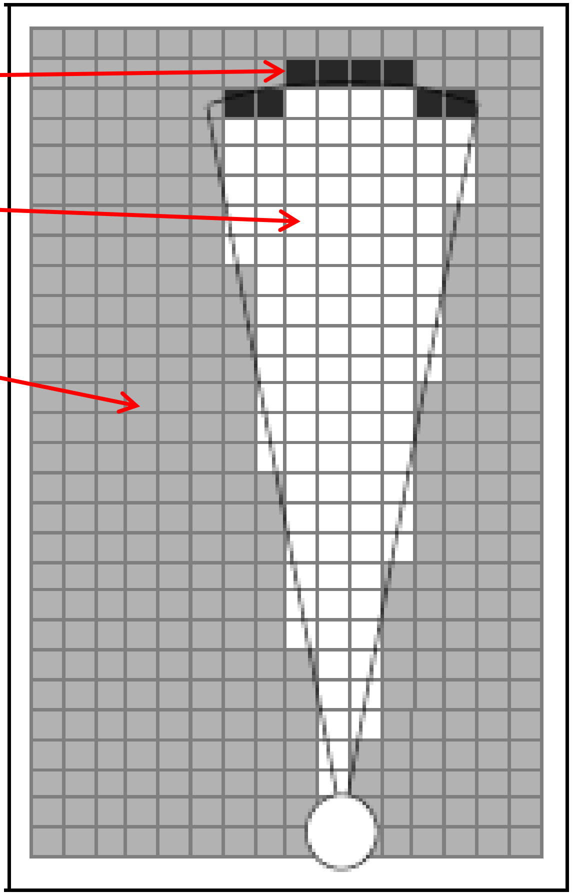


Three Basic Map Types



	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



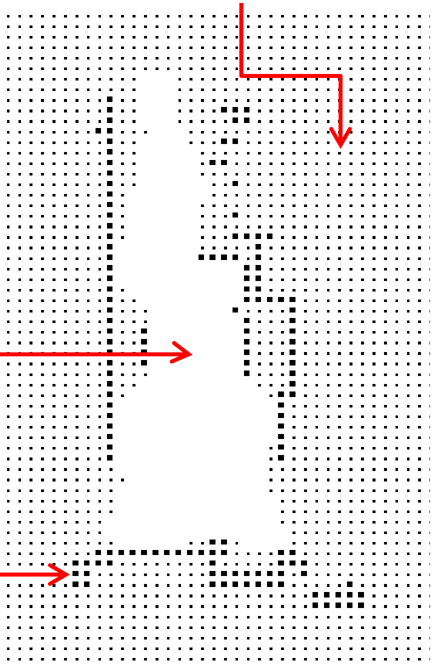
- Occupied cells
- Free cells
- Unknown cells

Frontier based Exploration (Grid Maps)

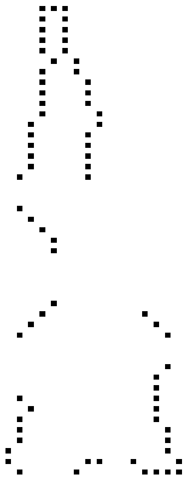
empty

unknown

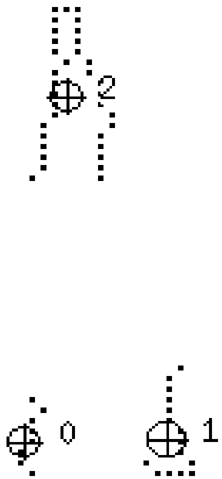
obstacle



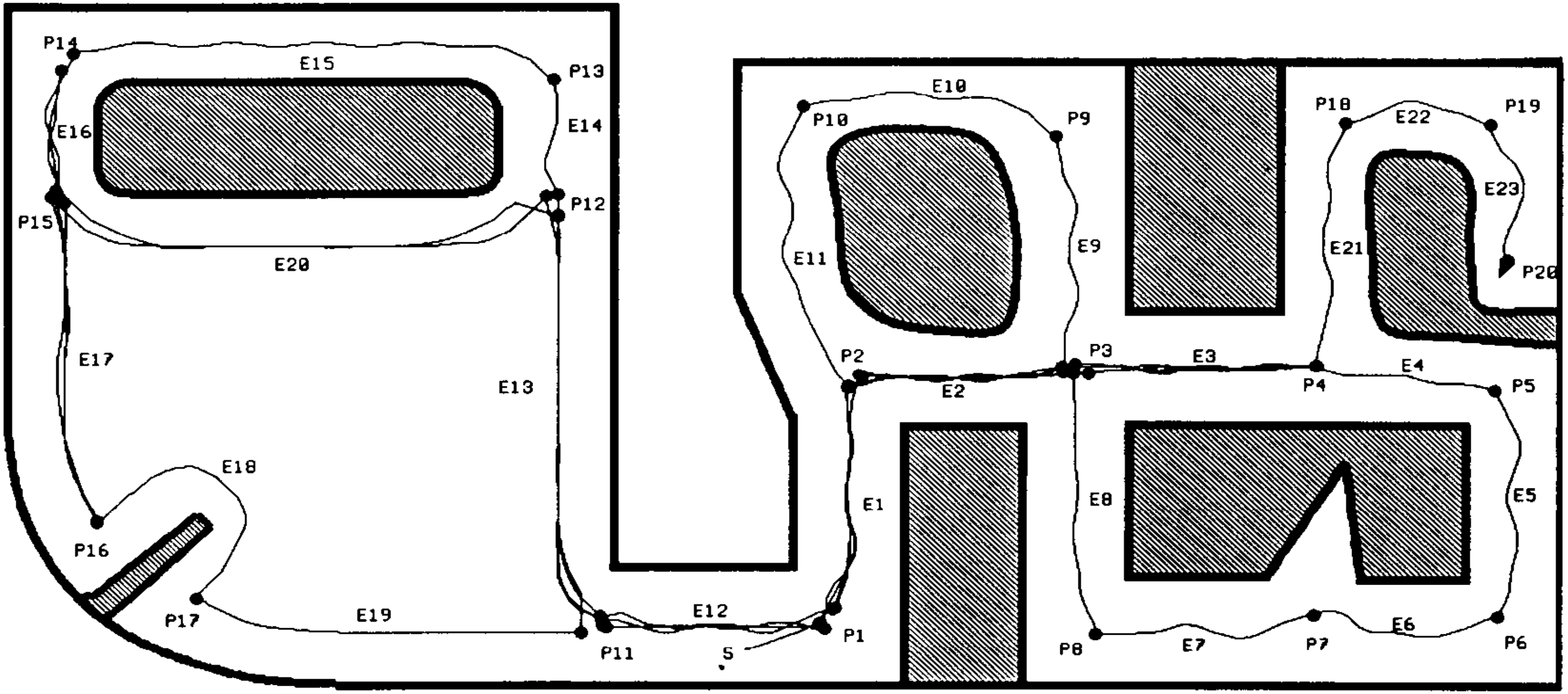
Frontier Cells



Frontier Targets

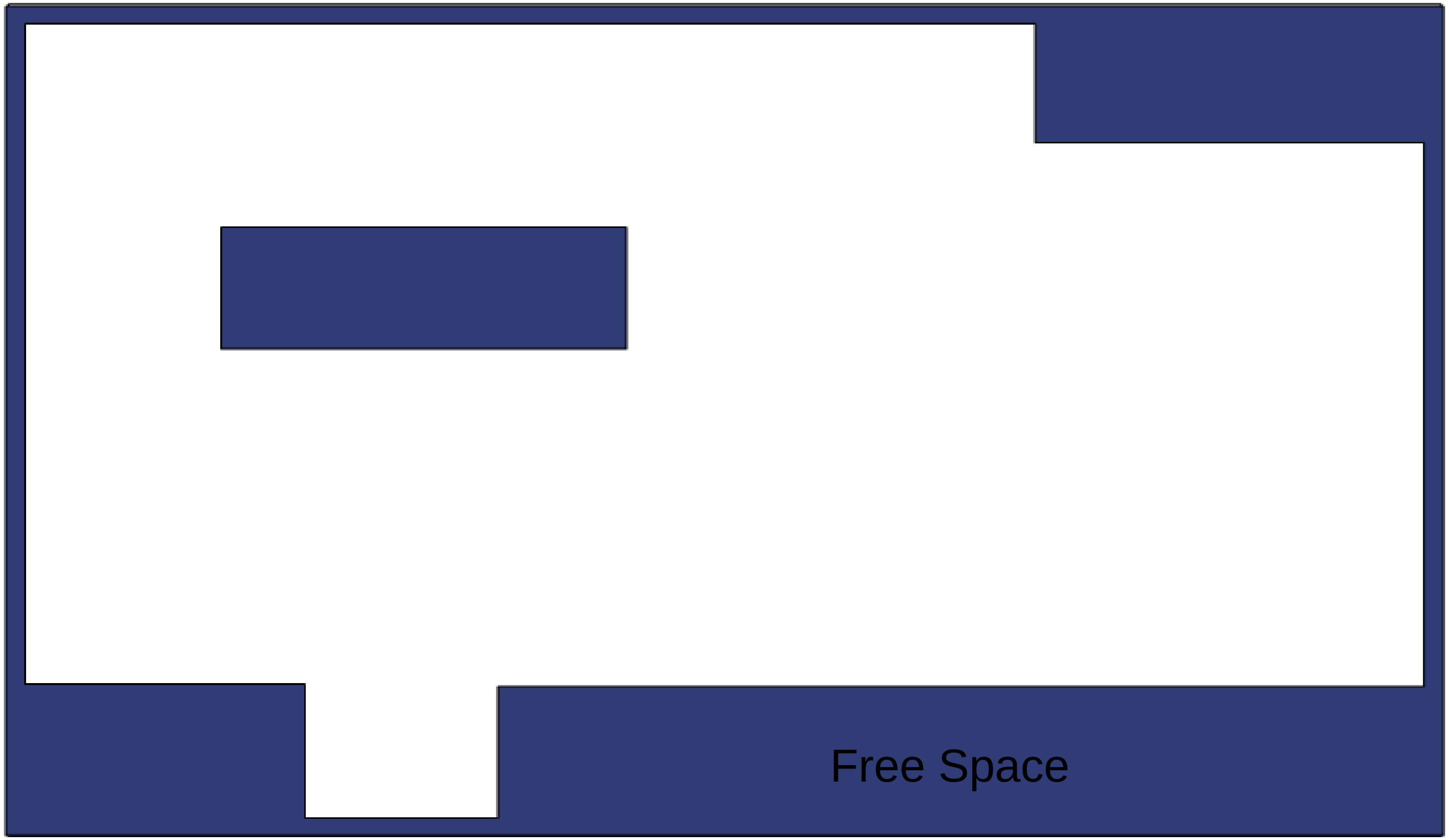


Topological Representations



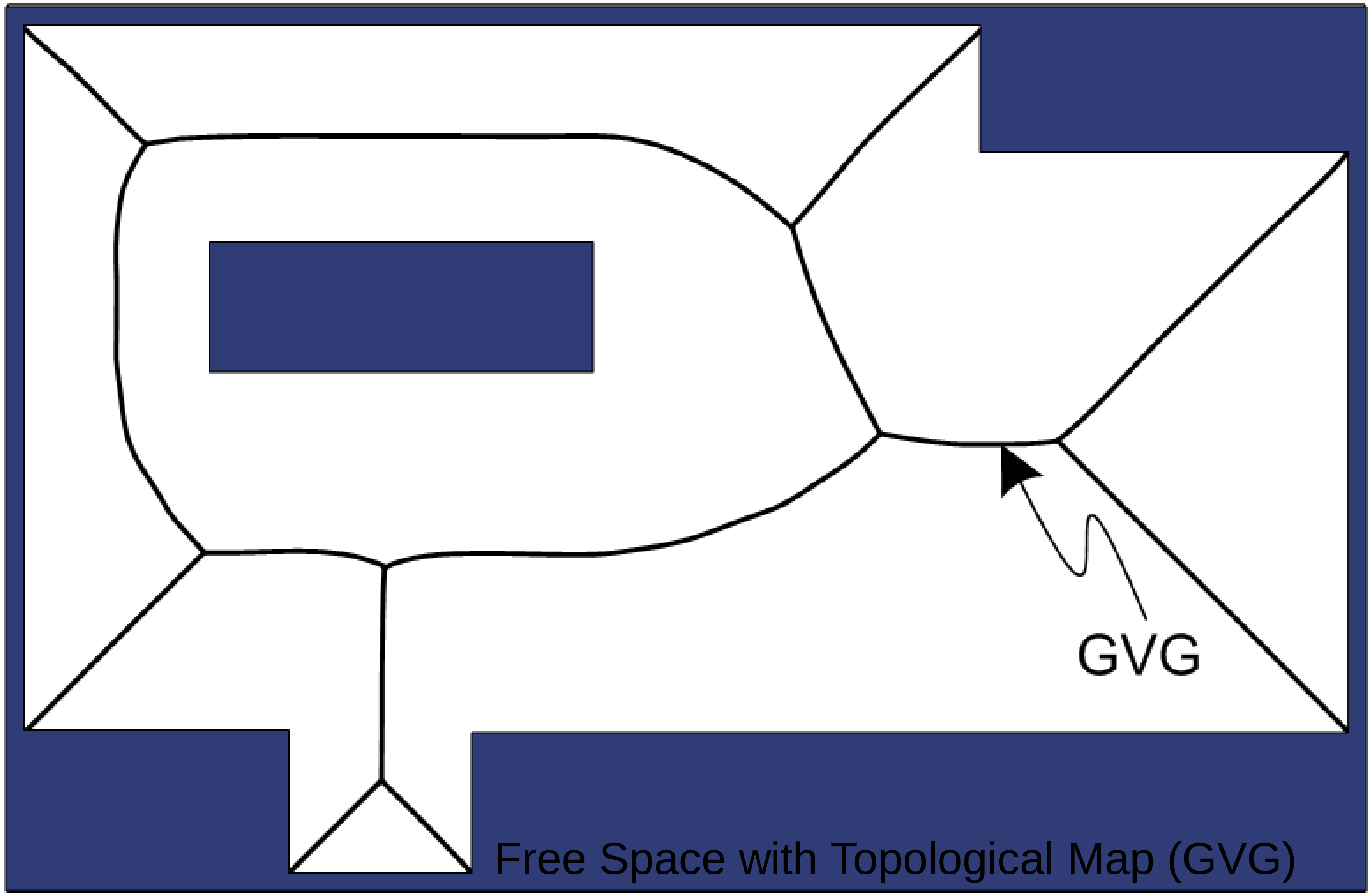
- B. J. Kuipers and Y.-T. Byun. “A robot exploration and mapping strategy based on a semantic hierarchy of spatial representations”. In *Journal of Robotics and Autonomous Systems*, 8: 47-63, 1991.

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.

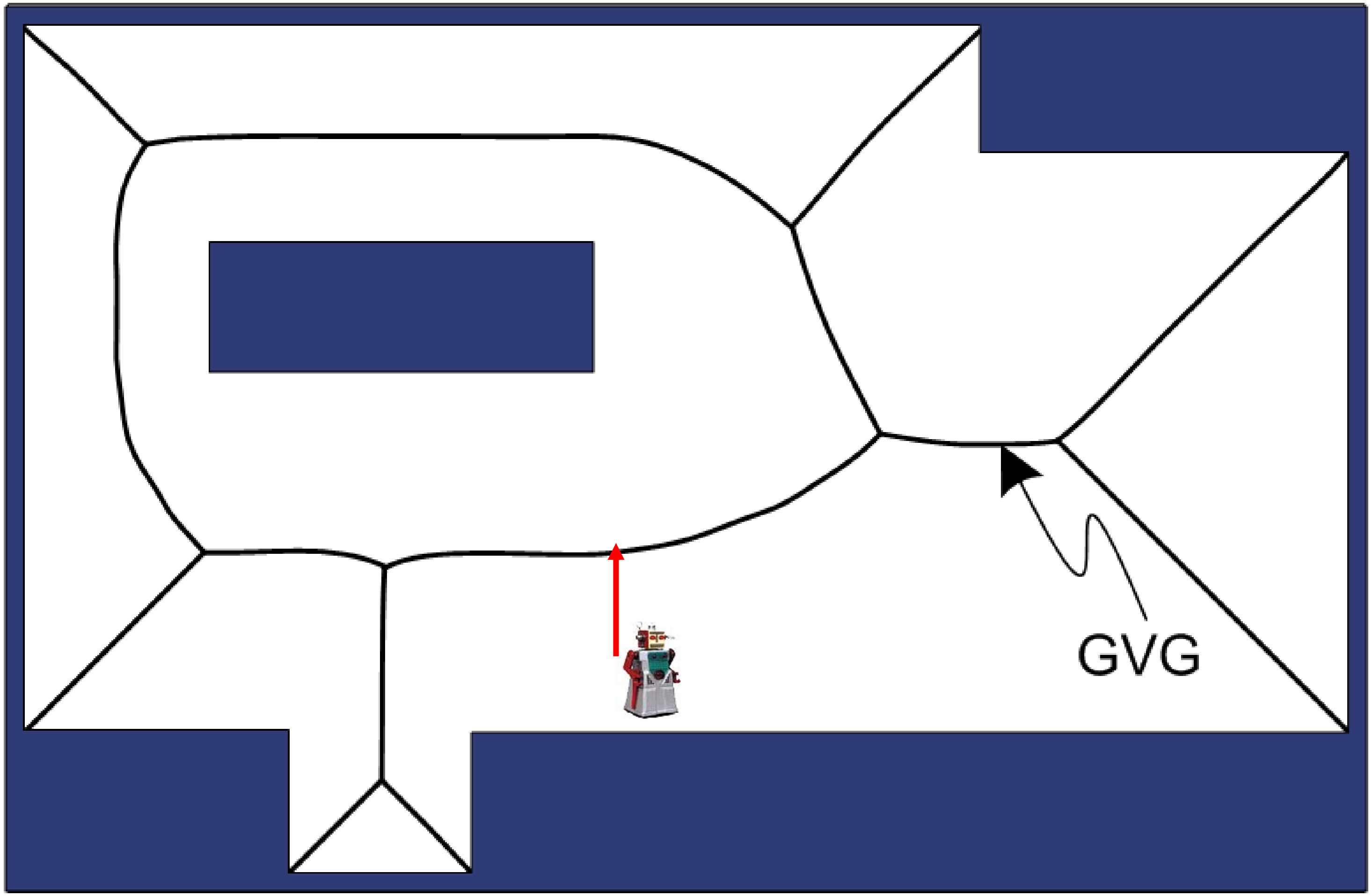
Generalized Voronoi Graph (GVG)



Free Space with Topological Map (GVG)

Generalized Voronoi Graph (GVG)

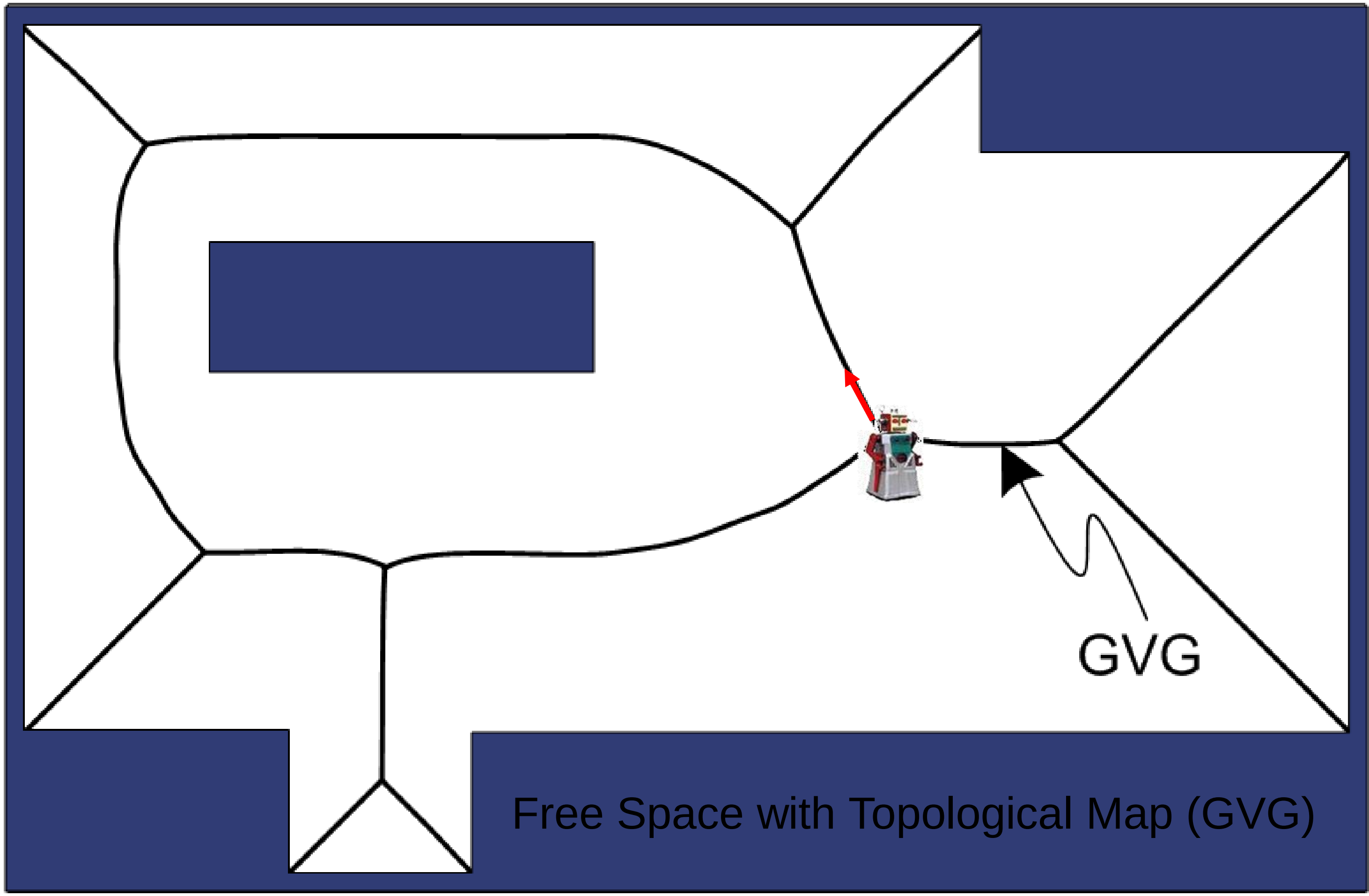
- Access GVG



Free Space with Topological Map (GVG)

Generalized Voronoi Graph (GVG)

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

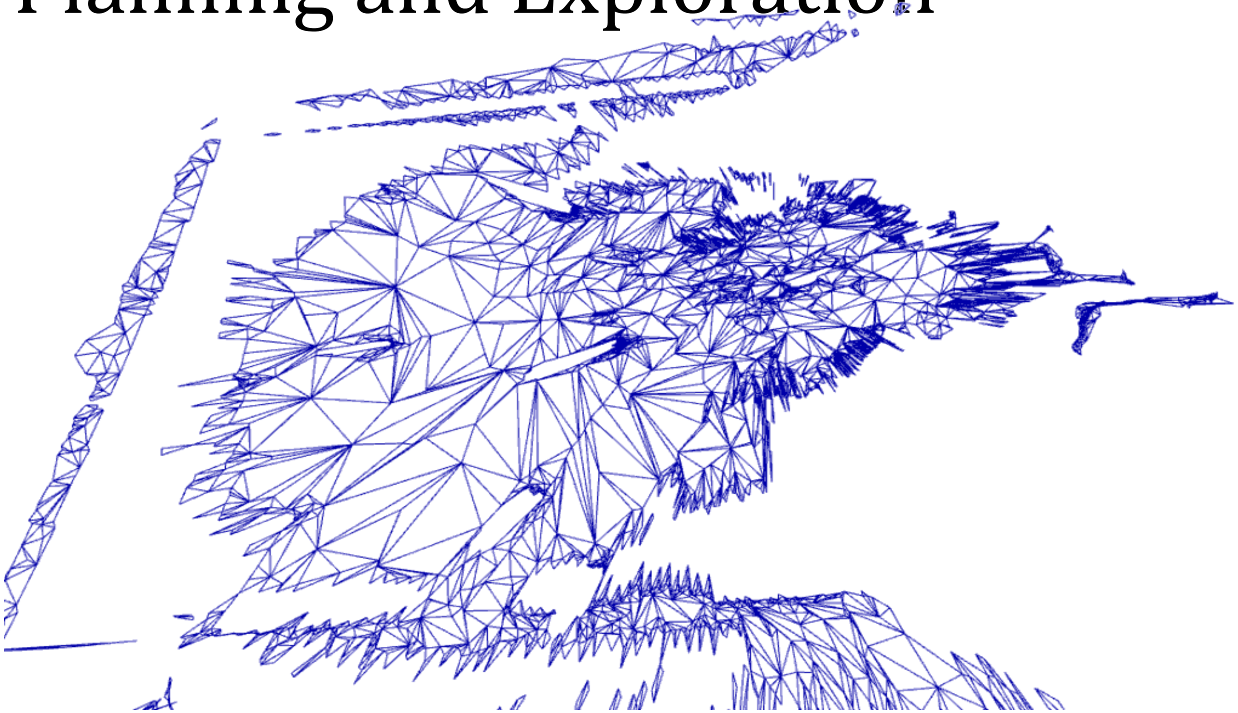


Exploration via Graph Search

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

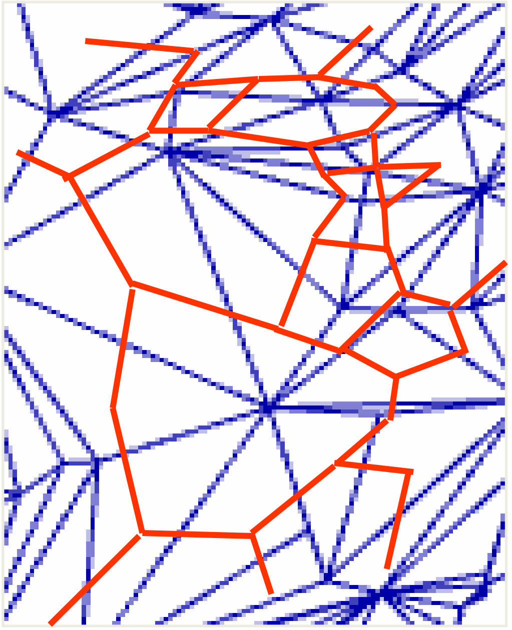
Irregular Triangular Mesh (ITM)

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



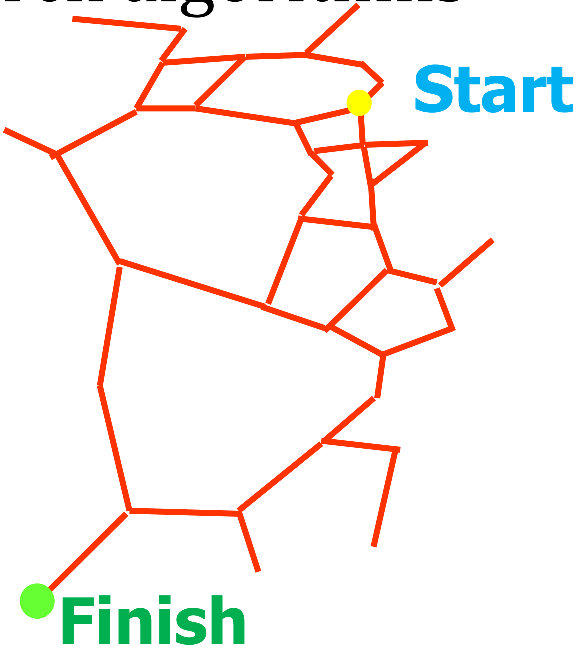
From 2.5D Representation to Topological

- Convert ITM into Connected Graph



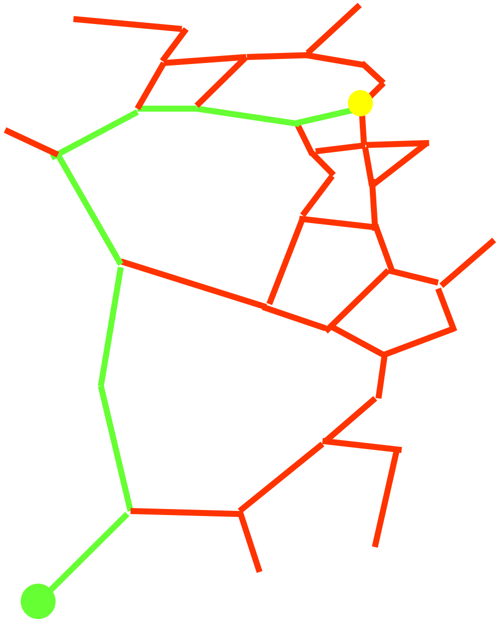
Planning

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



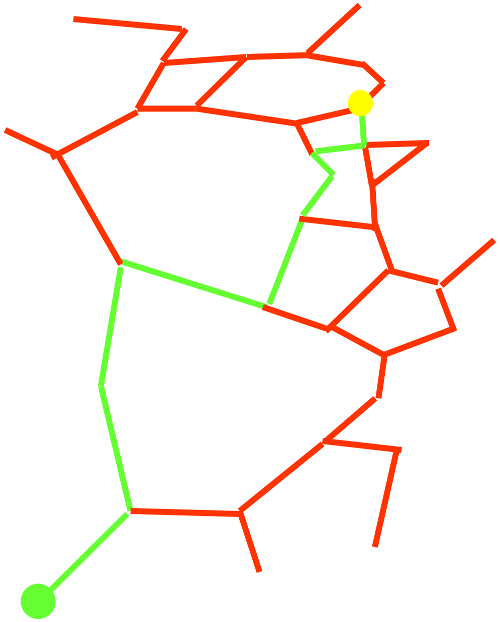
Planning

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



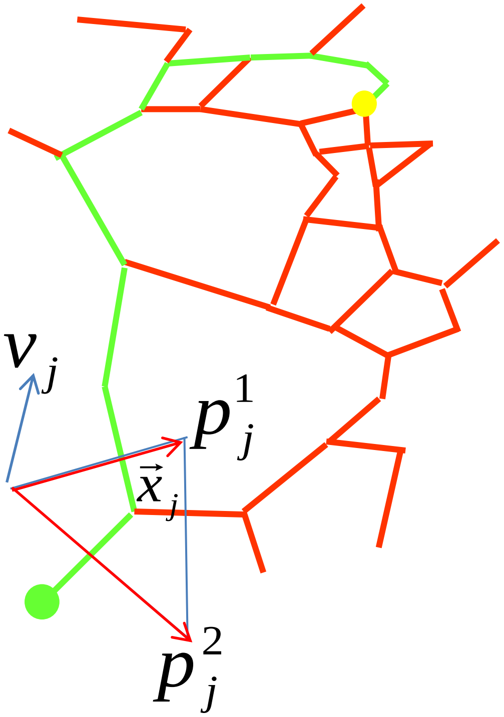
Planning

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



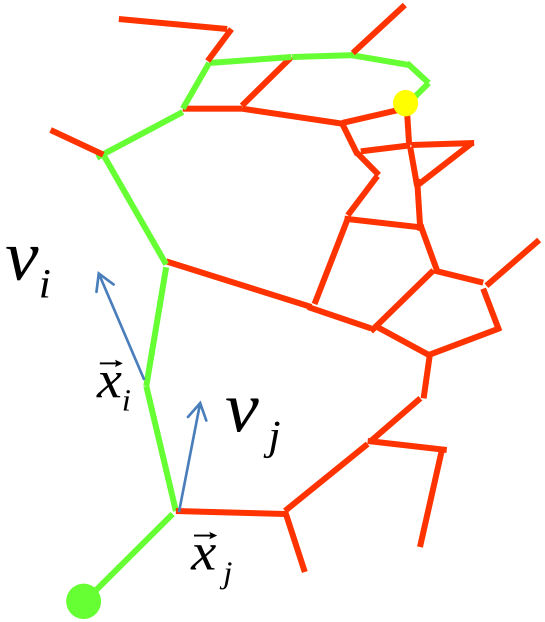
Planning

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



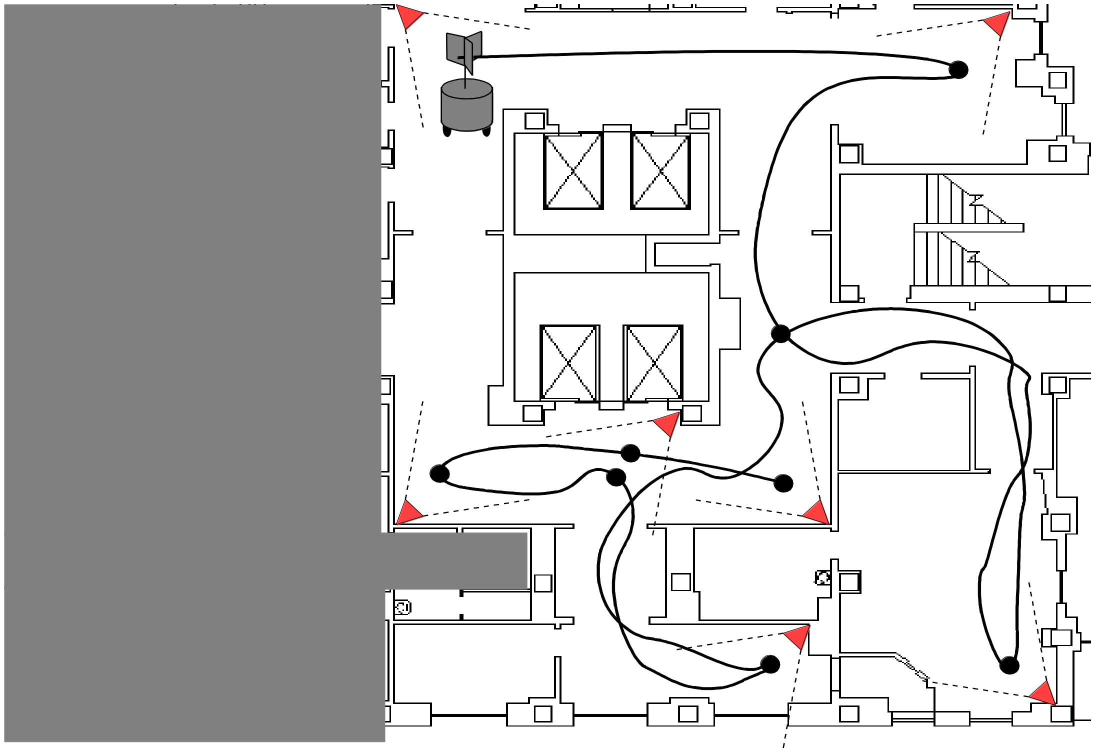
Planning

- 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 Planning Problem

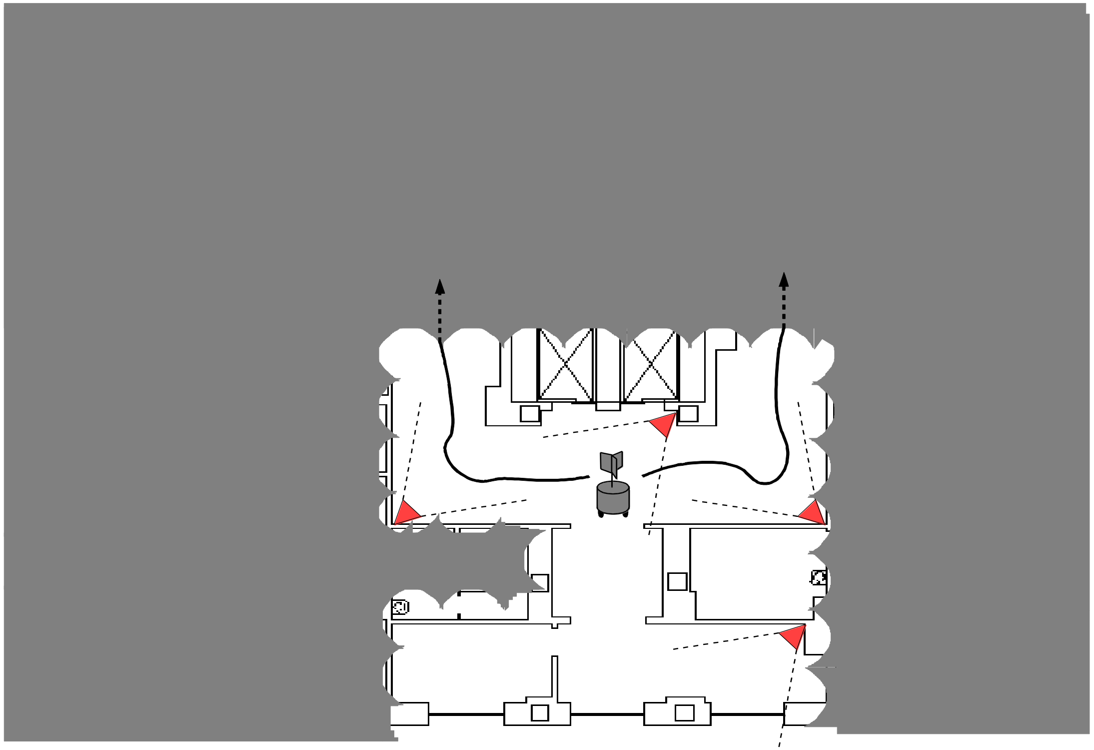
Two fundamental problems for path planning during exploration and mapping:



Exploration Planning Problem

Two fundamental problems for path planning during exploration and mapping:

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



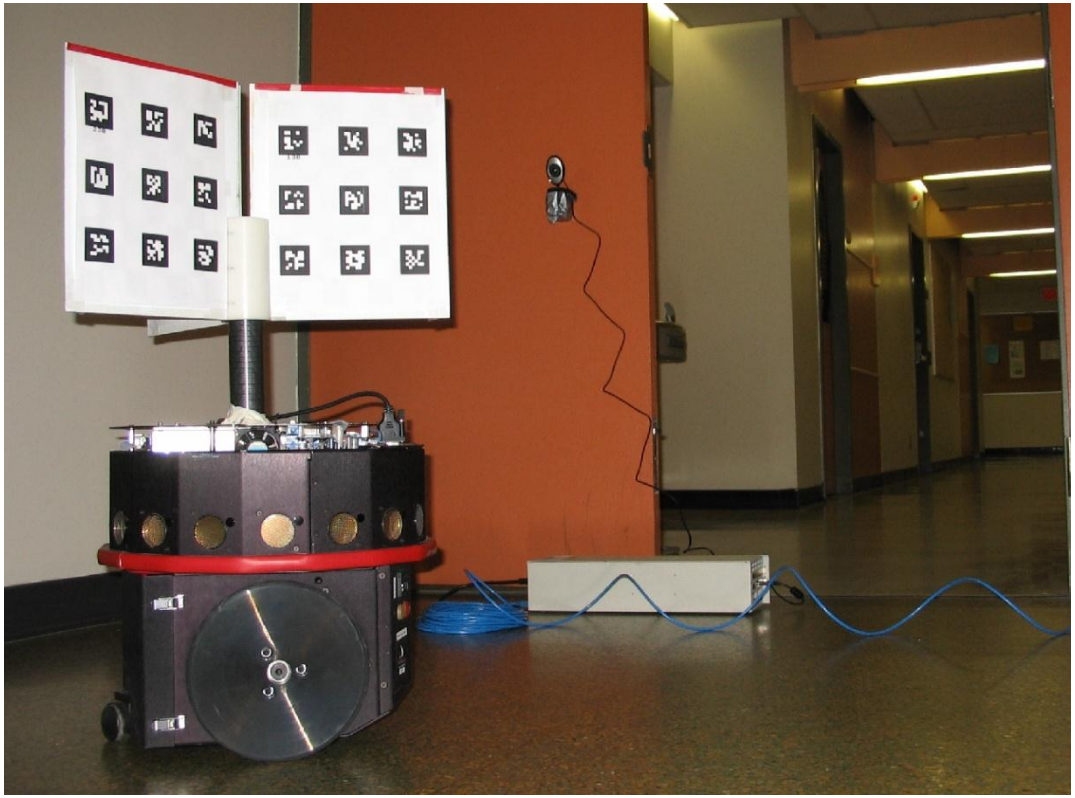
Previous Localization Planning

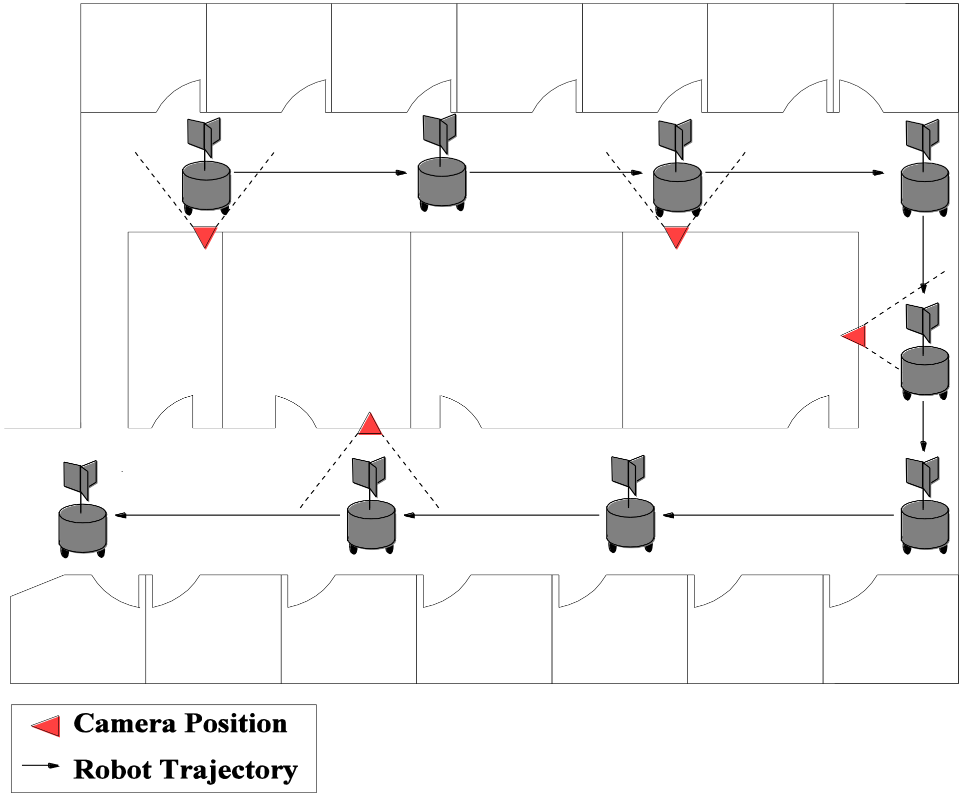
- Reduce measure of map or position entropy
- Variety of graph search planning algorithms (breadth first, A*-search, RRT)
- Evaluate paths with simulation, or Cramer-Rao bounds for expected uncertainty
- e.g. [Fox et al RAS 1998], [Sim and Roy ICRA 2005], [He et al ICRA 2008], [Censi et al ICRA 2008]

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

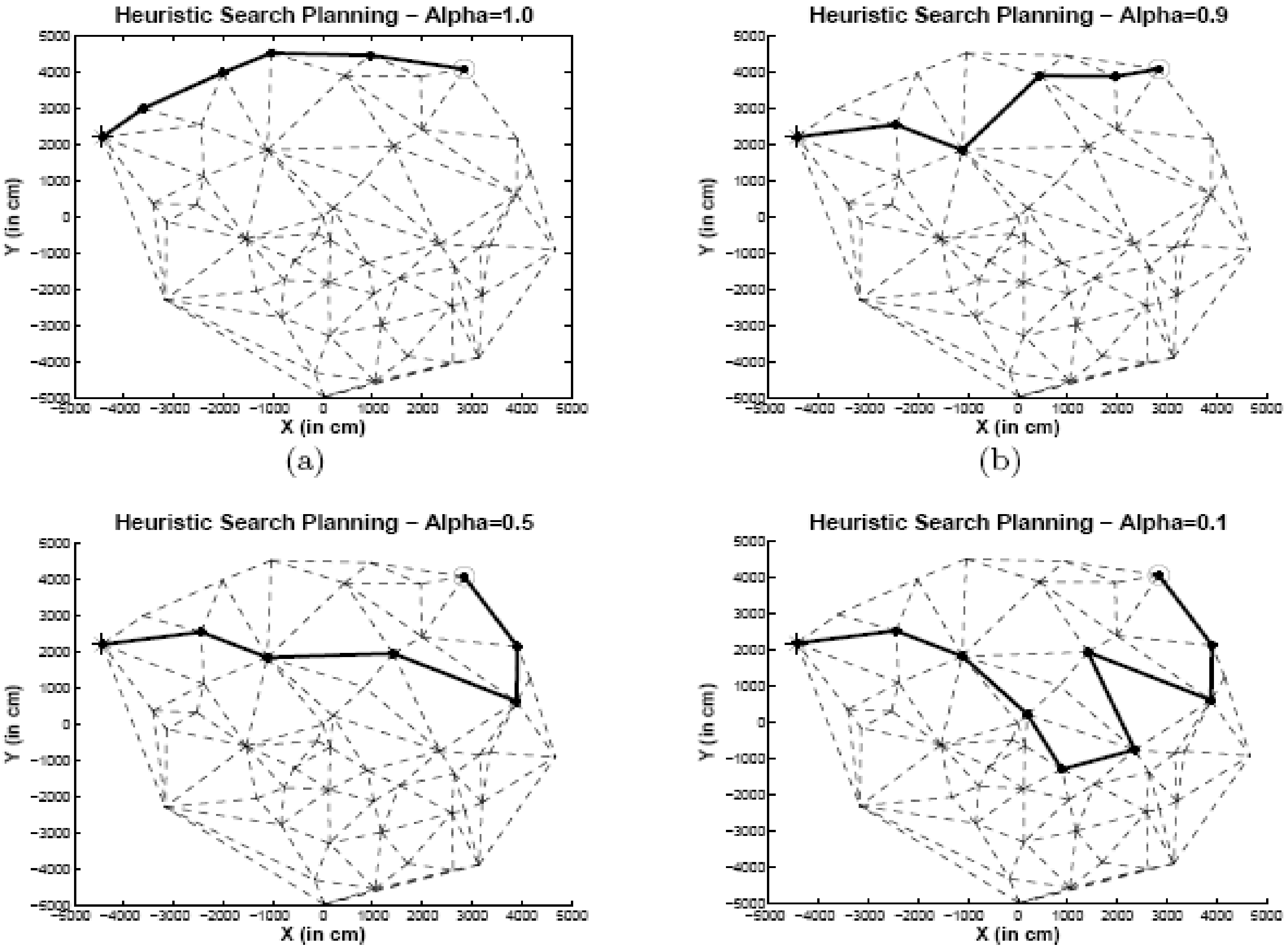
- Decision (exploration vs. exploitation)
- Target Node
- Path Planning through the known graph
  - Work with D. Meger and G. Dudek [IROS 2008]
  - A* based strategy
  - Cost: $C(p) = \omega_d length(p) + \omega_u trace(P(p))$
  - Distance-based "cost-to-go" heuristic function *h* used to compute estimated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



(a) (b)

(c) (d)

Heuristic Search

- Graph search to optimize cost function

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

- 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

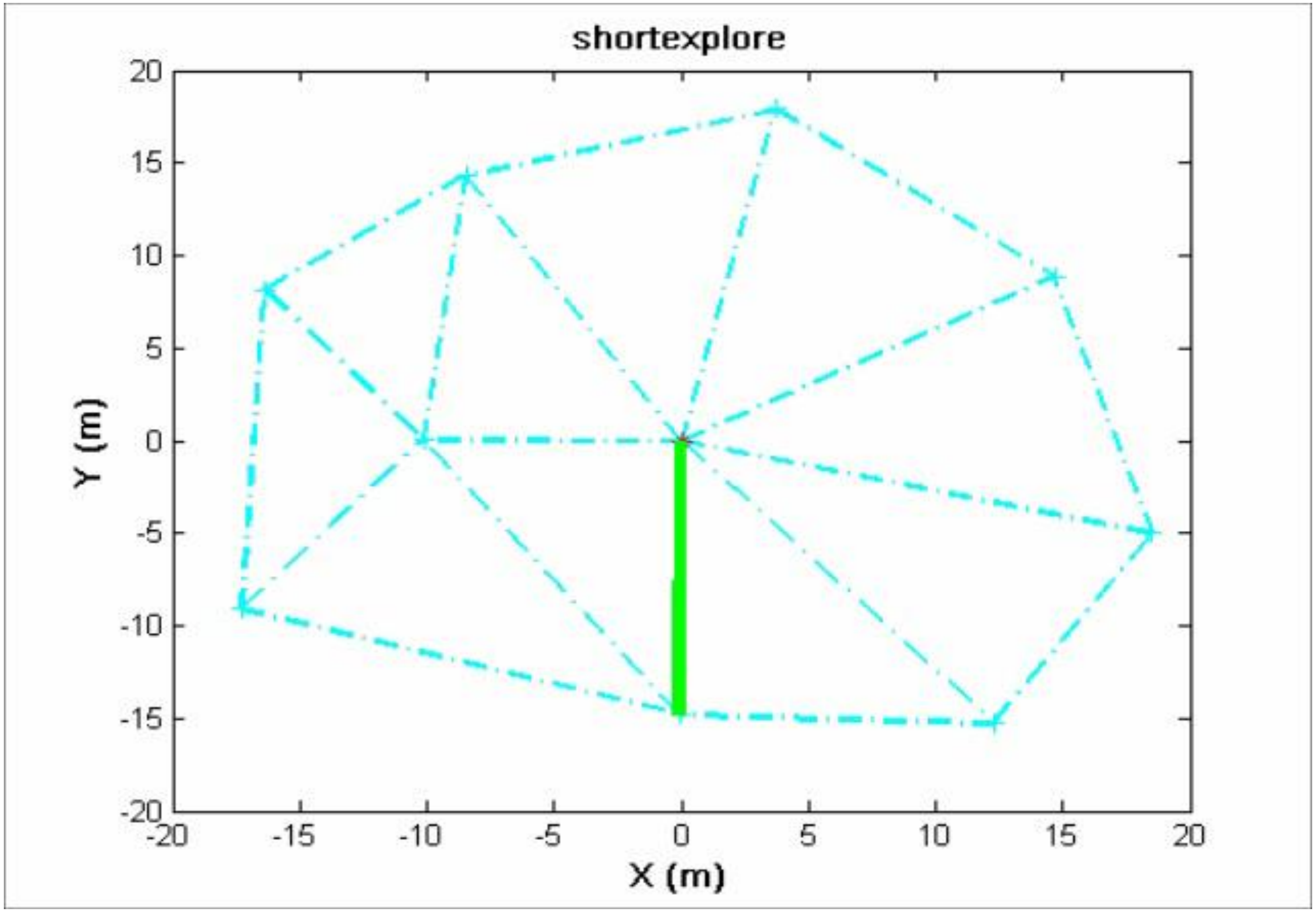
$$C(n) \quad = \quad f(n) + h(n)$$

Estimated cost through n Cost so far Estimated cost to go

Exploration and Uncertainty Reduction

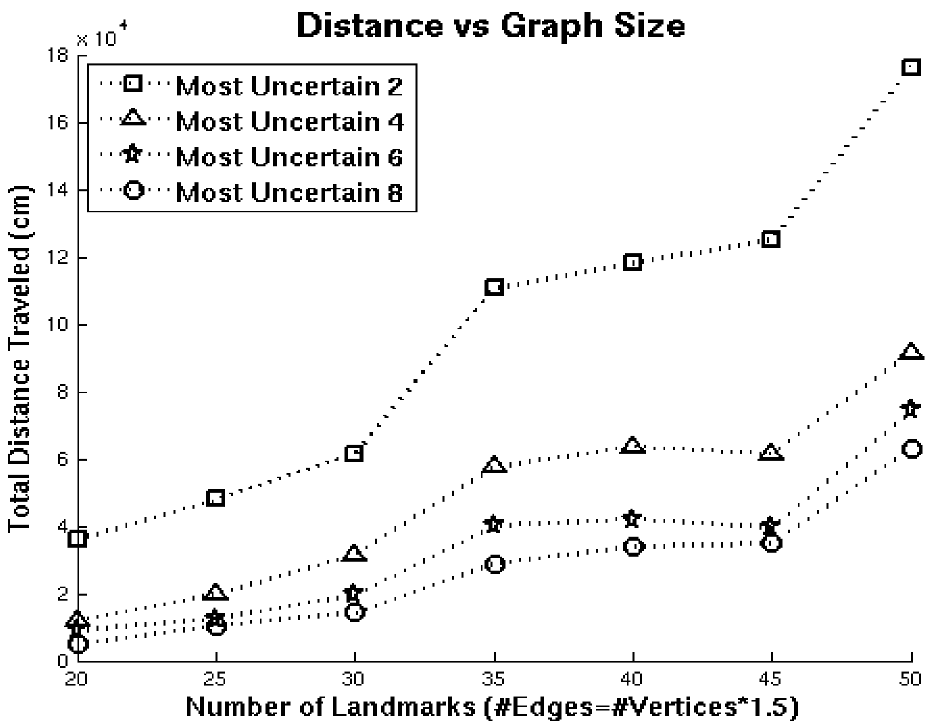
- Decision (exploration vs. exploitation)
- Target Node
- Path Planning through the known graph
- Exploration Strategies
  - One Step Exploration
  - Ear based exploration (submitted to IROS 2012)

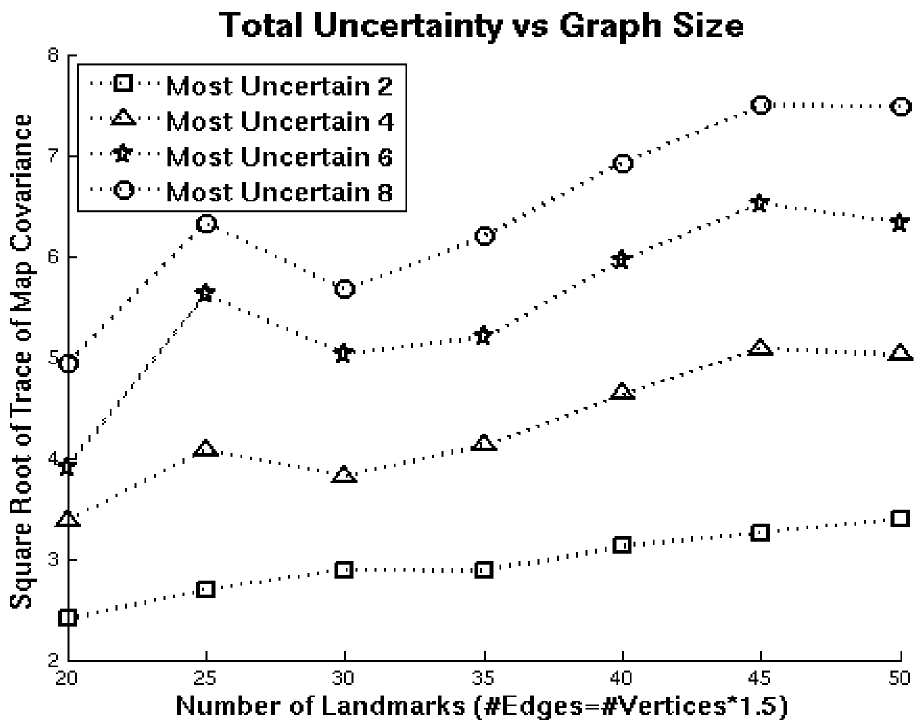
Shortest Node P(exploit)=0.3



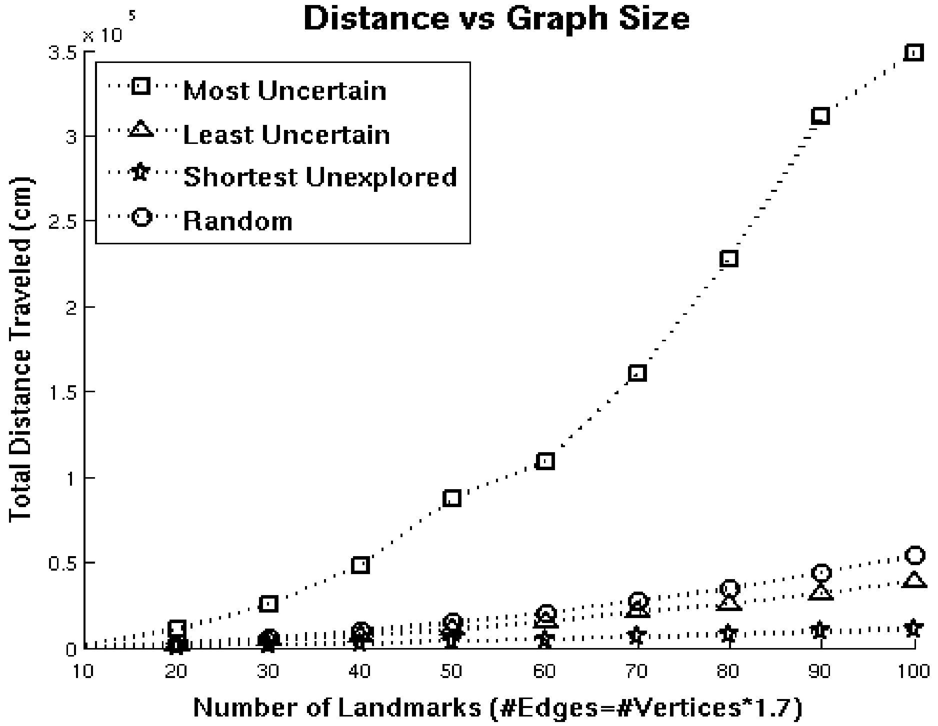
Experimental Results

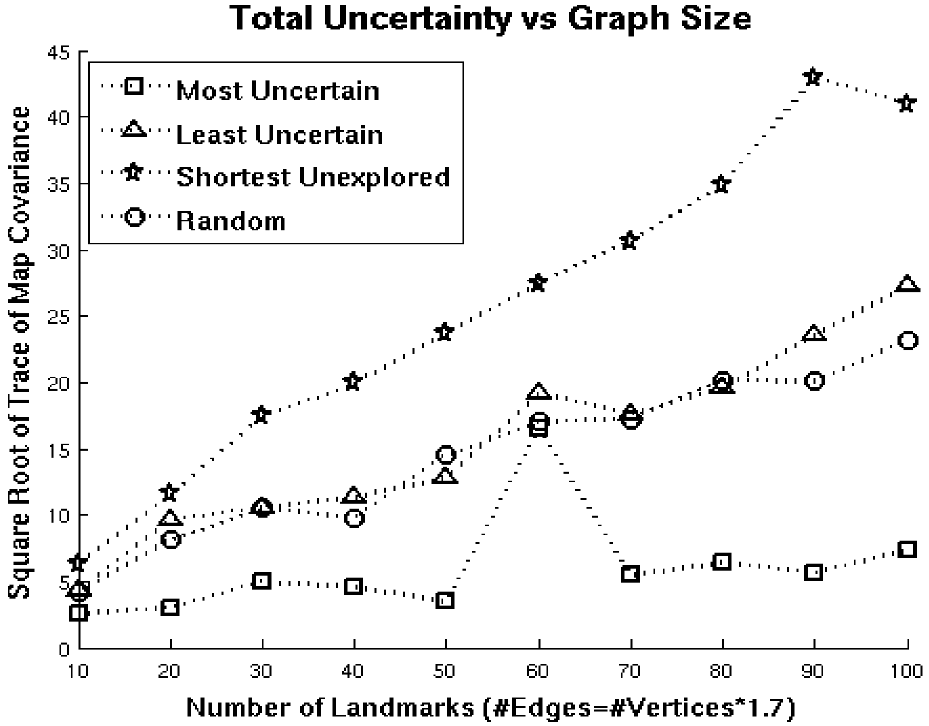
Bounded Uncertainty





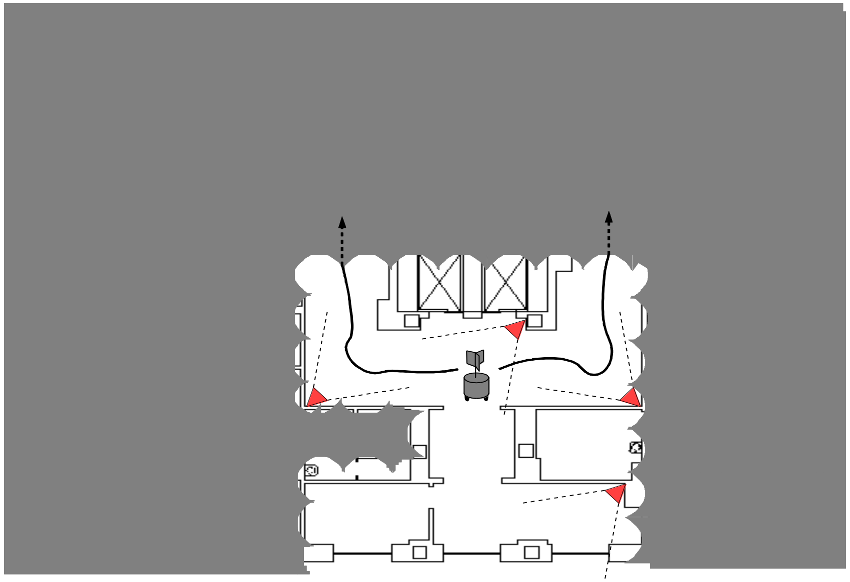
Experimental Results Different Strategies





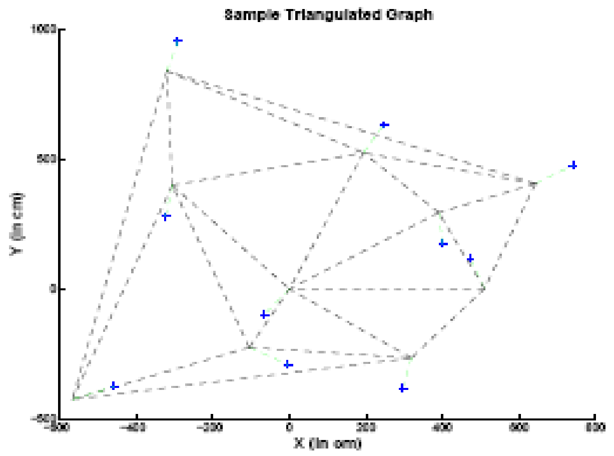
Planning Exploratory Steps

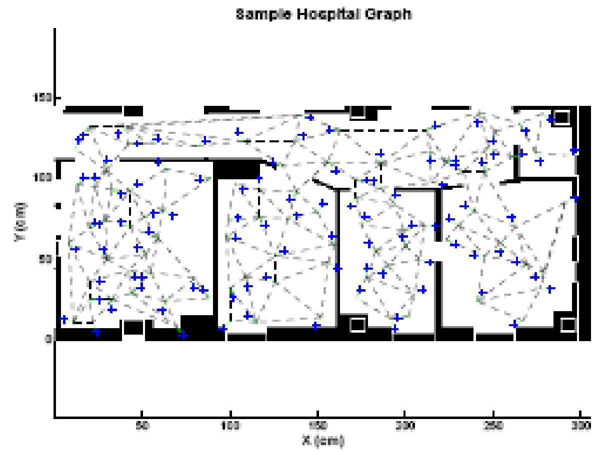
- Choose motion in unexplored space to locate additional camera nodes
- Planner cannot simulate these paths
- Evaluated 2 strategies: 1) nearest camera and 2) a randomly selected camera



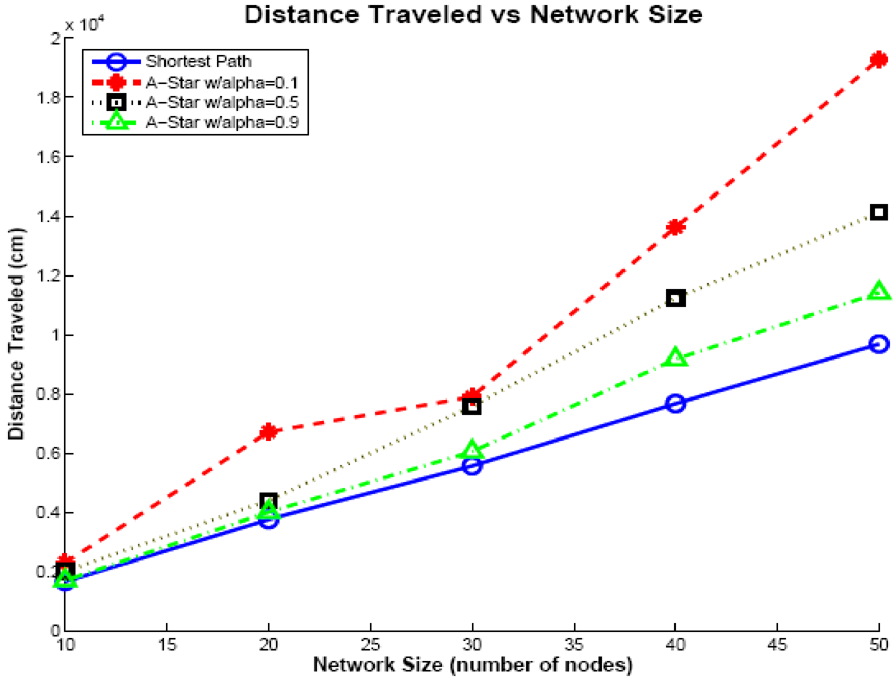
Simulation Results

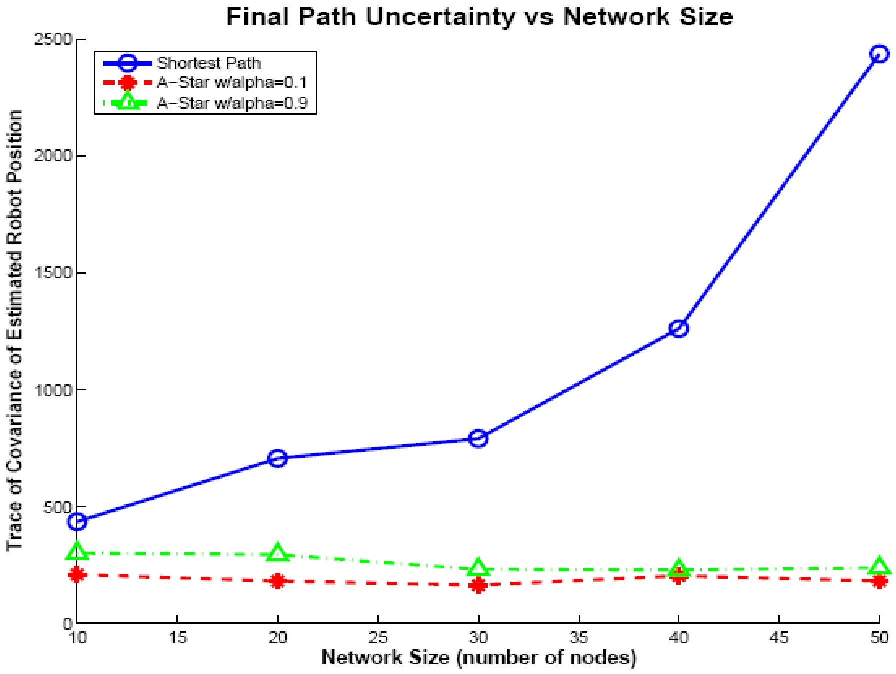
- Compared planners over many trials
- 3 realistic network types (2 shown)
- 3 methods for comparison:
  - Depth-first
  - Return to origin
  - Return to nearest explored



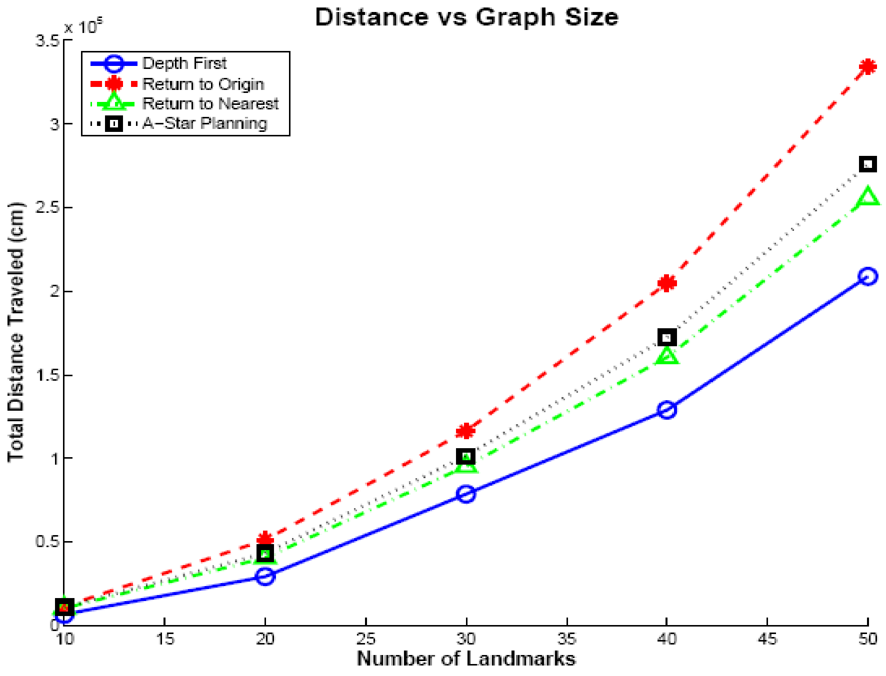


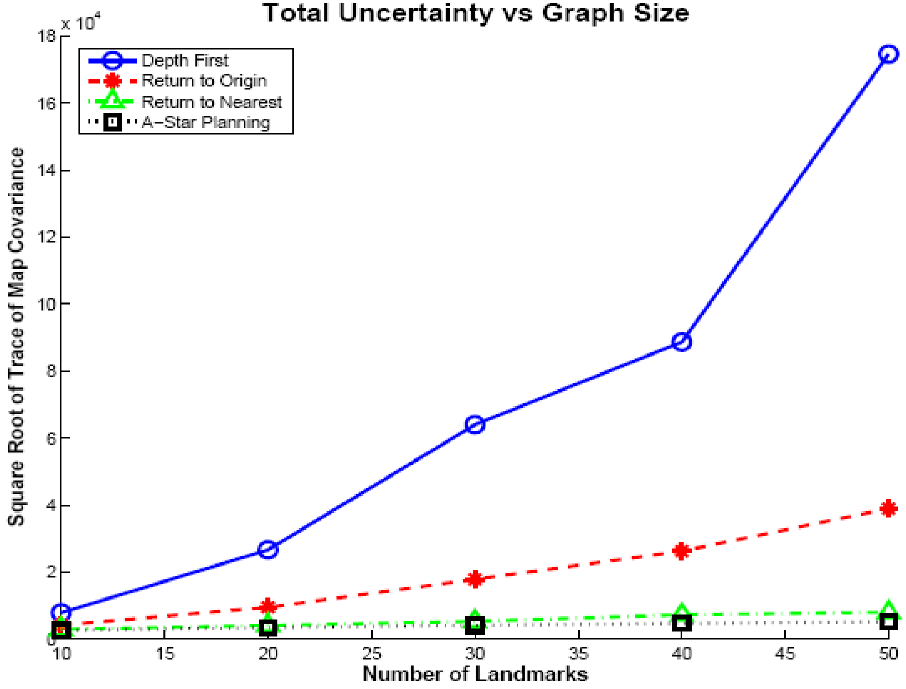
Simulated Relocalization Results


Distance Traveled vs Network Size


Final Path Uncertainty vs Network Size

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.
- B. Yamauchi, “Frontier-based exploration using multiple robots”, In Second International Conference on Autonomous Agents, Minneapolis, MN, 1998, pp. 47–53.
- Makarenko, A.A. Williams, S.B. Bourgault, F. Durrant-Whyte, “An experiment in integrated exploration”, In IEEE/RSJ International Conference on Inte.lligent Robots and System, vol.1, pp 534-539, 2002.
- 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.
- R. Sim and N. Roy, “Global a-optimal robot exploration in slam”. In *International Conference on Robotics and Automation, pp. 661– 666, 2005*.
- 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?