Introduction to Mobile Robotics

Multi-Robot Exploration

Wolfram Burgard
Cyrill Stachniss
Giorgio Grisetti
Maren Bennewitz
Christian Plagemann

Motivation

Whenever teams of mobile robots are used, the question arises, how to control them in order to optimze the performance of the whole team.

- Exploration
- Path planning
- Action planning …

Exploration: The Problem

Given:

- **Unknown environment**
- **Team of robots**

Task:

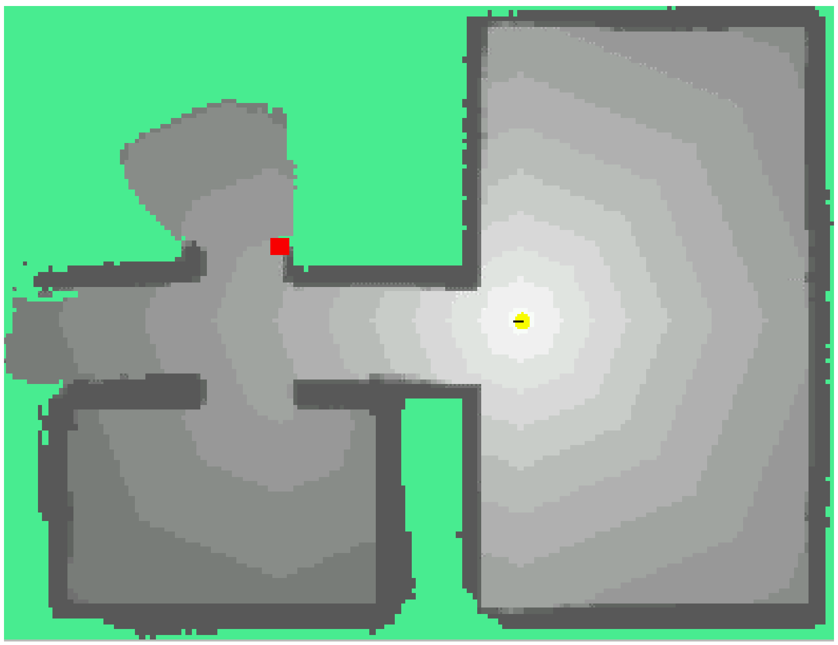
- **Coordinate the robots to efficiently learn a complete map of the environment**

Complexity:

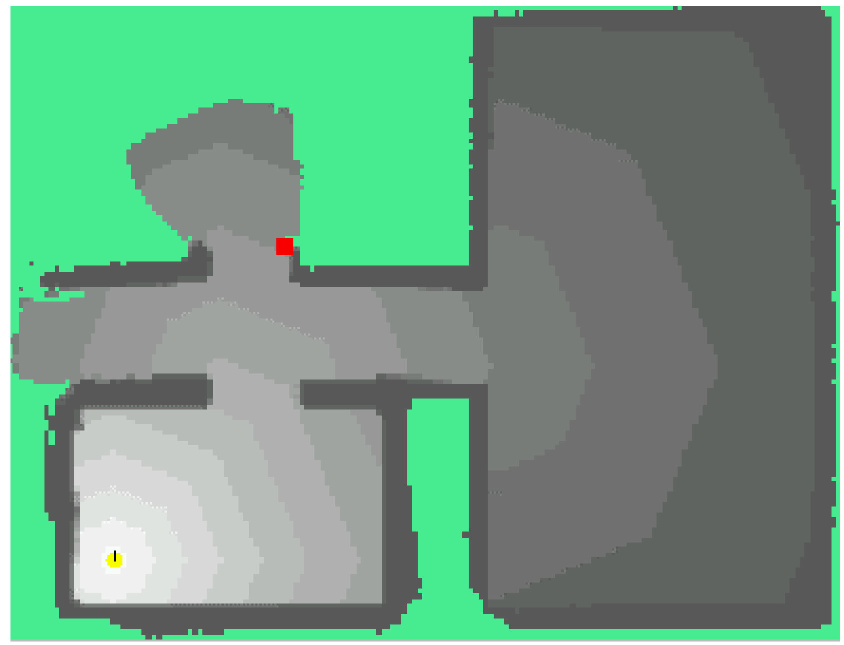
- **NP-hard for single robots in known, graph-like environments**
- **Exponential in the number of robots**

Example

Robot 1:



Robot 2:



Levels of Coordination

- No exchange of information
- Implicit coordination: Sharing a joint map
  [Yamauchi et.al, 98]
  - Communication of the individual maps and poses
  - Central mapping system
- Explicit coordination: Determine better target locations to distribute the robots
  - Central planner for target point assignment

Idea

1. Choose target locations at the frontier to the unexplored area by trading off the expected information gain and travel costs.
2. Reduce utility of target locations whenever they are expected to be covered by another robot.
3. Use on-line mapping and localization to compute joint map.

The Coordination Algorithm (informal)

1. **Determine the frontier cells.**
2. **Compute for each robot the cost for reaching each frontier cell.**
3. **Choose the robot with the optimal overall evaluation and assign the corresponding target point to it.**
4. **Reduce the utility of the frontier cells visible from that target point.**
5. **If there is one robot left go to 3.**

The Coordination Algorithm

1. Determine the set of frontier cells
2. Compute for each robot i the cost $V^i_{x,y}$ for reaching each frontier cell
3. Set the utility $U_{x,y}$ of all frontier cells to 1
4. While there is one robot left without a target point
   (a) Determine a robot i and a frontier cell $\langle x, y \rangle$ which satisfy

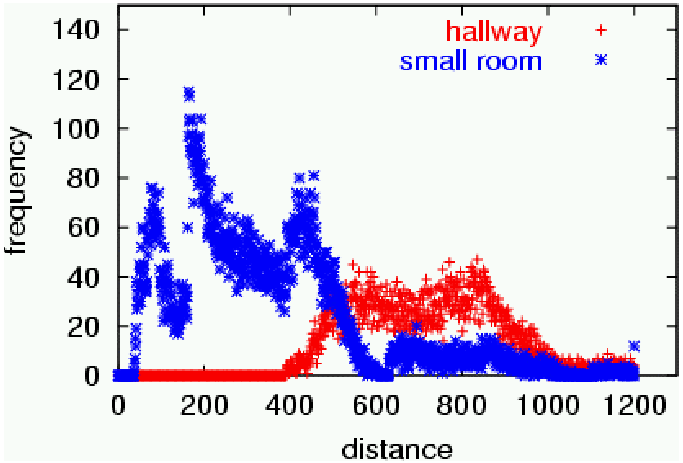
   $$(i, \langle x, y \rangle) = \underset{(i', \langle x', y' \rangle)}{\operatorname{argmax}} \; U_{x',y'} - V^{i'}_{x',y'}$$

   (b) Reduce the utility of each target point $\langle x', y' \rangle$ in the visibility area according to

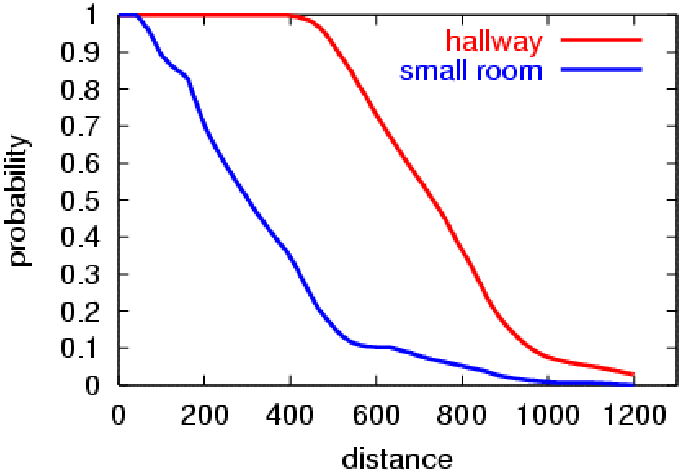
   $$U_{x',y'} \leftarrow U_{x',y'} \cdot (1 - P(|| \langle x, y \rangle - \langle x', y' \rangle ||))$$

Estimating the Visible Area

Distances measured during exploration:

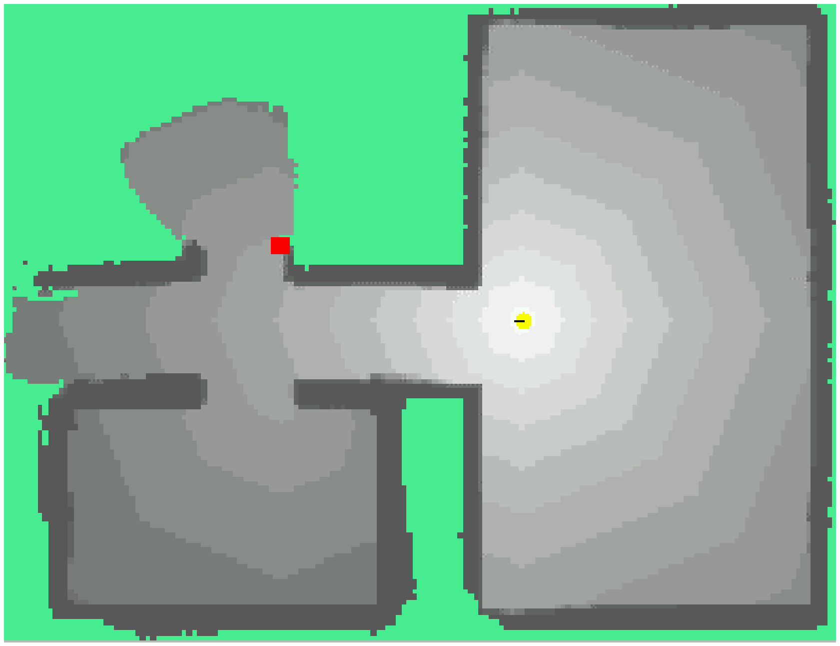


Resulting probability of measuring at least distance d:

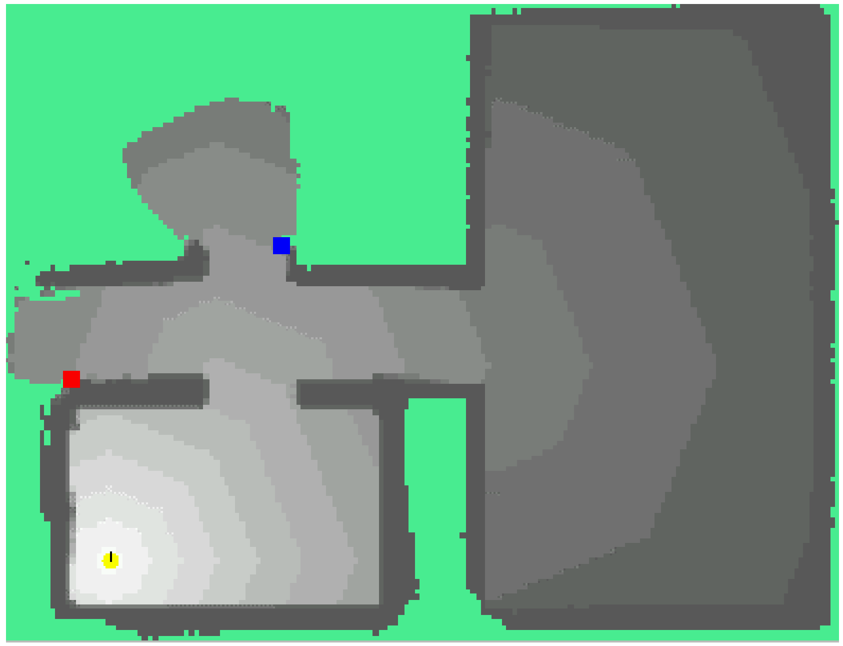


Application Example

First robot:

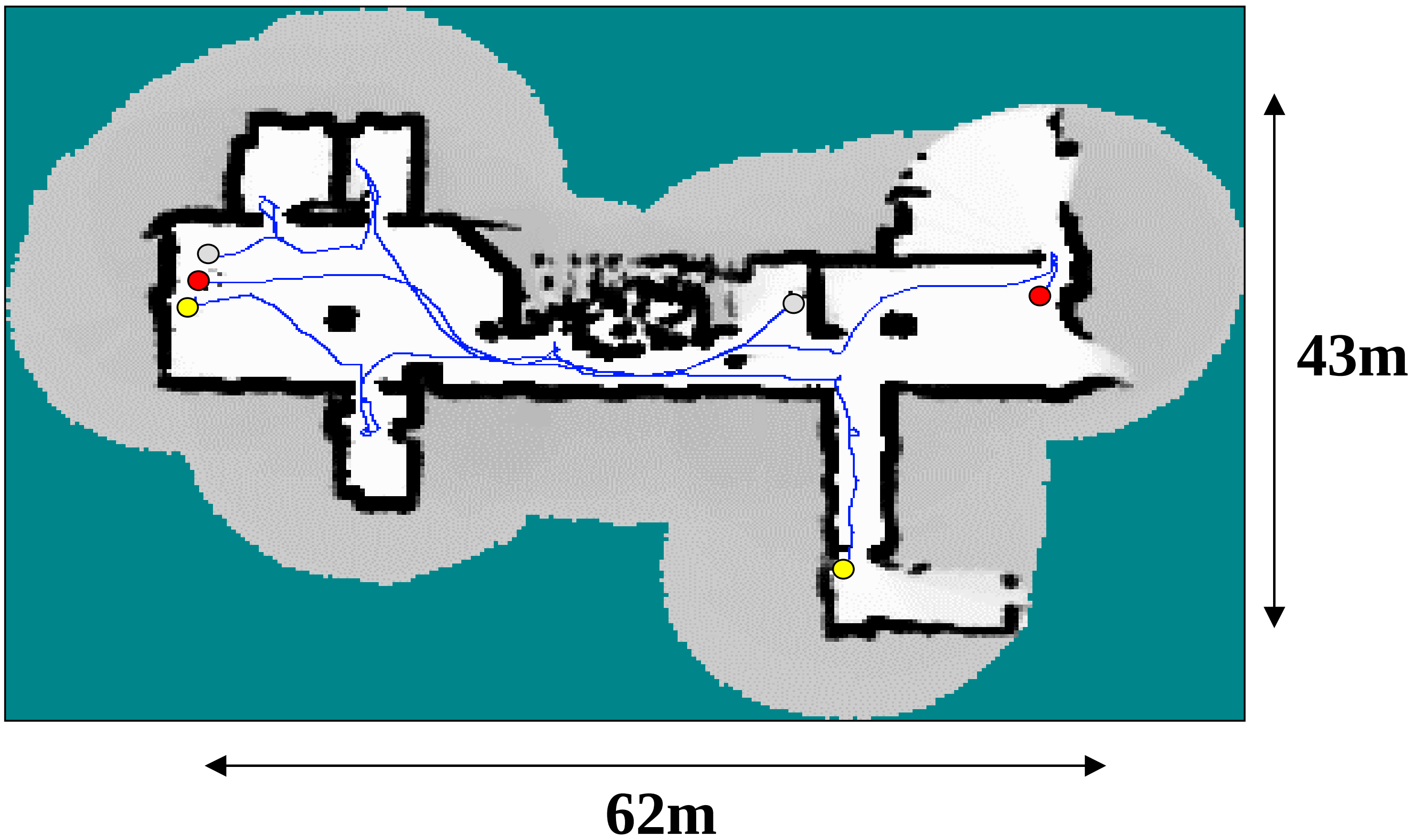


Second robot:

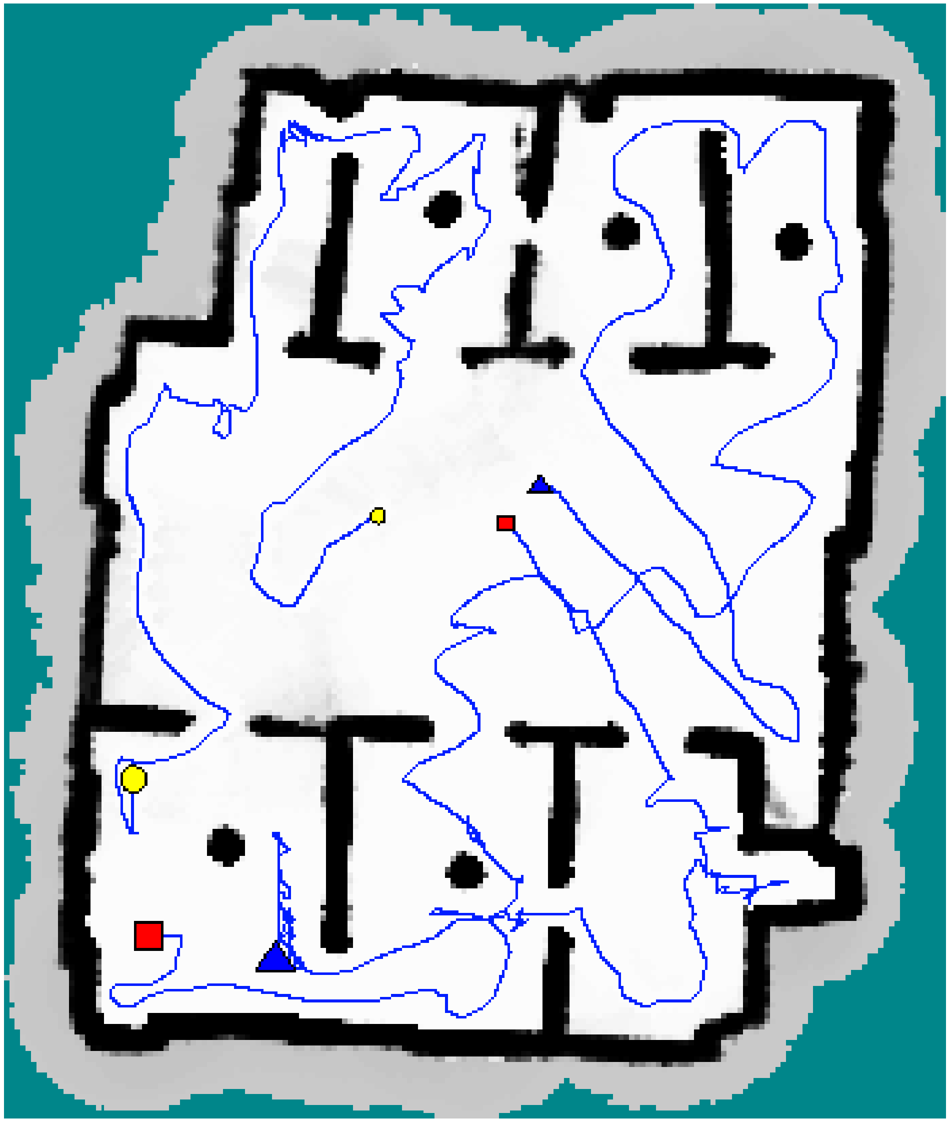


Multi-Robot Exploration and Mapping of Large Environments

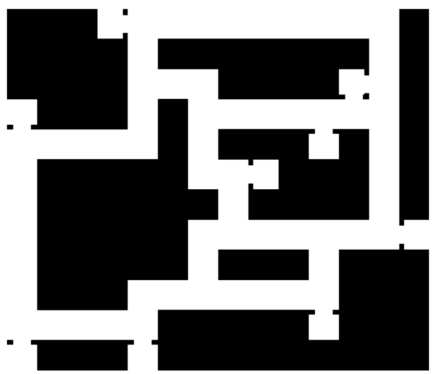
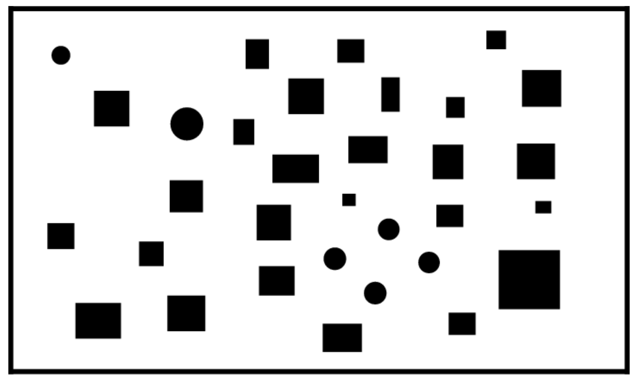
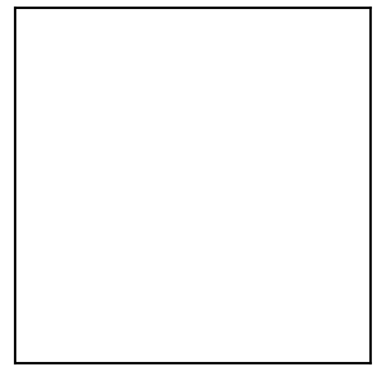
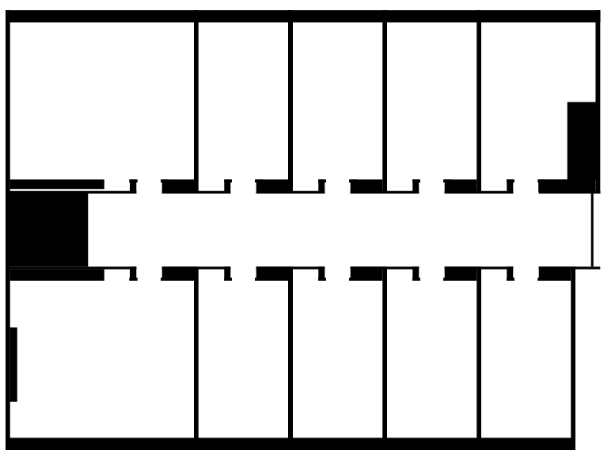
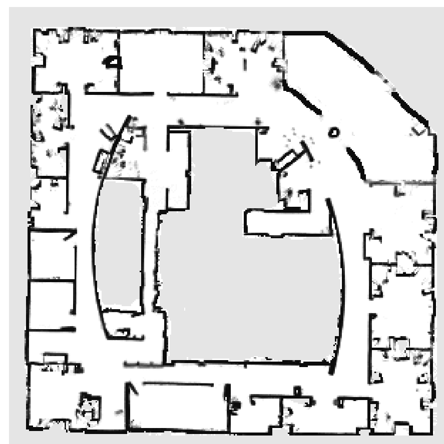
Resulting Map (constructed in 8 minutes!)



Another Application

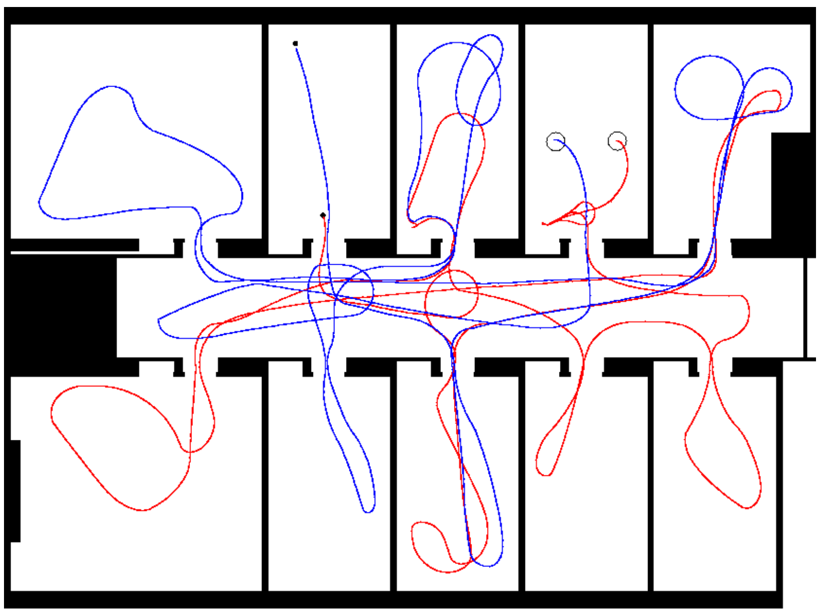


Maps Considered

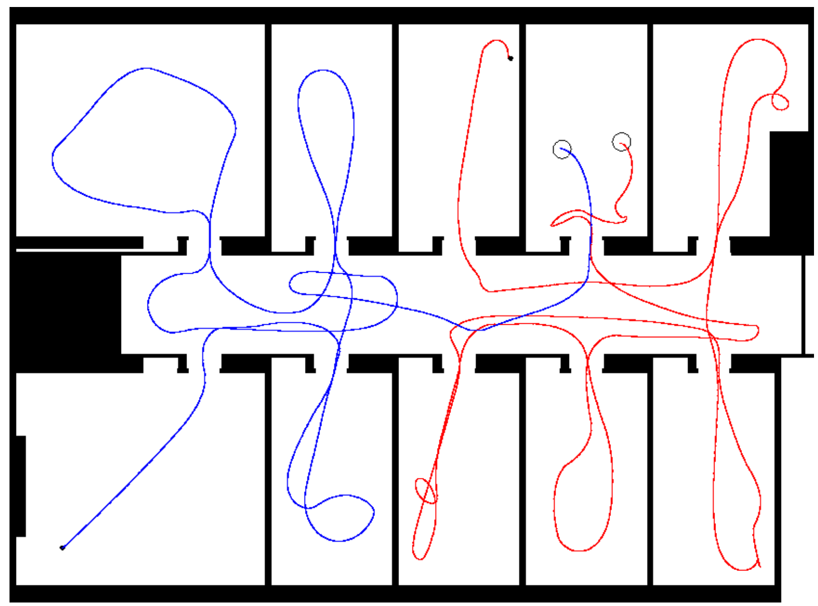






Typical Trajectories

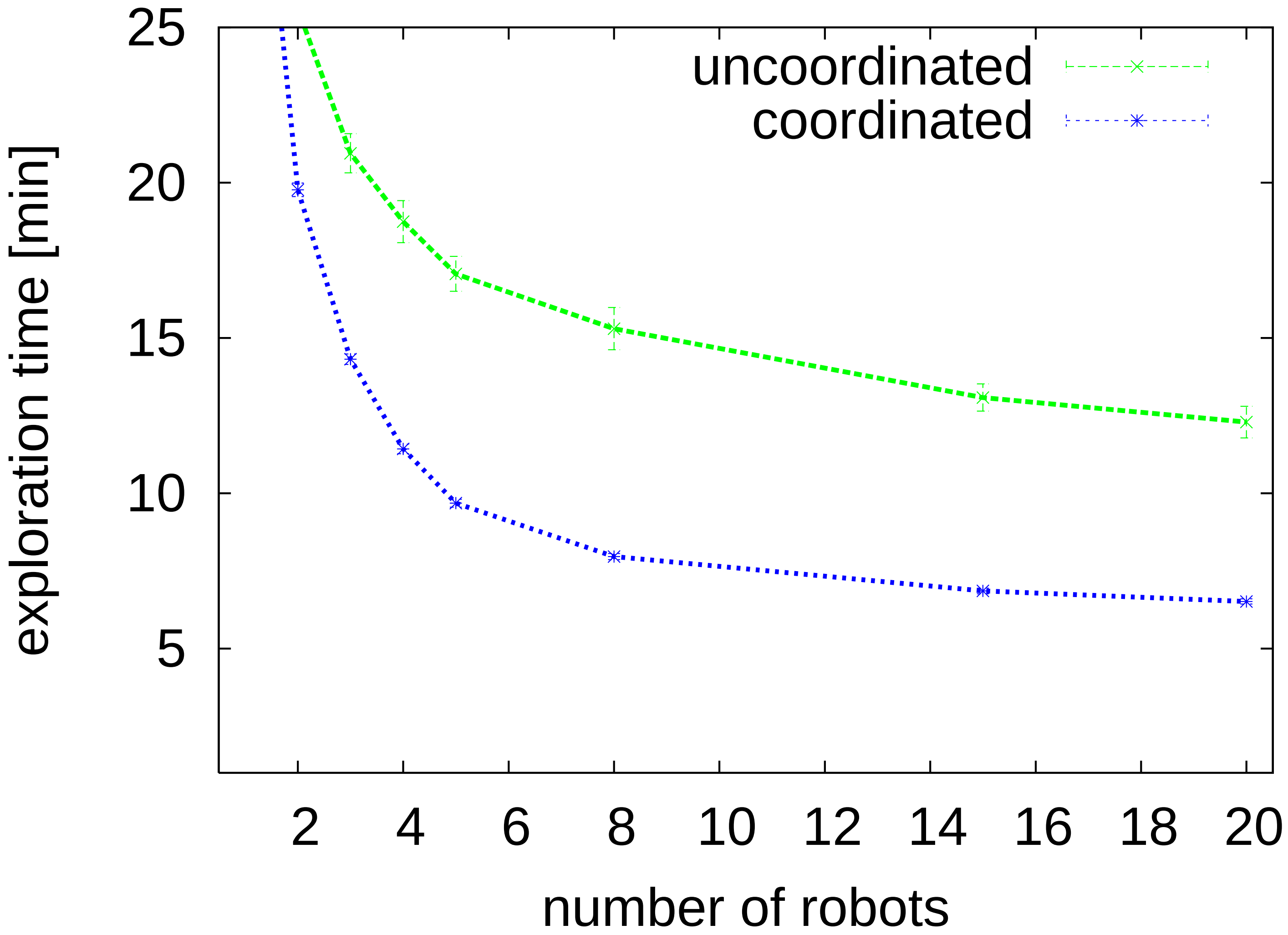
Implicit coordination:



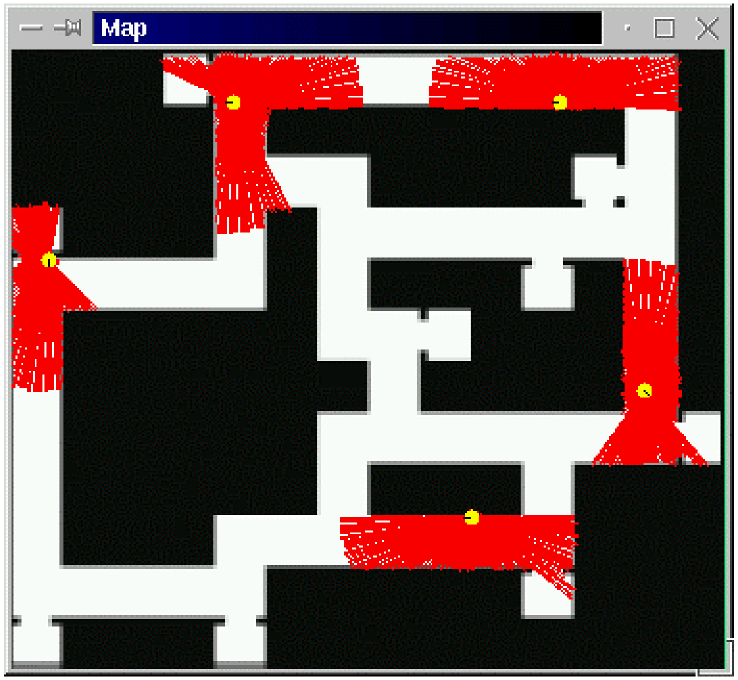
Explicit coordination:

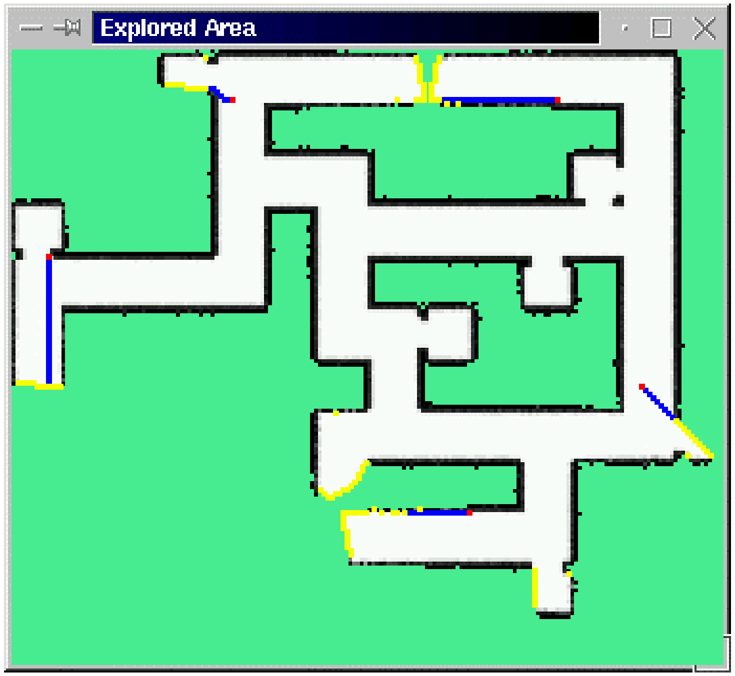


Exploration Time



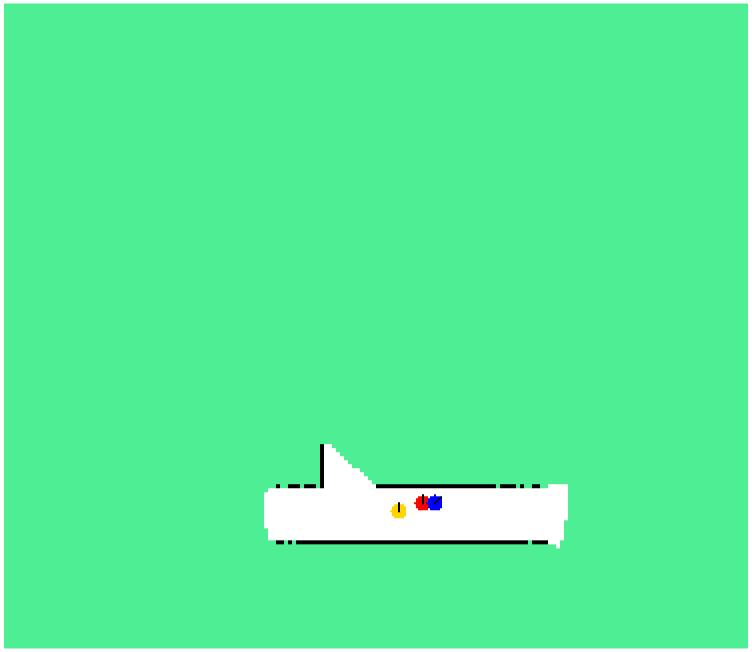
The Simulation Tool



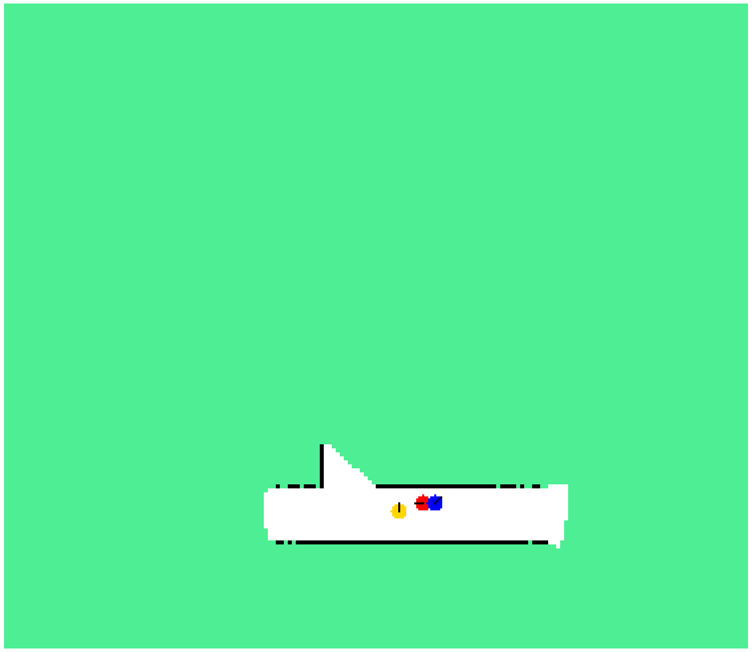


Example

Implicitly coordinated:

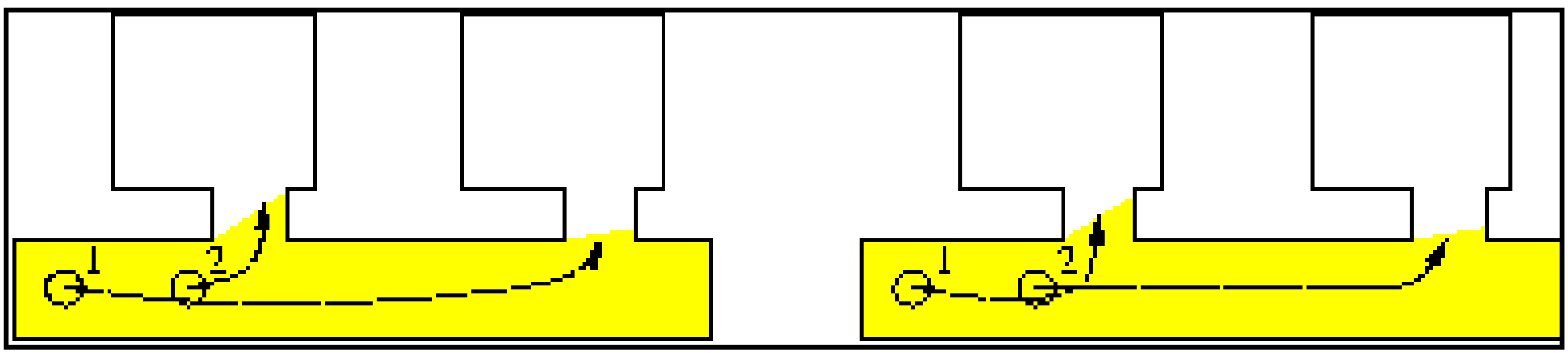


Explicitly coordinated:



Optimizing Assignments

- The current system performs a greedy assignment of robots to target locations



- What if we optimize the assignment?

Optimizing Assignment Algorithm

Algorithm 2 Goal selection determining the best assignment over all permutations.

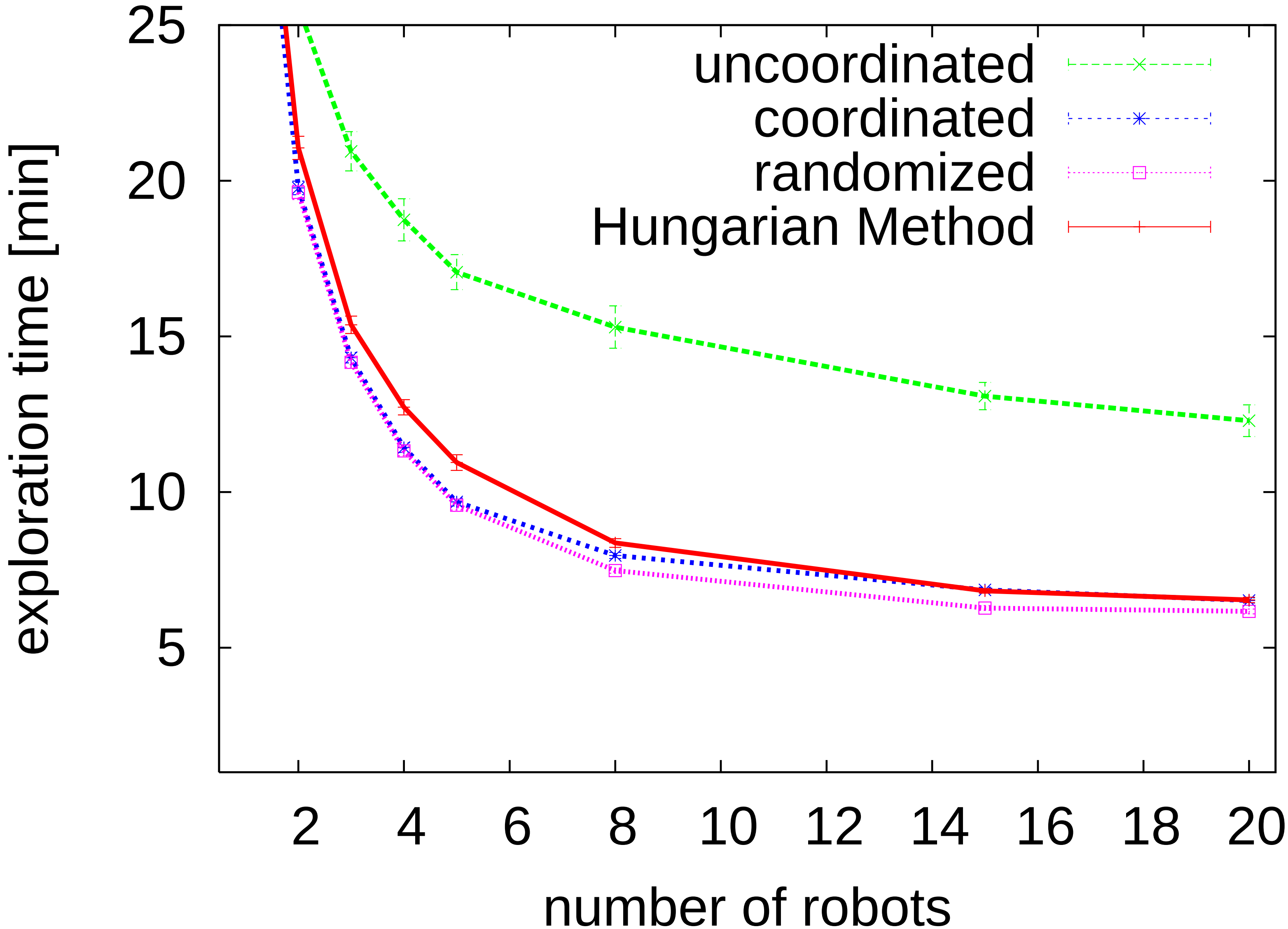
1: Determine the set of frontier cells.
2: Compute for each robot i the cost V_t^i for reaching each frontier cell.
3: Determine target locations $t_1, \ldots, t_n$ for the robots $i = 1, \ldots, n$ that maximizes the following evaluation function: $\sum_{i=1}^{n} U(t_i \mid t_1, \ldots, t_{i-1}, t_{i+1}, \ldots, t_n) - \beta \cdot (V_{t_i}^i)^2$.

Other Coordination Techniques

- Hungarian Method:
  - Optimal assignment of job to machines given a fixed cost matrix.
  - Similar results that the presented coordination technique.

- Market economy-guided approaches:
  - Robots trade with targets.
  - Computational load is shared between the robots

Exploration Time



Summary on Exploration

- Coordination technique that distributes the robots over the environment.
- Considers the cost of an action and the expected utility of reaching the corresponding frontier (target location)
- Has been implemented and tested on real robots.
- Significantly reduces the overall exploration time compared to previous approaches.

Open Problems

- Unknown starting locations
- Exploration under position uncertainty
- Limited communication abilities
- Efficient exchange of information
- ...