CSE-571
Robotics

**Exploration**

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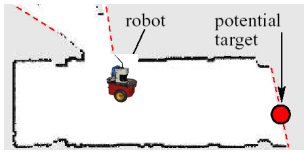
## Single Robot Exploration

- 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 /…)

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## Frontier-Based Exploration



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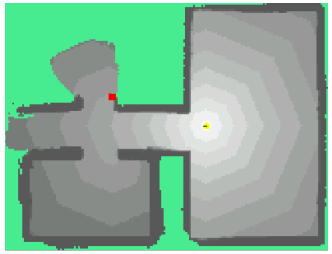
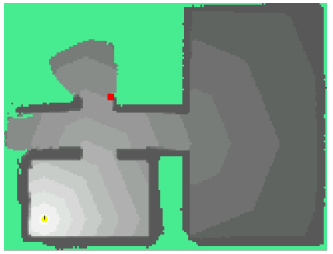
## Multi-Robot Exploration

**Robot 1:**



**Robot 2:**



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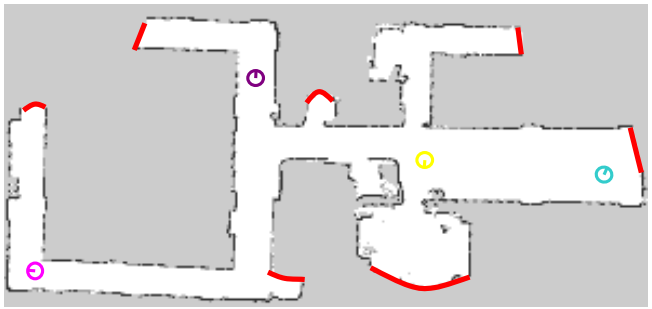
## Coordinated Exploration



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

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

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



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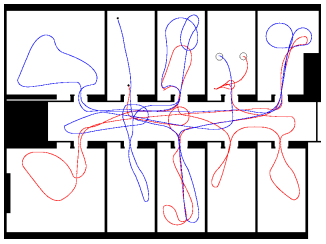
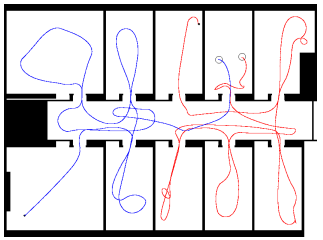
## Typical Trajectories in an Office Environment

Implicit / no coordination:



Explicit coordination:





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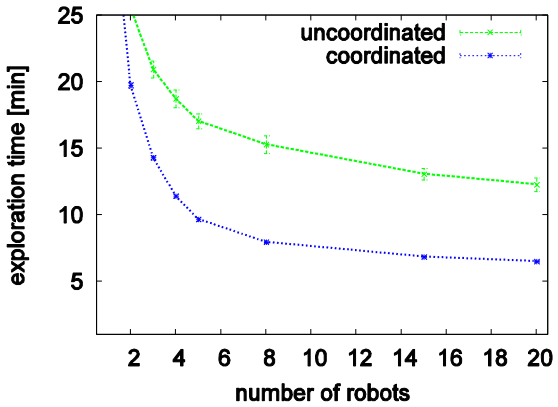
## Exploration Time



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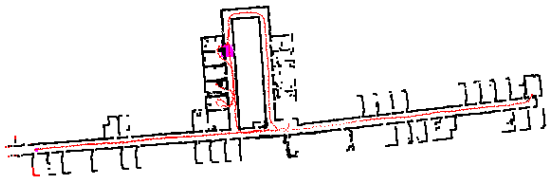
## Multi-Robot Mapping With Known Start Locations





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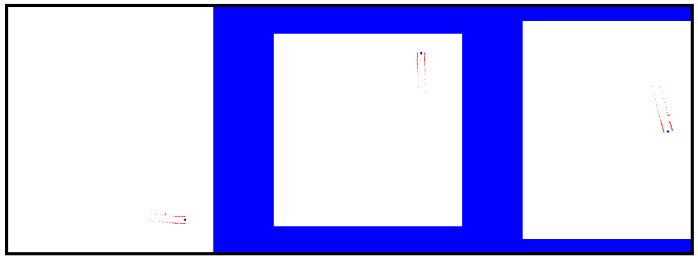
## Why are Unknown Start Locations Hard?




- 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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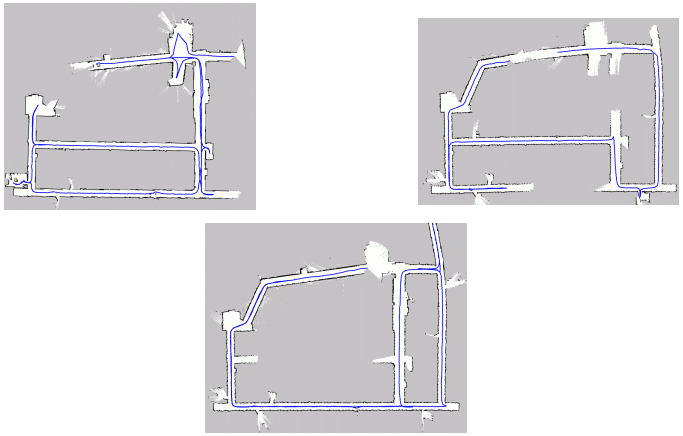
## Multi-robot Map Merging





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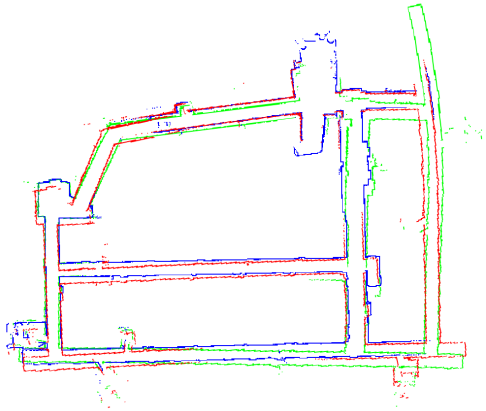
## Multi-robot Map Merging





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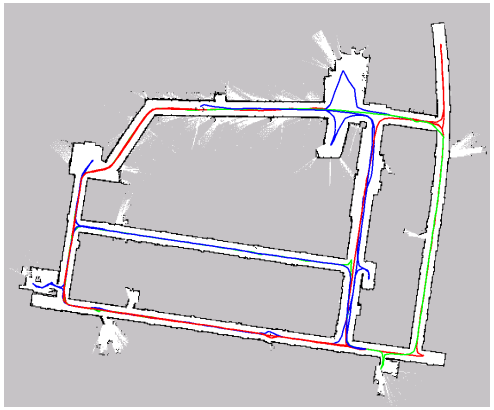
## Multi-robot Map Merging





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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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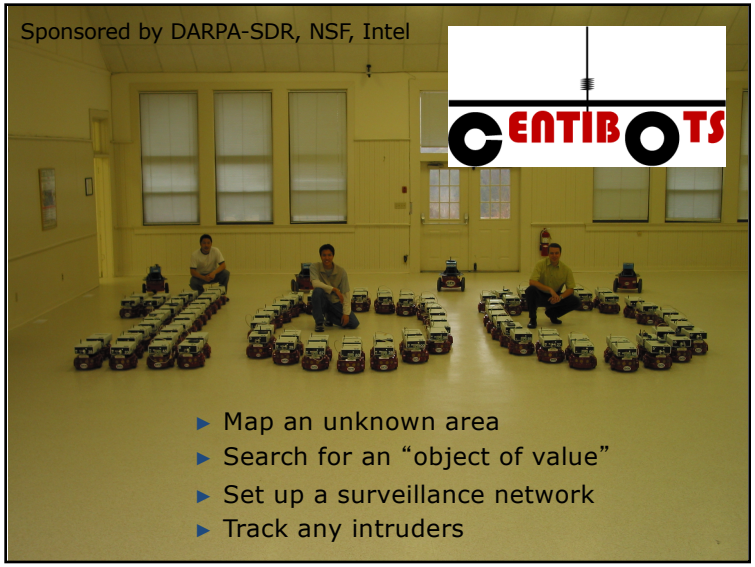


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## CentiBots: Experimental Evaluation

- Rigorously tested 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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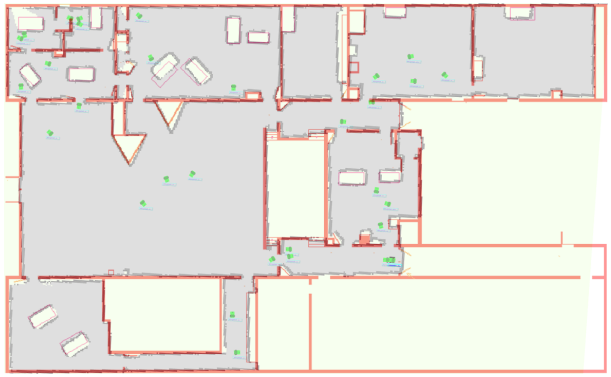
## Comparison to "Ground Truth Map"





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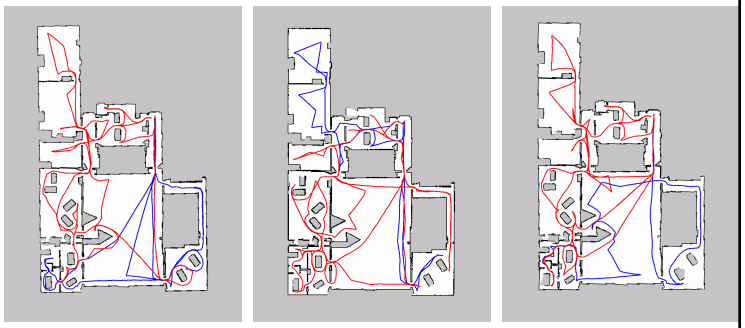
## Three Mapping Runs





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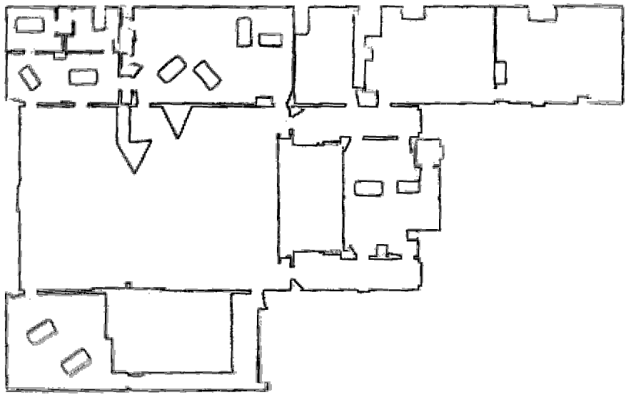
## Three Overlayed Maps





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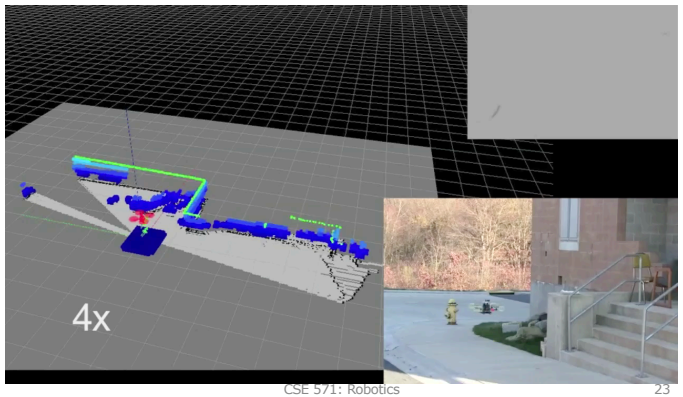
Courtesy of Vijay Kumar

## 3D Exploration

[Shen-Michael-Kumar: IJRR-2012]



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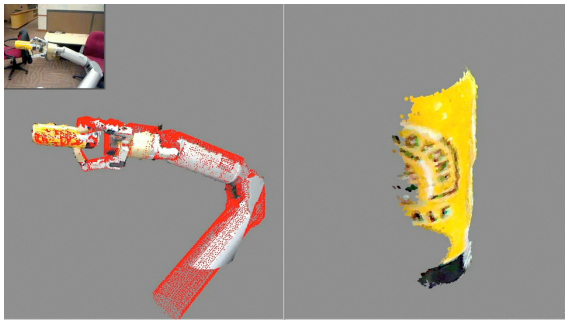
[Krainin-Henry-Ren-F: IJRR-11]

## 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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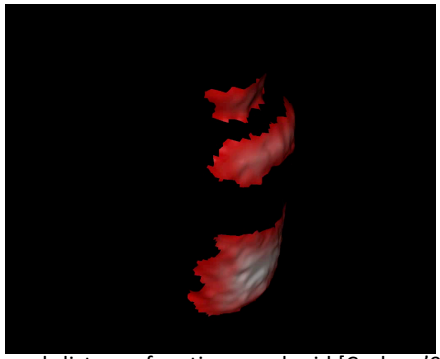
[Krainin-F-Curless: ICRA-11]

## Uncertainty in Object Surface



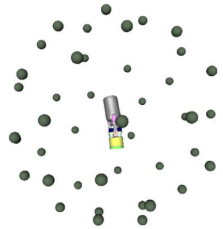
- Signed-distance function voxel grid [Curless '96]
- Surface uncertainty from beam-based noise model





## 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

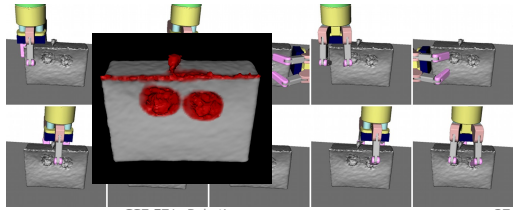






## Re-Grasp Selection

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

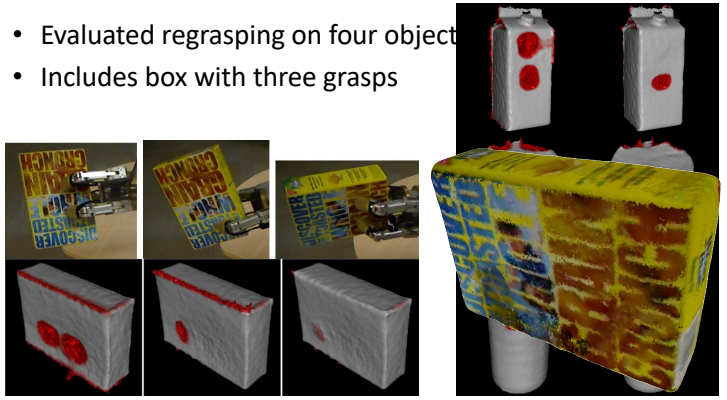






## Multiple Grasp Results

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



## Active Object Modeling

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