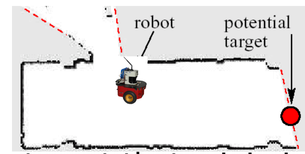
CSE-571
Robotics

Exploration

Single Robot Exploration

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

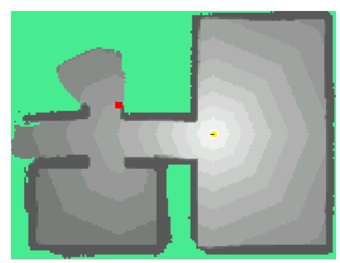


- Select the target that minimizes a cost function (e.g. travel time / distance /…)

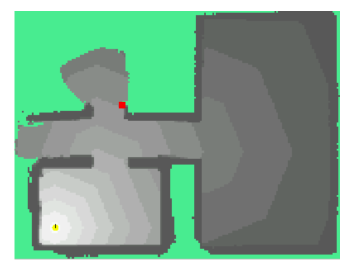
Frontier-Based Exploration

Multi-Robot Exploration

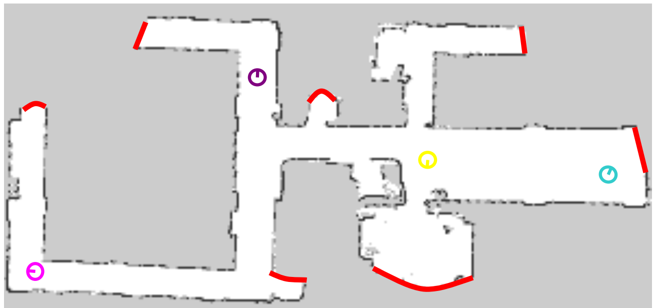
Robot 1:



Robot 2:



Coordinated Exploration



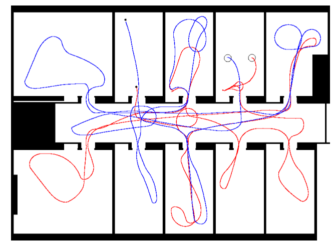
$$C(\theta) = \sum_{(i,j)\in\theta} \text{dist}(i,j) \qquad U(\theta) = \sum_{(i,j)\in\theta} \text{explore}(i,j)$$

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

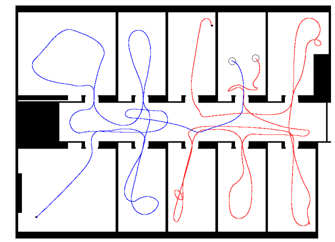
[Burgard et al. 00],
[Simmons et al. 00]

Typical Trajectories in an Office Environment

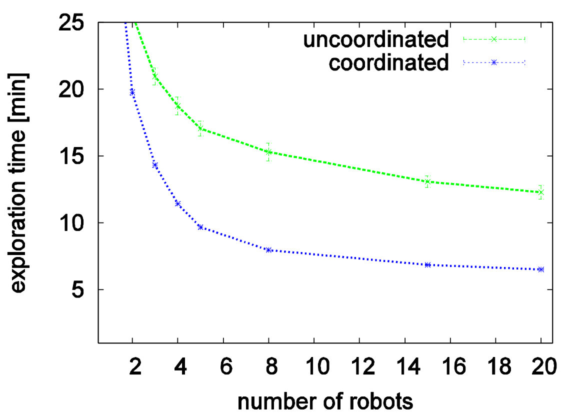
Implicit / no coordination:



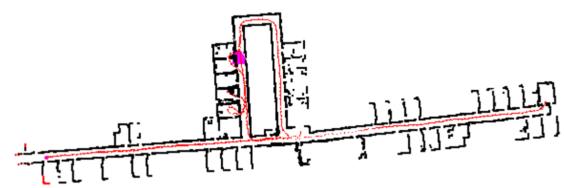
Explicit coordination:



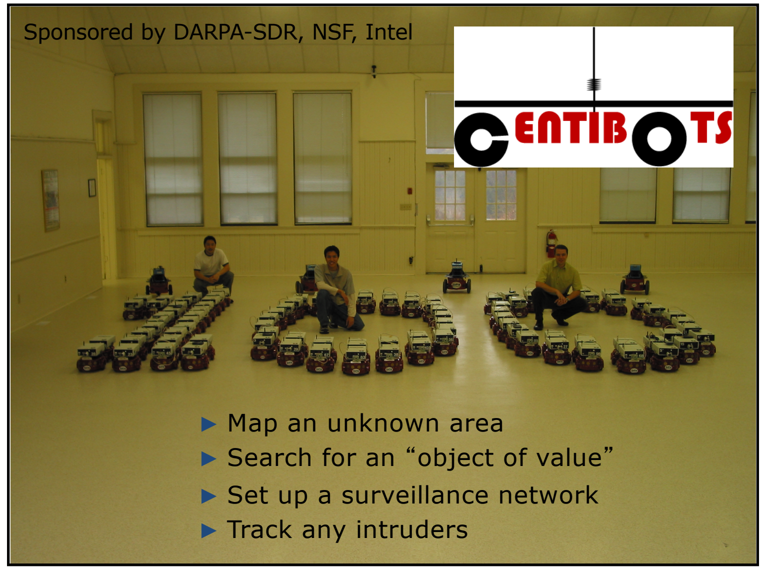
Exploration Time



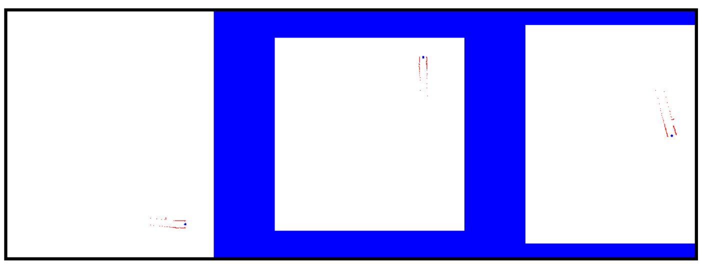
Multi-Robot Mapping With Known Start Locations



Multi-Robot Mapping With Known Start Locations



Why are Unknown Start Locations Hard?

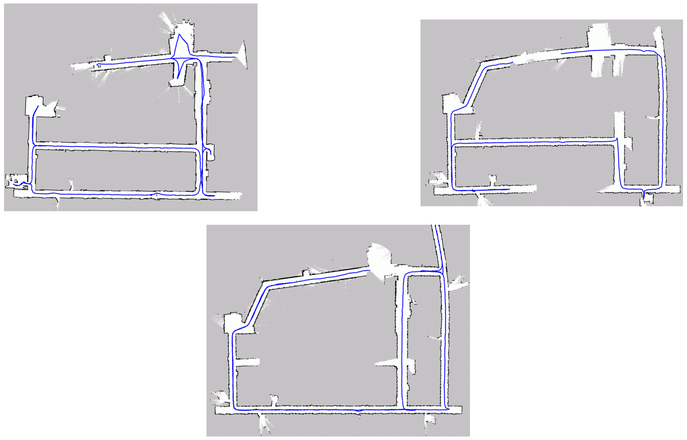


- Need to know whether or not maps overlap
- Need to know how maps overlap

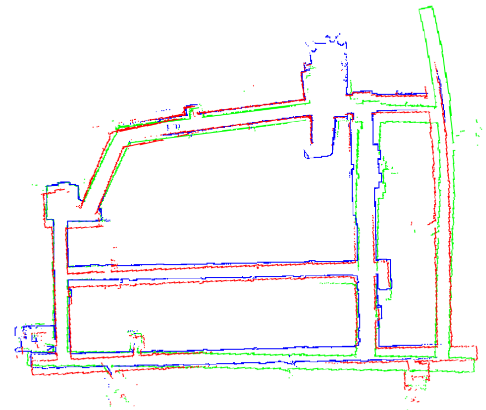
Multi-robot Map Merging

- 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

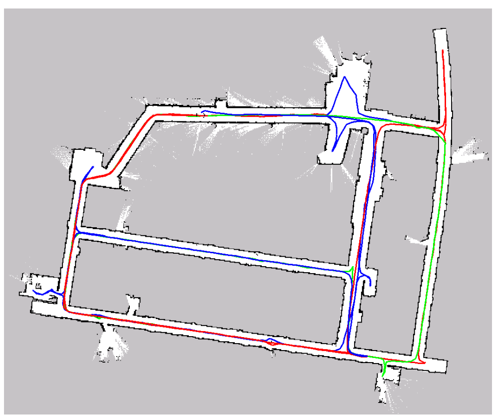
Multi-robot Map Merging



Multi-robot Map Merging



Multi-robot Map Merging



Estimating relative locations

- Idea: Localize one robot in other robot's map using particle filter
- Problems:
  - Only partial map available
  - Other robot might be outside the map
  - Map grows
  - Impossible to keep track of all locations inside and outside the partial map
- Solution: Only keep track of trajectories that overlapped map at some time

Partial map localization (intuition)

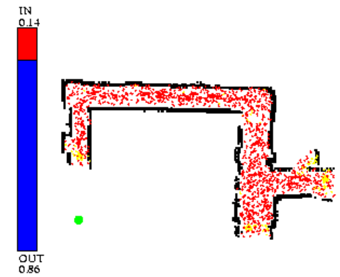
- Overlapping trajectories

$$p(x_t \mid z_{1:t}, u_{1:t-1}) =$$
$$\alpha_t \; p(z_t \mid x_t) \cdot \left[\int p(x_t \mid x_{t-1}, u_{t-1}) p(x_{t-1} \mid z_{1:t-1}, u_{1:t-2}) dx_{t-1} + p(x_t \mid n_{t-1}, u_{t-1}) p(n_{t-1} \mid z_{1:t-1}, u_{1:t-2}) \right]$$

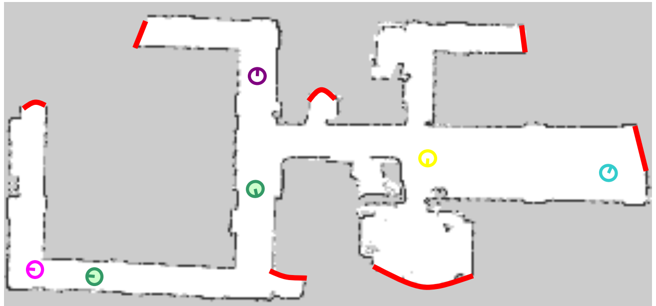
- Non-overlapping trajectories

$$p(n_t \mid z_{1:t}, u_{1:t-1}) = \alpha_t \; p(z_t \mid outside)(1-\varepsilon) p(n_{t-1} \mid z_{1:t-1}, u_{1:t-2})$$

Partial map localization (example)



Coordination



$$C(\theta) = \sum_{(i,j)\in\theta} \begin{cases} \text{dist}(i,j) & \text{if } j \text{ is frontier} \\ \text{dist}(i,j) + \text{meet}(i,j) & \text{if } j \text{ is hypothesis} \end{cases} \qquad U(\theta) = \sum_{(i,j)\in\theta} \begin{cases} \text{explore}(i,j) & \text{if } j \text{ is frontier} \\ p(j)\,\text{merge}(i,j) & \text{if } j \text{ is hypothesis} \end{cases}$$

Hypotheses become potential goals

[Burgard et al. 00], [Simmons et al. 00], [Zlot et al. 02]

Experimental setup

Coordinated exploration with three robots
from unknown start locations

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

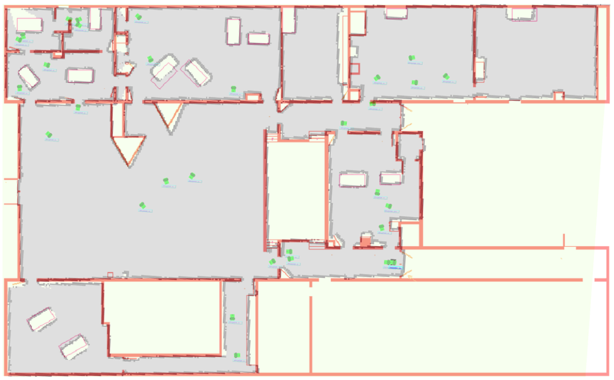
Shown is the perspective of one robot

CentiBots: Experimental Evaluation

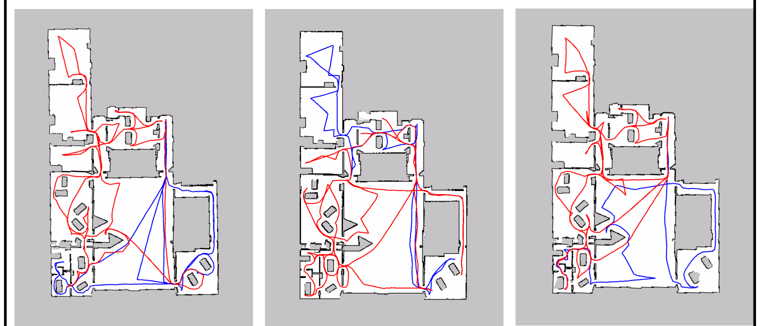
- Rigorously tested by outside evaluation team
- No testing allowed in 1/2 of environment
- Limited communication
- No intervention / observation during experiment
- Comparison to "ground truth" map

Control Center and Test Team

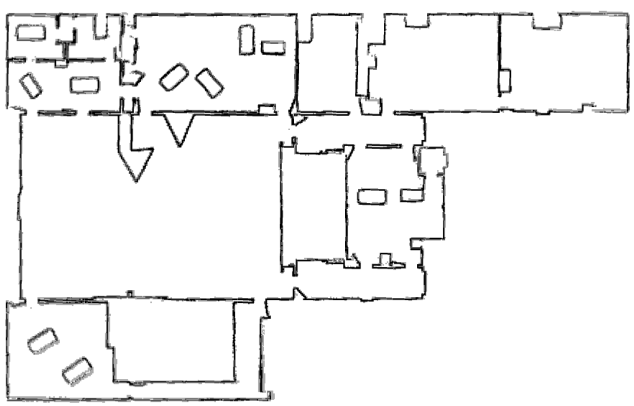
Comparison to "Ground Truth Map"



Three Mapping Runs



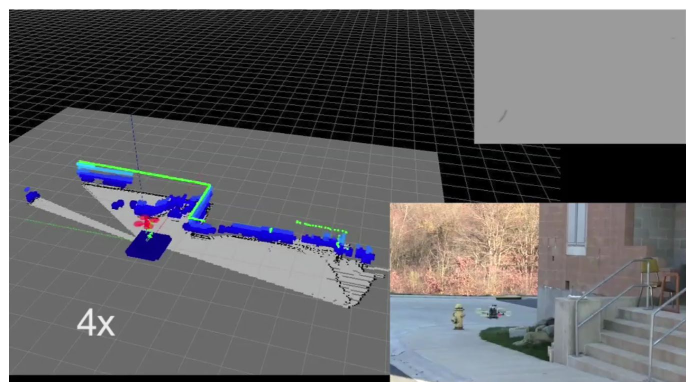
Three Overlayed Maps



Courtesy of Vijay Kumar

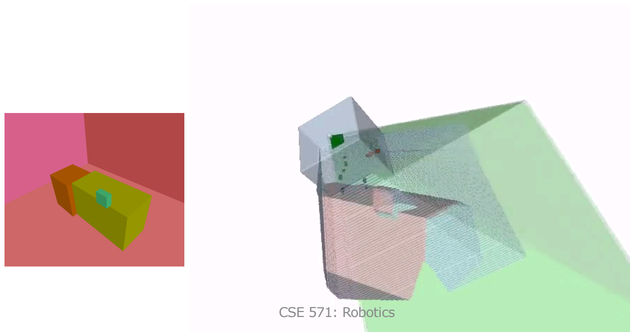
3D Exploration

[Shen-Michael-Kumar: IJRR-2012]



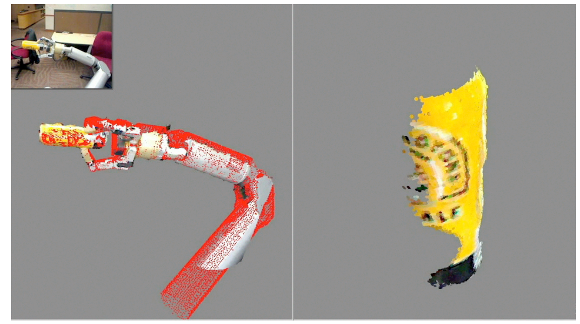
Active Mapping

- View selection for mapping and segmentation



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

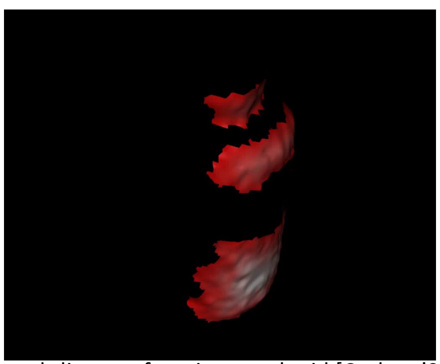
Active Object Modeling: Joint Tracking and Modeling



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

[Krainin-F-Curless: ICRA-11]

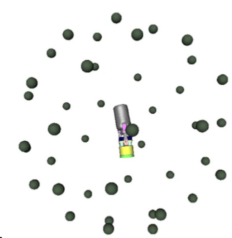
Uncertainty in Object Surface



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

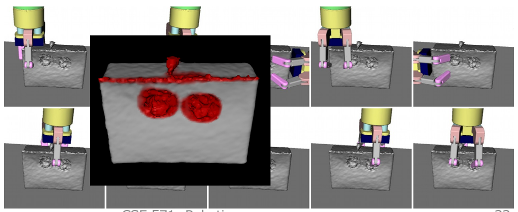
View Selection Algorithm

- 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



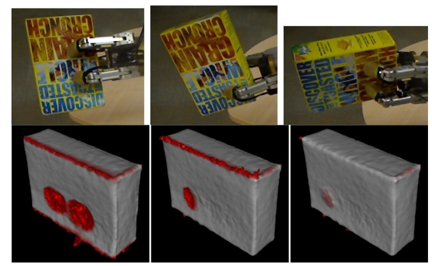
Re-Grasp Selection

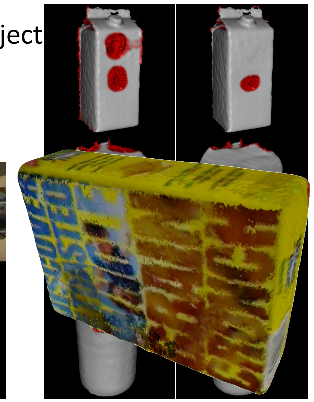
- Generate candidate grasps [Diankov '10]
- Select grasp by maximum information gain, accounting for occlusion caused by grasp



Multiple Grasp Results

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





Active Object Modeling