

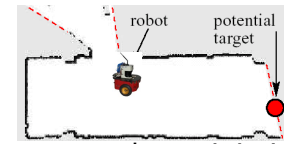
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Exploration

1

Single Robot Exploration

- Frontiers between free space and unknown areas are potential target locations
- Going to frontiers will gain information



- Select the target that minimizes a cost function (e.g. travel time / distance /...)

2

Frontier-Based Exploration

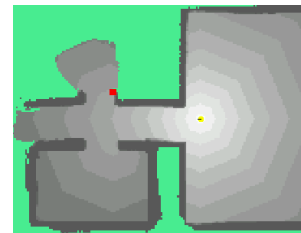


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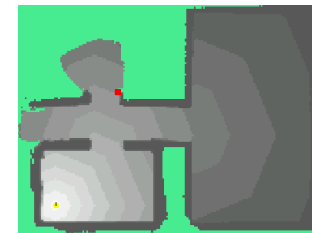
3

Multi-Robot Exploration

Robot 1:



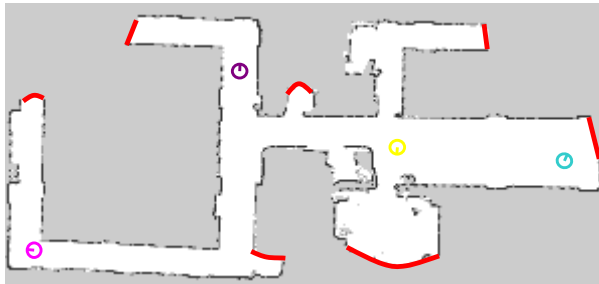
Robot 2:



4

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Coordinated Exploration



$$C(\theta) = \sum_{(i,j) \in \theta} \text{dist}(i,j)$$

$$U(\theta) = \sum_{(i,j) \in \theta} \text{explore}(i,j)$$

$$\theta^* = \arg \max_{\theta} (U(\theta) - C(\theta))$$

[Burgard et al. 00],
[Simmons et al. 00]

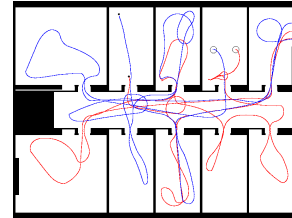
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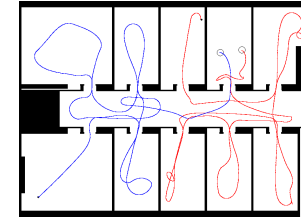
5

Typical Trajectories in an Office Environment

Implicit / no coordination:



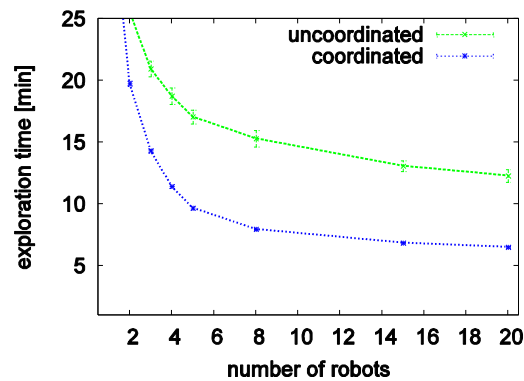
Explicit coordination:



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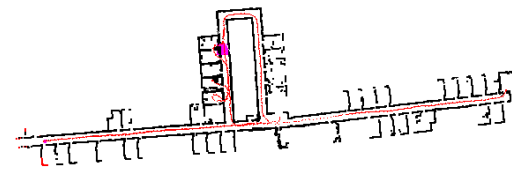
Exploration Time



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Multi-Robot Mapping With Known Start Locations

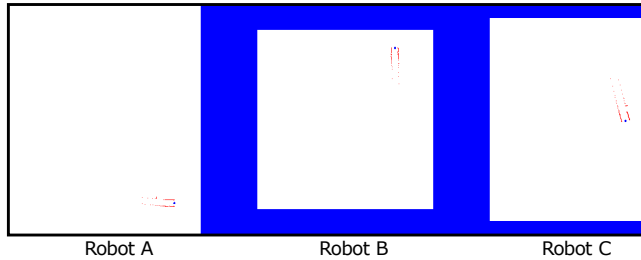


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Why are Unknown Start Locations Hard?



- ▶ Need to know whether or not maps overlap
- ▶ Need to know how maps overlap

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Multi-robot Map Merging

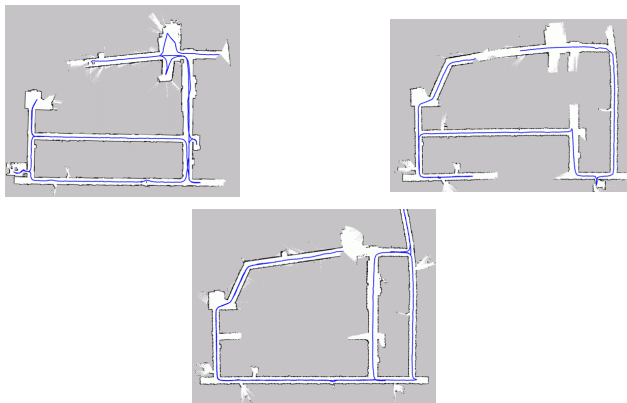
- **Problems**
 - Number of possible merges is **exponential** in number of robots
 - Cannot merge maps by simply **overlaying** them
- **Wanted**
 - **Scalability, robustness**
 - Merge maps **as soon as possible**

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Multi-robot Map Merging

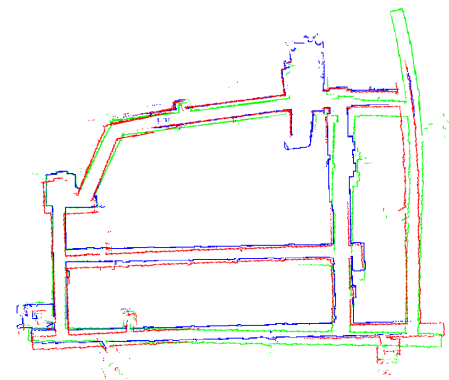


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Multi-robot Map Merging

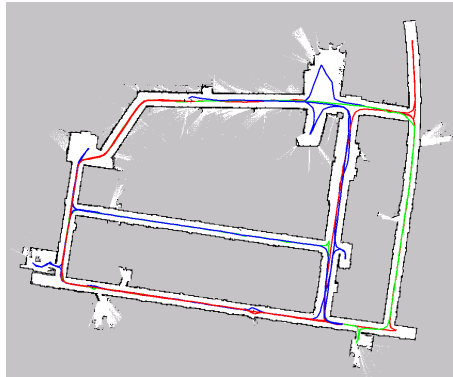


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Multi-robot Map Merging



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Experimental setup



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Coordinated exploration with three robots
from unknown start locations

The robots are fully autonomous.
All computation is performed on-board.

Shown is the perspective of one robot

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Sponsored by DARPA-SDR, NSF, Intel



- ▶ Map an unknown area
- ▶ Search for an "object of value"
- ▶ Set up a surveillance network
- ▶ Track any intruders

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CentiBots: Experimental Evaluation

- Rigorously evaluated by **outside evaluation team**
- **No testing** allowed in 1/2 of environment
- **Limited communication**
- No intervention / observation during experiment
- Comparison to **“ground truth”** map

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Control Center and Test Team



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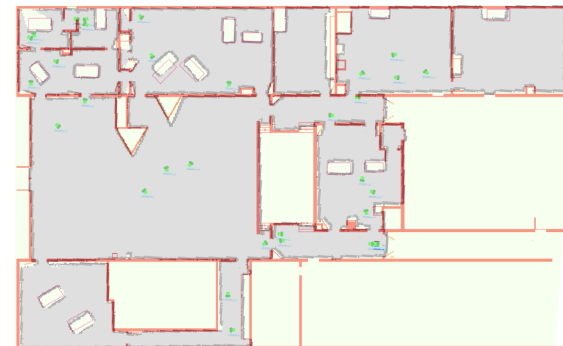


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Comparison to “Ground Truth Map”

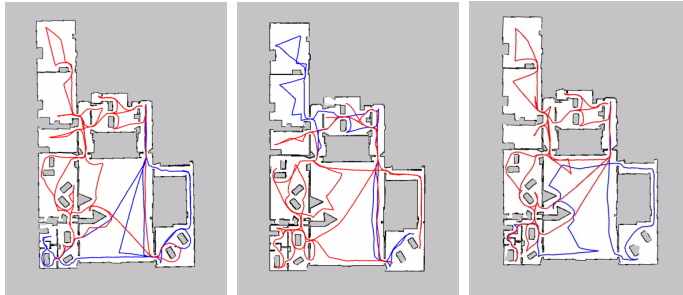


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Three Mapping Runs

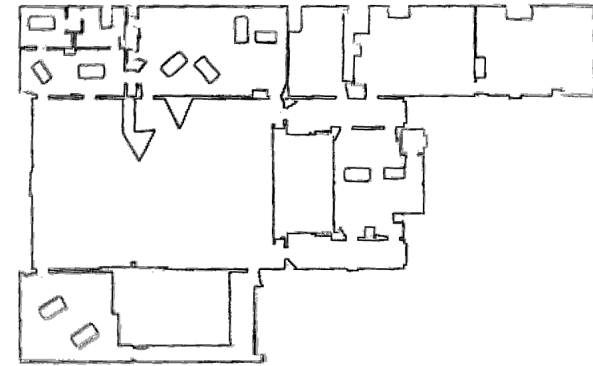


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Three Overlaid Maps



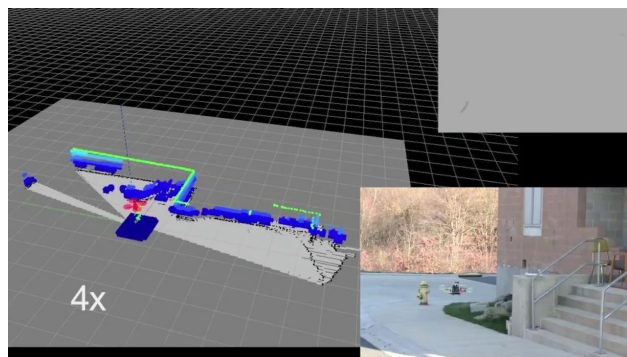
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Courtesy of Vijay Kumar 3D Exploration

[Shen-Michael-Kumar: IJRR-2012]

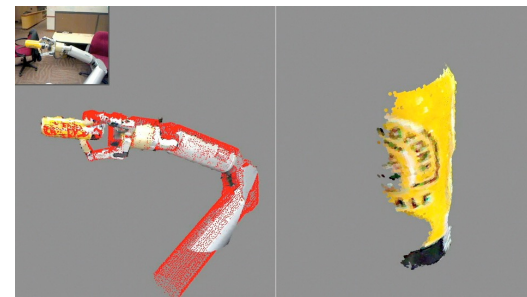


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[Krainin-Henry-Ren-F: IJRR-11] Active Object Modeling: Joint Tracking and Modeling



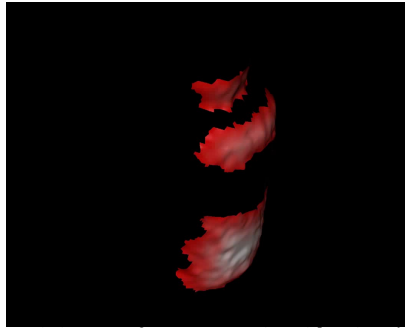
- EKF with articulated ICP over manipulator joint angles, camera pose and pose of (partial) object

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Uncertainty in Object Surface



- Signed-distance function voxel grid [Curless '96]
- Surface uncertainty from beam-based noise model

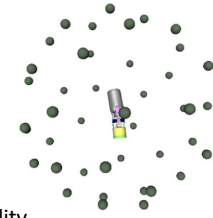
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View Selection Algorithm

- Conceptually similar to Planetarium Algorithm [Connolly '85]
- Procedure:
 - Generate kinematically achievable viewpoints
 - Compute information gain (quality) for each viewpoint
 - Select view as tradeoff between quality and cost



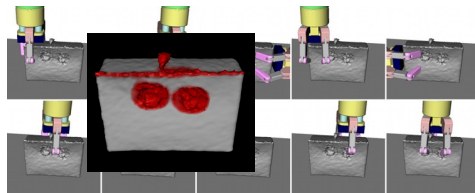
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Re-Grasp Selection

- Generate candidate grasps [Diankov '10]
- Select grasp by maximum information gain, accounting for occlusion caused by grasp



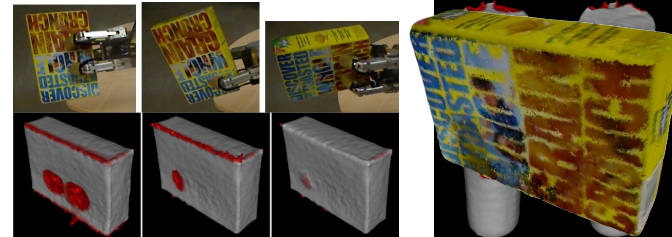
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Multiple Grasp Results

- Evaluated regrasping on four objects
- Includes box with three grasps



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Active Object Modeling

Next Best View Planning for 3D In-Hand Modeling

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