Coordinated Multi-Robot Exploration

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AIS in Freiburg

- Robot navigation and coordination
- State estimation and models
- Interaction
- Adaptive techniques
- Applications of mobile robots
- Autonomous systems
- Multi-robot control
- ...

Probabilistic Robotics
Robot Projects: Interactive Tour-guides

Rhino:

Albert:

Minerva:
Platforms
Mapping the MIT Kilian Court
Mapping the MIT Kilian Court
Robot Projects: Acting in the Three-dimensional World

Herbert:

Zora:

Groundhog:
Multi-Level Surface Maps

- Map size: 195 by 146 m
- Cell resolution: 10 cm
- Number of data points: 20,207,000
Large Scale MLS Map with Multiple Nested Loops

- 374 local MLS maps
- 68,162,000 data points
- area of 300x250 meters
- 5 nested loops with a length of ~2,300m
- cell size of 50cm x 50cm.
- requires 55 MB of memory for storage
Projects

- Desire (BMBF)
- CoSy (EC)
- muFly (EC)
- RAWSEEDS (EC)
- INDIGO (EC)
- Graduate School Embedded Microsystems (DFG)
- MultiBot (DFG, SFB/TR8)
- ThreeDSpace (DFG, SFB/TR8)
- ObjectSpace (DFG, SFB/TR8)
- Situation Recognition (Siemens)
- Autonomous Navigation (Toyota)
Dimensions of Mobile Robot Navigation

- Mapping
- Localization
- Motion Control
- Exploration
- Integrated Approaches

SLAM

[Makarenko et al., 02]
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
Related Work

• **Single robot exploration:**
  [Albers et.al, 99], [Gonzales-Banos & Latombe, 98], [Lee & Recce, 97], [Lumelsky et. al., 90], [Taylor & Kriegman, 93]

• **Multi-robot exploration:**
  • **Reduction of odometry error during map-building**
    [Rekleitis et.al, 97], [Kurazume & Shigerni, 94]
  • **Coordination for efficient exploration**
    • Straight line distance to estimate costs
      [Singh & Fujimura, 93]
    • Implicit coordination by sharing a joint map
      [Yamauchi et.al, 98]
Coordination for Multi-Robot Exploration

- Robots share a common map.
- The frontiers between known and unknown areas are potential target locations.
- Find a good assignment of target locations to robots
- Goal: Minimize overall exploration time
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.
Coordination Algorithm

1. Determine the frontiers (targets)

2. Compute the travel cost $V(i,t)$ of each robot $i$ to each target location $t$

3. Assign an initial Utility $U(t) = 1$ to each frontier

4. While a robot exists that has no target assigned
   - Choose $(i^*, t^*) = \arg\max_{(i,t)} U(t) - V(i,t)$
   - $U(t') = U(t') - P_{\text{visible}}(t^*, t')$
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
   $$(i, \langle x, y \rangle) = \argmax_{(i', \langle x', y' \rangle)} U_{x',y'} - V^i_{x',y'}$$
   (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:

Probability of measuring certain distance:

\[ P_{\text{visible}}(t^*, t') \]
Application Example

First robot:

Second robot:
Real-World Experiment
Decentralized Realization

- The different robots compute bids for target locations
- A central arbiter chooses the optimal bids for the individual robots

- Computational load is shared among the robots

[Simmons et al., 00]
Multi-Robot Exploration and Mapping of Large Environments

Multi-Robot Mapping and Exploration

Carnegie Mellon
October 1999
Resulting Map (constructed in 8 minutes!)
Real-World Experiment: Implicitly Coordinated Exploration
Real-World Experiment: Explicitly Coordinated Exploration
Experimental Comparison of Explicit and Implicit Coordination

- Simulation experiments with two and three robots
- Compare overall exploration performance

![Diagram of an environment with dimensions 26.4 m x 19.5 m]
Typical Trajectories

Implicit coordination:

Explicit coordination:
Area Explored

Two robots:

Three robots:
Exploration Time

![Graph showing the time needed for uncoordinated and coordinated exploration with different numbers of robots. The x-axis represents the number of robots (1, 2, 3), and the y-axis represents the time needed in [10s]. There are error bars indicating variability.]
Simulation System for Systematic Evaluations

- Models sensor noise,
- models interferences between robots, and
- assumes that the relative positions are known.
- Allows arbitrary numbers of robots,
- can deal with different environments,
- allows the analysis of different initial deployment positions, and
- different strategies for re-planning the target locations.
The Simulation Tool
Example

Implicitly coordinated:

Explicitly coordinated:
Exploration Time

exploration time [min]

number of robots

uncoordinated
coordinated
The Exploration Game: A Game-Theoretic View

- At each point of time:
  - The utility of reaching an unexplored area first is
    \[ C - d \]
    where \( C \) is a large constant
    and \( d \) is the distance to the area.
  - If the area is not reached first, the utility is \(-d\).
## Example Situation

![Game Graph](image)

<table>
<thead>
<tr>
<th></th>
<th>R2: a</th>
<th>R2: b</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1: a</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>R1: 98</td>
<td>2</td>
<td>-5</td>
</tr>
<tr>
<td>R1: 94</td>
<td>100</td>
<td>90</td>
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<tr>
<td>R1: b</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>R2: 95</td>
<td>5</td>
<td>95</td>
</tr>
<tr>
<td>R2: -10</td>
<td></td>
<td>-10</td>
</tr>
</tbody>
</table>

[courtesy by Berhard Nebel]
Choosing the point, nobody else but oneself is closest, is the dominant strategy.

This characterises the Nash equilibrium.

The game theoretic solution corresponds to the greedy algorithm:

- Iteratively, we select the pair of location and robot which are closest to each other and that has not been chosen yet.
- This is not the optimal solution (i.e., it does not maximize social welfare).
Optimization of Assignments

- Assignment (1a, 2b) reduces overall completion time compared to (2a, 1b).
- Exponentially many potential assignments (still in P?)
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:
   $$\sum_{i=1}^{n} U(t_i \mid t_1, \ldots, t_{i-1}, t_{i+1}, \ldots, t_n) - \beta \cdot (V_{t_i}^i)^2.$$ 

- Solution by randomized search.
Simulation Results
Other Coordination Techniques

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

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

The graph shows the exploration time for different numbers of robots, categorized as uncoordinated, coordinated, randomized, and Hungarian Method. As the number of robots increases, the exploration time decreases significantly for all methods, indicating improved efficiency with more robots.
Extensions

- Limited Communication Range
- Limited Communication Bandwidth
- Heterogeneous Platforms
- Heterogeneous Sensors
Limited Communication Range

- Robots typically form clusters when the communication range is limited.
- We coordinate the robots in the individual clusters.
- Robots that cannot communicate are far apart (sensor range $<<$ communication range).
Experiment with real robots
Effect of the Communication Range

![Graph showing the effect of communication range on exploration time. The y-axis represents exploration time in minutes, and the x-axis represents the communication range as a percentage of the maximum distance in the map. The graph compares the exploration times for 1 robot, 2 robots coordinated, 3 robots coordinated, 4 robots coordinated, and 5 robots coordinated.]
Limited Bandwidth

- Local and global map frequently changes
- Why not only transmit incremental changes
- To save bandwidth, robots exchange compact polygonal approximations
Incremental Update

- Each robot maintains a polygonal approximation of its map

- Incremental updates are computed using the minimum edit distance

- Edit distance operations are transmitted via the network
Example: Incremental Update
Refining Approximations

- Douglas-Peucker Algorithm is used to recursively refine the approximation
- Step-by-step refinement according to a given splitting frequency

Step: 0 1 2 3 4 5
Incremental Update
Merging Environmental Models

- Each robot integrates the knowledge obtained by its team-mates into a map.
- Polygonal approximations are used to model the areas not observed by the robot itself.
- In case of ambiguities, the priority occupied, free, and then unknown is used.
Merging Maps

map of R3

data of R1

data of R2

ground truth

solution obtained by R3
Exploration with Abstractions
Even for low bandwidth networks, the error of the polygonal model is small.
Influence of the Bandwidth

- Exploration times for unlimited and 10kB/s limited exploration are almost equal.
- Exploration at 1kB/s requires only 30% more time than required for the unlimited case.
What Next?

Can we still get better?
Utilizing Structure

- Corridors typically provide multiple transitions to rooms (unobserved places) compared to rooms.
- The more transitions to unknown regions a place has, the better the robots can distribute themselves over the environment.
- How can we (a) extract such information and (b) use it to improve the distribution of the robots.
Key Question

Can we use semantic information about the type of the places to improve multi-robot coordination?
Motivation

- Indoor environments can be decomposed into different places
- How can we **determine** the type of place a robot is at and how can we **utilize** it to improve navigation tasks?
Observations
Observations

Corridor

Room
Observations

Corridor

Room

Doorway
Place Classification Using Boosting

**Observation:**
There exists a variety of simple features $f_i$ we can define on laser range scans.

**Problems:**
Each single feature $f_i$ gives poor classification rates.

**Idea:**
Combine multiple simple features to form a strong classifier using AdaBoost.
Simple Features

- $f = \frac{1}{N} \sum d_i$
- $\text{gap} = d > \theta$
- $f = \#\text{gaps}$
- $f = \text{area}$
- $f = \text{perimeter}$
- $f = d$
Learning

Room features

Corridor features

Doorway features

AdaBoost

multi-class classifier
Classification

observation → features → Multi-class classifier → Corridor
Application Result

Training
# examples: 16045

Test
# examples: 18726
classification: 94%

Corridor  Room  Doorway
Application to a New Environment

Training map
Application to a New Environment
Experiments with a Moving Robot
Classifying a Target Location

- Since the surroundings of a frontier location are partially unexplored, the classification of those places is quite noisy.
- To improve robustness, we apply an HMM along a simulated trajectory towards the goal.
Hidden Markov Model

\[ Bel(\xi_t) = \alpha P(z_t|\xi_t) \sum_{\xi_{t-1}} P(\xi_t|\xi_{t-1}, u_{t-1}) Bel(\xi_{t-1}) \]

- **Normalizer**
- **Motion model**
- **Observation likelihood**

Likelihood of the observation, given to robot is at a certain type of place.
Application to Exploration

- Assign a higher utility to regions that probably provide more frontiers to unknown areas.

- **Advantage:** Only minimal changes to the assignment algorithm.
Improved Coordination for Multi-Robot Exploration

1. Determine the frontiers (targets)
2. Compute the travel cost $V(i,t)$ of each robot $i$ to a target $t$
3. Assign a utility:
   $$U(t) = \begin{cases} 
   c > 1 & \text{if } t \text{ is a corridor location} \\
   1 & \text{otherwise}
   \end{cases}$$
4. While a robot exists that has no target assigned
   - Choose $(i^*,t^*) = \arg \max U(t) - V(i,t)$
   - $U(t') = U(t') - P_{\text{visible}}(t^*, t')$
Evaluation

- Considering semantic place information leads to a significantly reduced exploration time.
By focusing the exploration on corridors, more potential target locations are available. This often results in a better distribution of robots over the environment. Up to ~20% less interference between robots.
Influence of the Estimation Error

![Graph showing the effect of estimation error on exploration time.]
Conclusions

- New approach for multi-robot coordination during exploration
- Techniques for dealing with limited communication ranges and bandwidth
- New approach to multi-robot exploration that utilizes classifications of places to guide the exploration process
Future Work

- Heterogeneous systems and sensors
- Outdoor environments
- Aerial and ground based vehicles
- More complex coordination actions (docking, rendezvous, deployment)
- Multi-robot SPLAM