CSE-571
Probabilistic Robotics

Multi-robot Mapping and Exploration

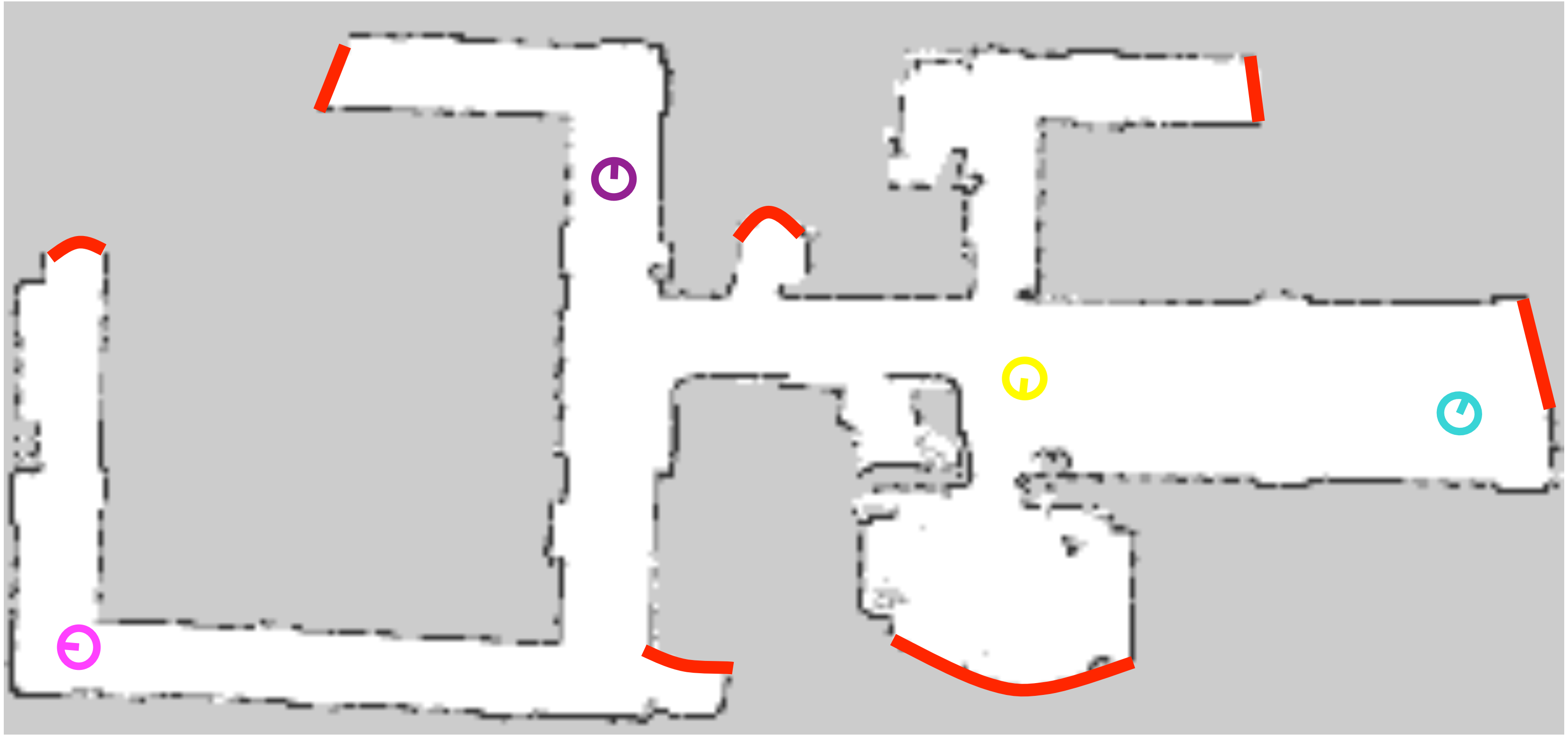
Sponsored by DARPA-SDR, NSF, Intel

CENTIBOTS

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

Mapping the Allen Center

Coordinated Exploration

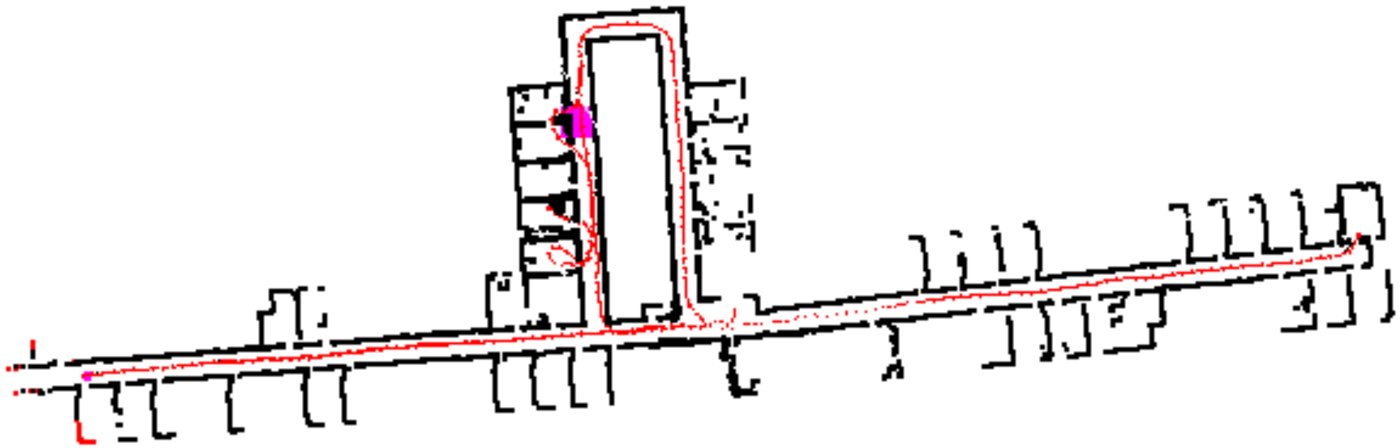


$$C(\theta) = \sum_{(i,j)\in\theta} \text{dist}(i,j) \qquad U(\theta) = \sum_{(i,j)\in\theta} \text{explore}(i,j)$$

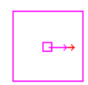
$$\theta^* = \arg\max_{\theta}\left(U(\theta) - C(\theta)\right)$$

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

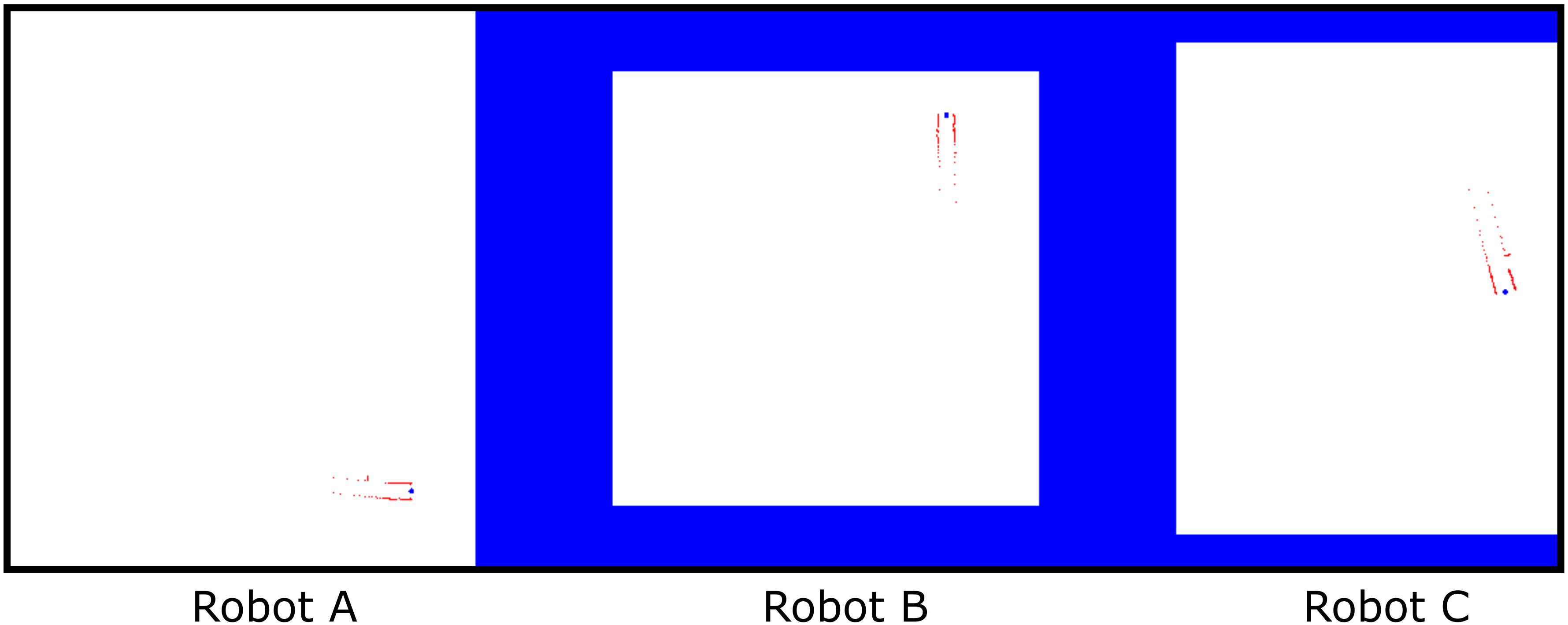
Multi-Robot Mapping With Known Start Locations



Multi-Robot Mapping With Known Start Locations



Why are Unknown Start Locations Hard?



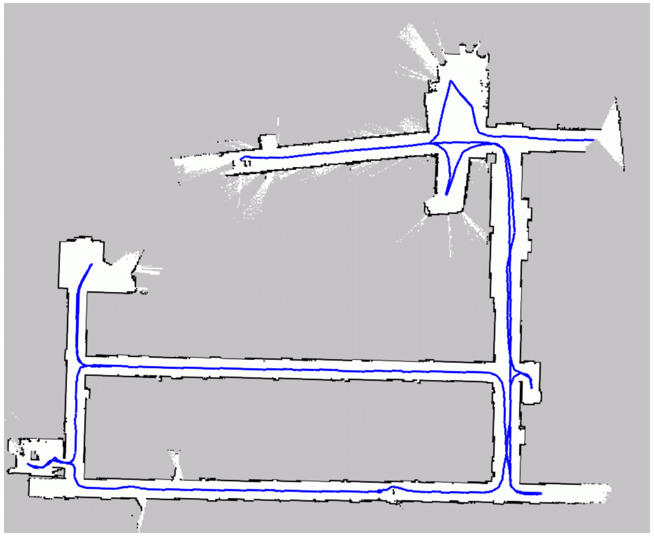
- Need to know whether or not maps overlap
- Need to know how maps overlap

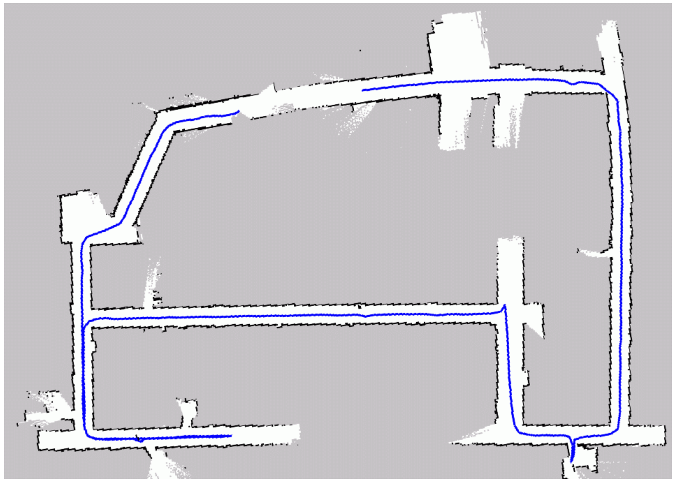
Multi-robot Map Merging

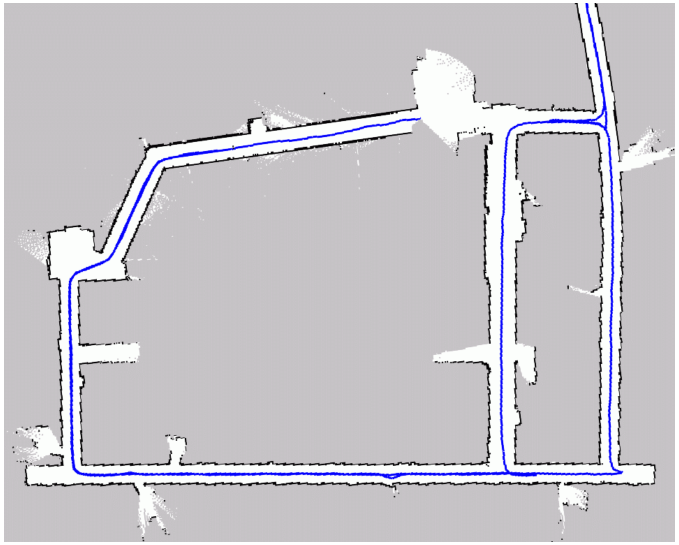
- Problems
  - Number of possible merges is exponential in number of robots
  - Cannot merge maps by simply overlaying them

- Wanted
  - Scalability, robustness
  - Merge maps as soon as possible

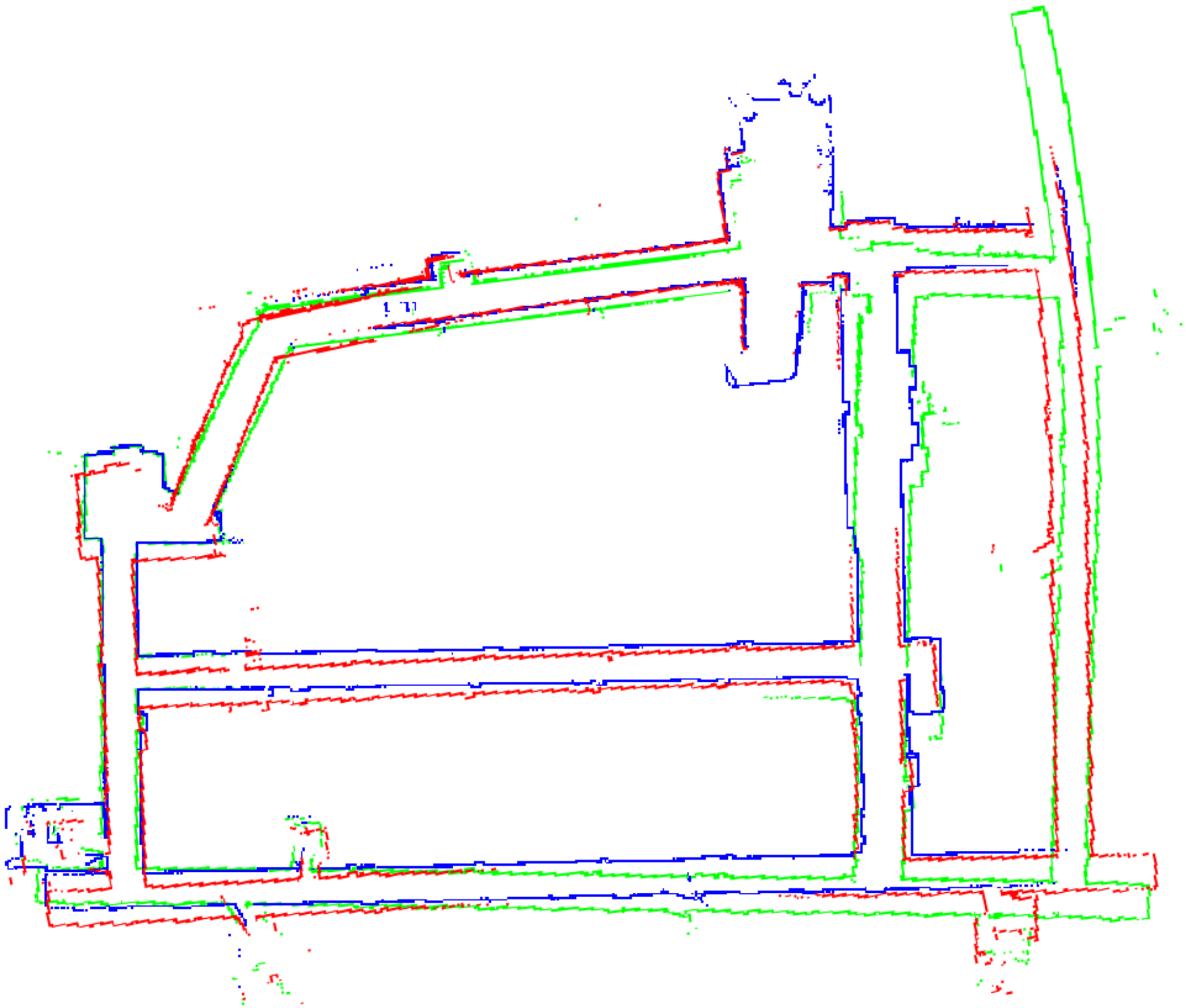
Multi-robot Map Merging



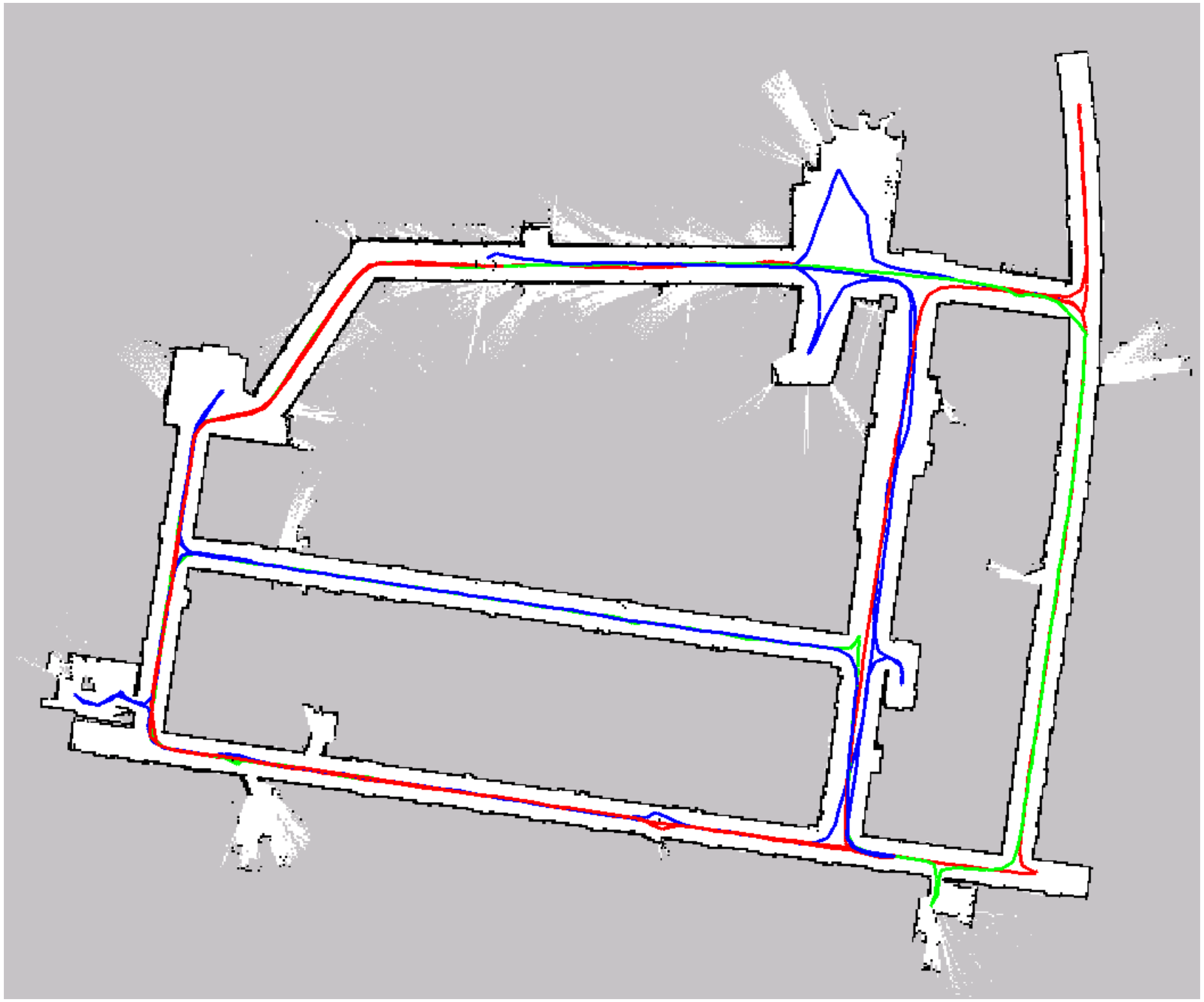




Multi-robot Map Merging



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

$$p(x_t \mid z_{1:t}, u_{1:t-1}) =$$

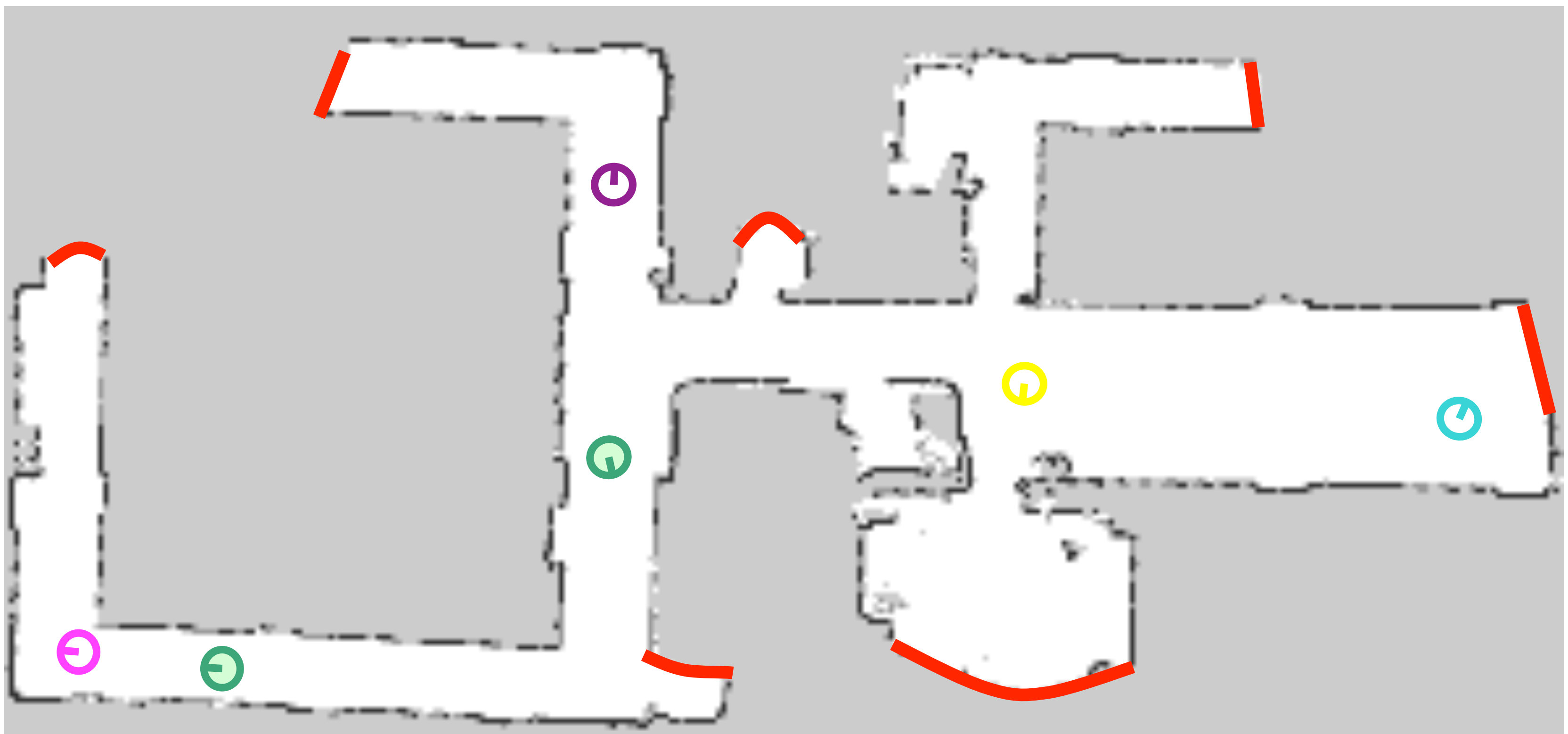
$$\alpha_t \; p(z_t \mid x_t) \cdot \left[\int p(x_t \mid x_{t-1}, u_{t-1}) p(x_{t-1} \mid z_{1:t-1}, u_{1:t-2}) dx_{t-1} + p(x_t \mid n_{t-1}, u_{t-1}) p(n_{t-1} \mid z_{1:t-1}, u_{1:t-2}) \right]$$

- 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

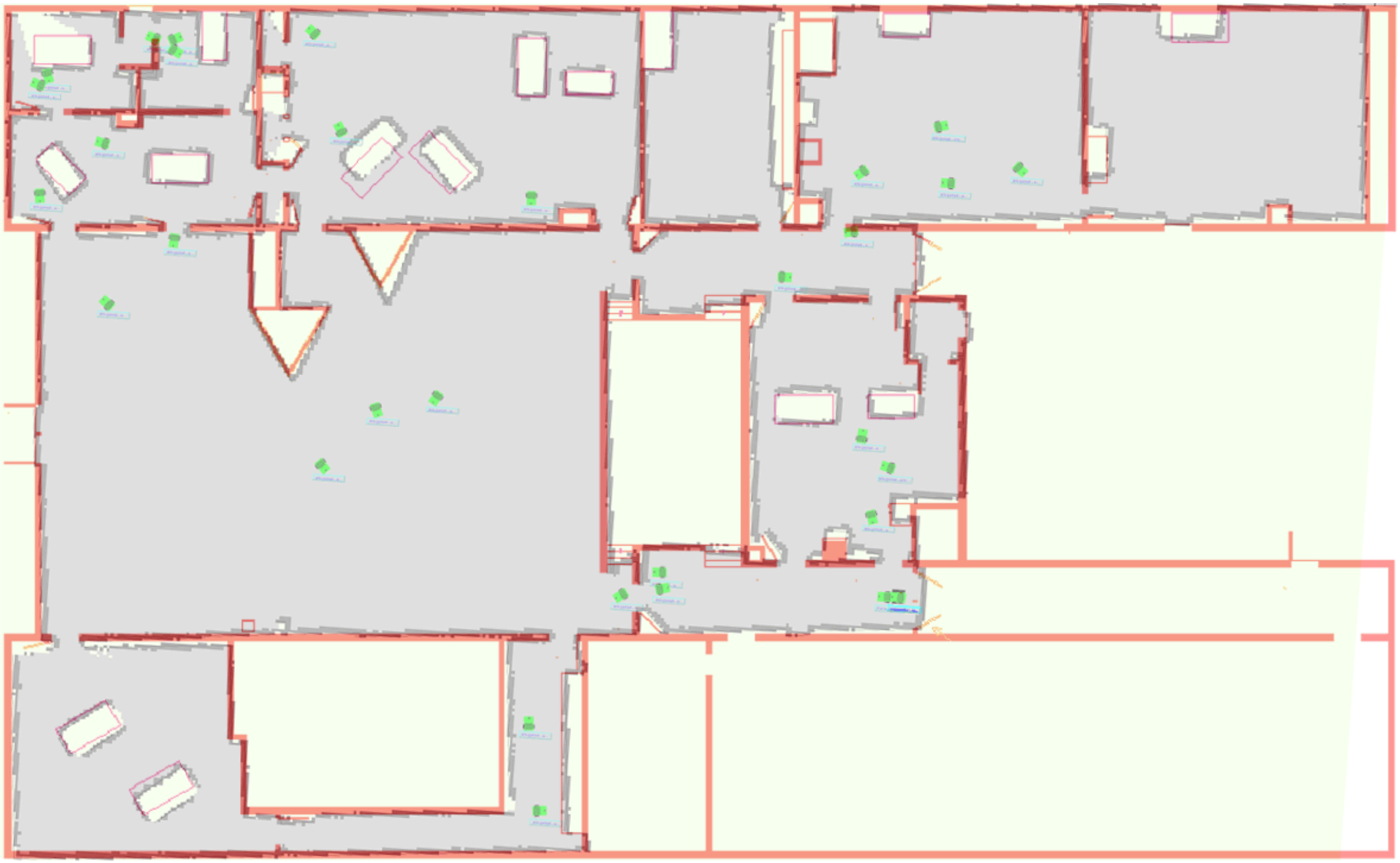
CentiBots: Experimental Evaluation

- Rigorously tested by outside evaluation team

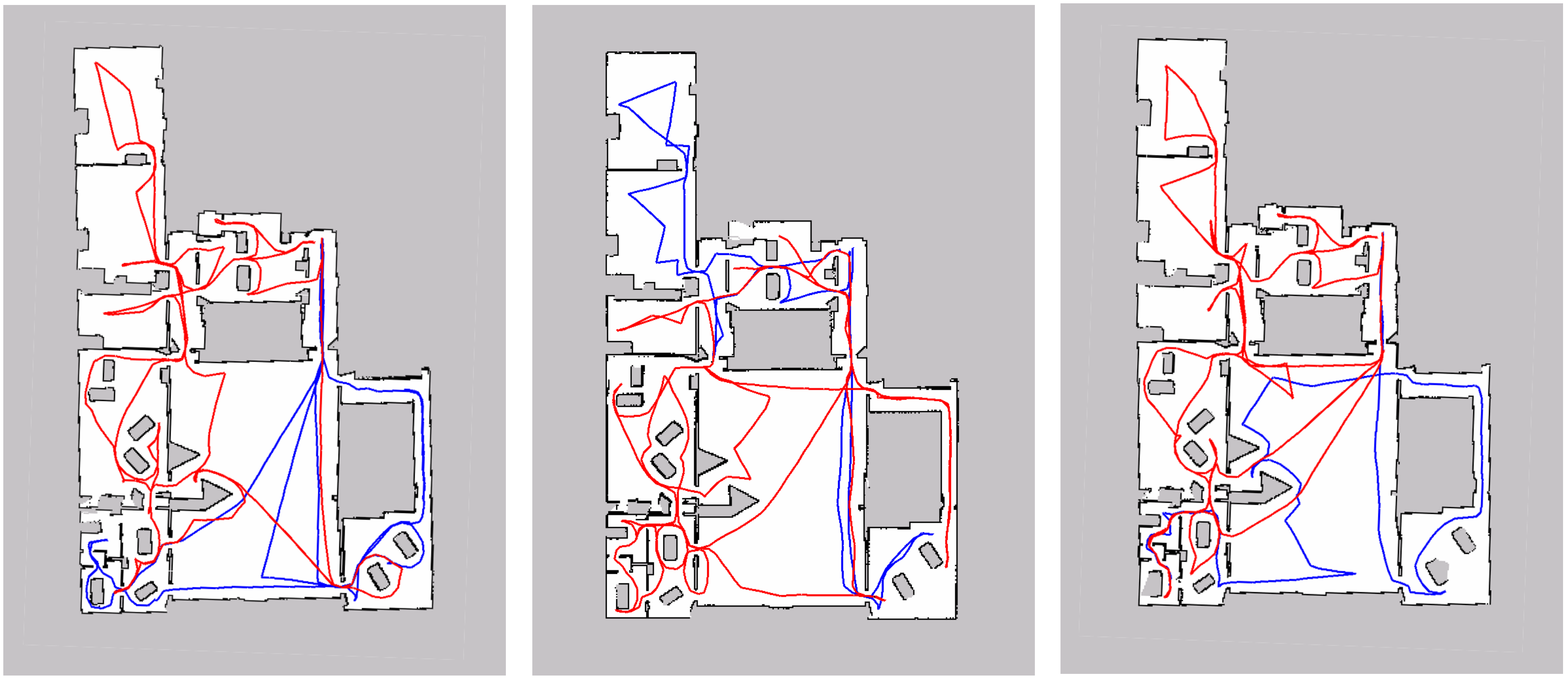
- No testing allowed in 1/2 of environment
- Limited communication
- No intervention / observation during experiment
- Comparison to "ground truth" map

Control Center and Test Team

Comparison to "Ground Truth Map"



Three Mapping Runs



Three Overlayed Maps