Multirobot exploration

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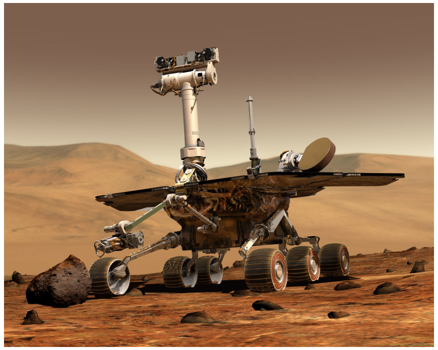
Multirobot Exploration



Mars exploration rover

A robot searching for victims at RoboCup 2014 Rescue competition

Roomba vacuum cleaner

Also search, patrolling, …

Multirobot Exploration in a Nutshell

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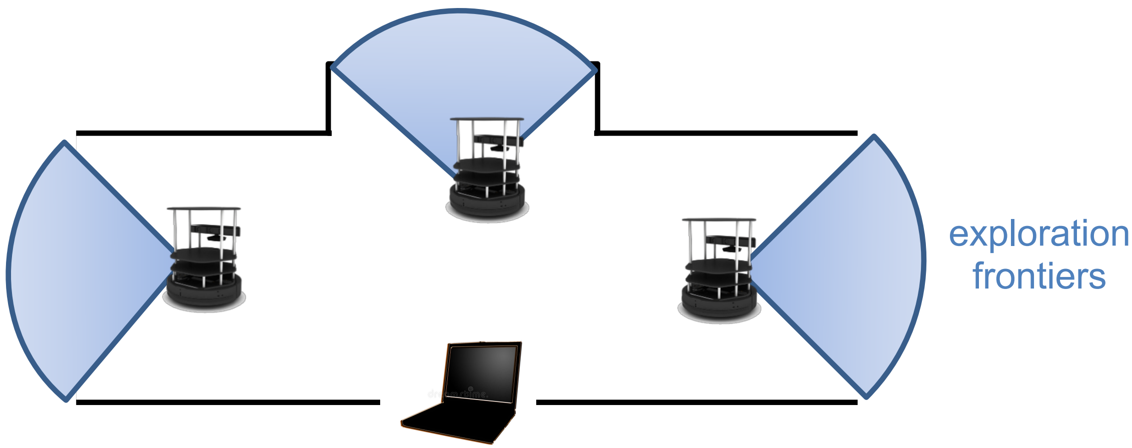
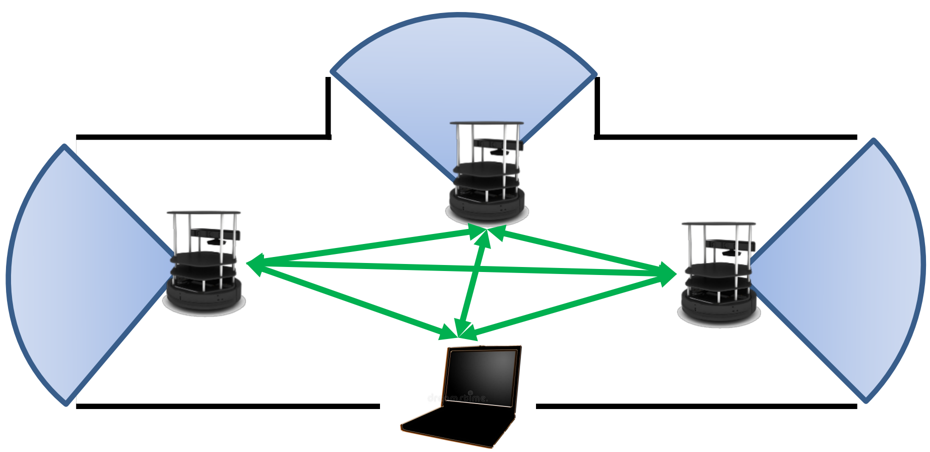
- A team of robots is deployed in an unknown environment to incrementally discover and map its physical features
- The exploration cycle: (1) Perception



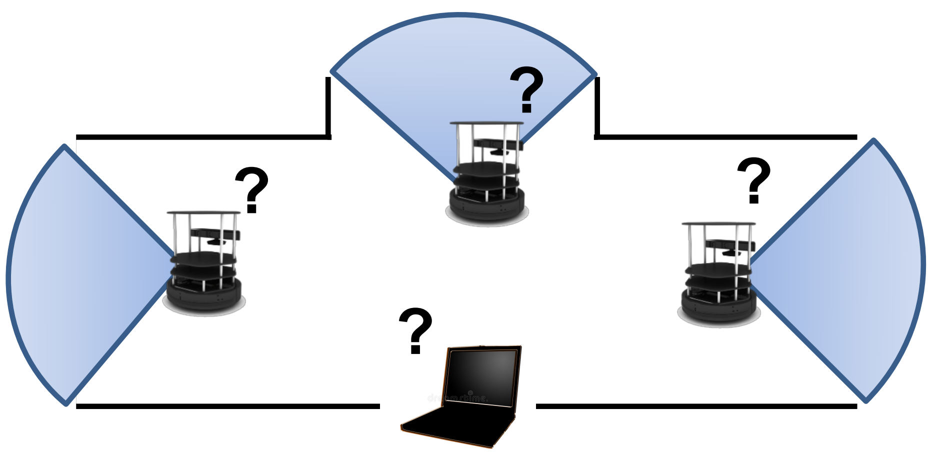
Multirobot Exploration in a Nutshell

- A team of robots is deployed in an unknown environment to incrementally discover and map its physical features
- The exploration cycle: (2) Integration of information



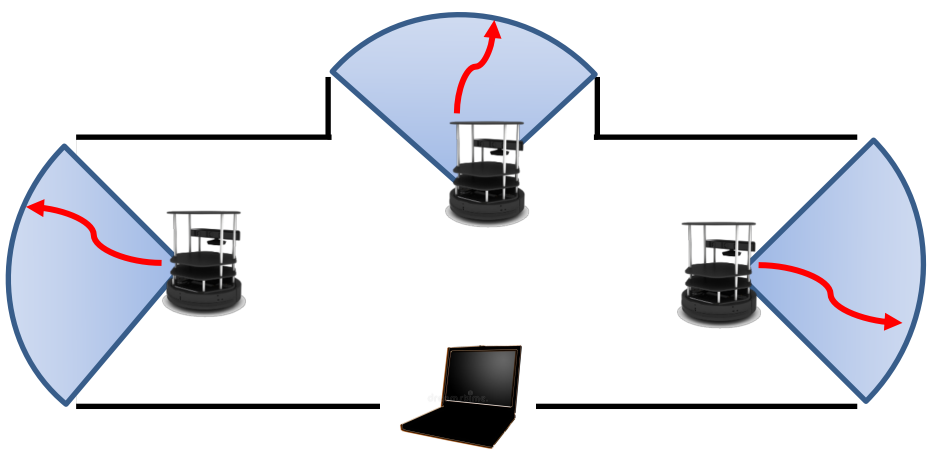
Multirobot Exploration in a Nutshell

- A team of robots is deployed in an unknown environment to incrementally discover and map its physical features
- The exploration cycle: (3) Decision on where to go next



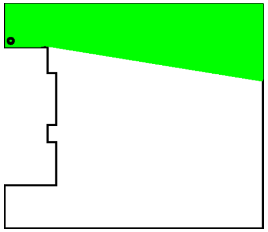
Multirobot Exploration in a Nutshell

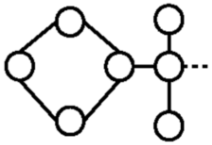
- A team of robots is deployed in an unknown environment to incrementally discover and map its physical features
- The exploration cycle: (4) Path planning

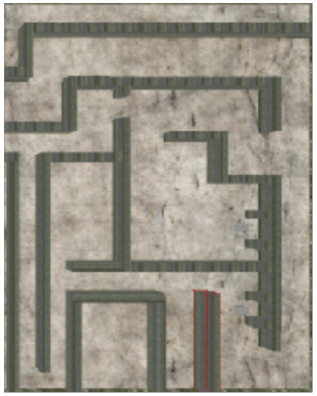


Related Work

- Theoretical approach: bounds, competitive ratio, … (e.g., [Deng et al., J ACM], [Tovey and Koenig, 2003])
- «Practical» approach: next best view methods (e.g., [Yamauchi, 1998], [Amigoni, 2008], [Julia et al., 2012]) and information-based methods (e.g., [Stachniss et al., 2005])







Challenges

1. **Communication constraints**
   - Typical assumption: robots can always communicate with each other with high-bandwidth and are always connected
   - This assumption does not hold in many real contexts
2. Need for **communication maps** that provide knowledge on whether robots can communicate from arbitrary locations
3. Need for **planning paths that guarantee connection** between robots

We provide algorithmic contributions
to address these challenges

Adding Communication Constraints

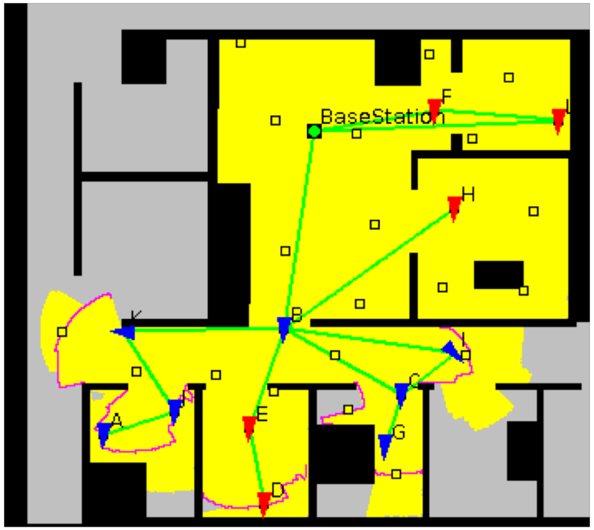
Different communication requirements can be imposed on the exploration mission:

I. None: robots are not required to communicate (e.g., [Fox et al., 2006])
II. Event-based: connection is triggered by particular events, such as when new data is acquired (recurrent connectivity, e.g., [Pei et al., 2013])
III. Continuous: robots must be connected at all times (e.g., [Rooker and Birk, 2007])

Recurrent Connectivity - Problem

"Connect with the Control Station each time new information is acquired from the exploration frontiers"

Challenge: is it possible to ensure such constraint without excessively hindering the exploration process?



Recurrent Connectivity - Solution

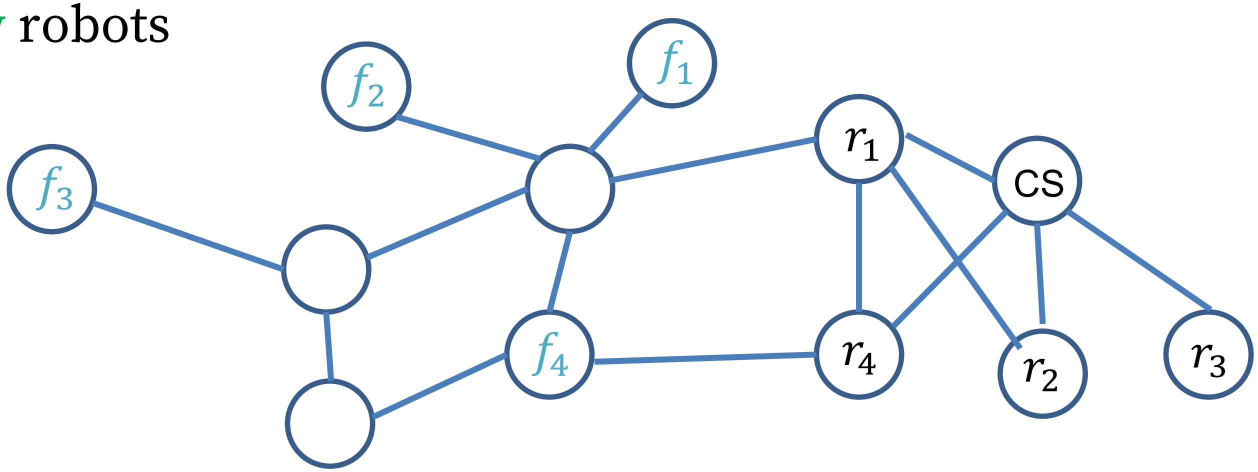
- Model the environment as a (multi)graph describing its physical and communication features
- "Ready" robots: those that have already sent (or relayed) data to the Control Station
- Compute new robots' deployment for groups of ready robots

A New Exploration Strategy

- Recurrent connectivity constraint:

  "Connect with the Control Station each time new information is acquired from the frontiers"

- Challenge: is it possible to ensure such constraint without excessively hindering the exploration process?
- Solution: asynchronous replanning, i.e., replan for groups of θ ready robots



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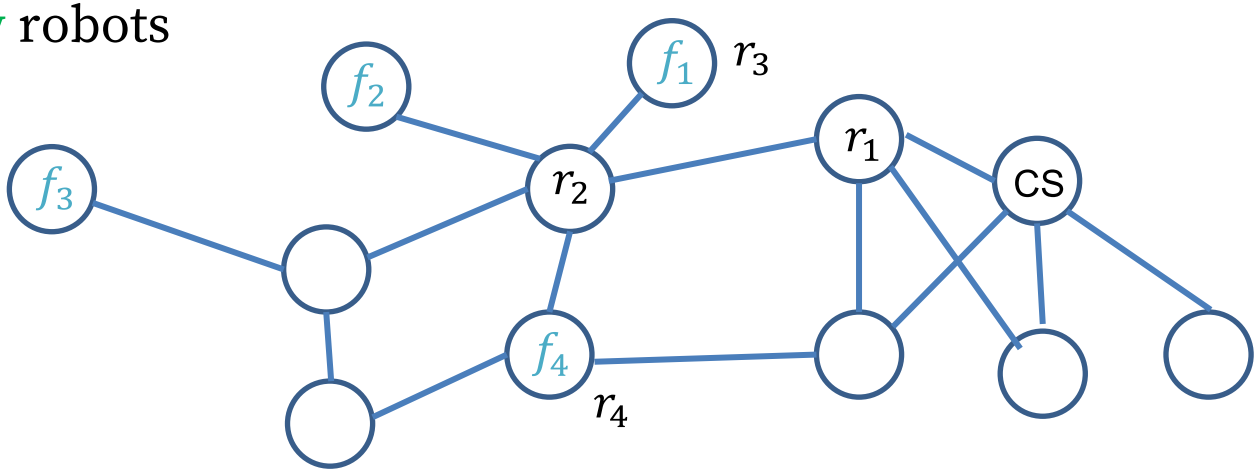

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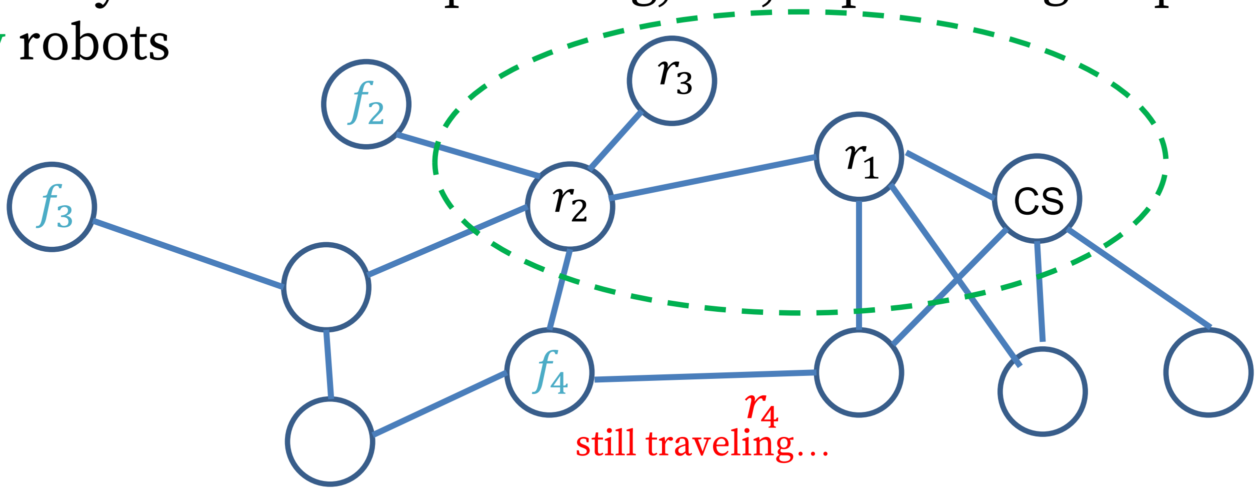

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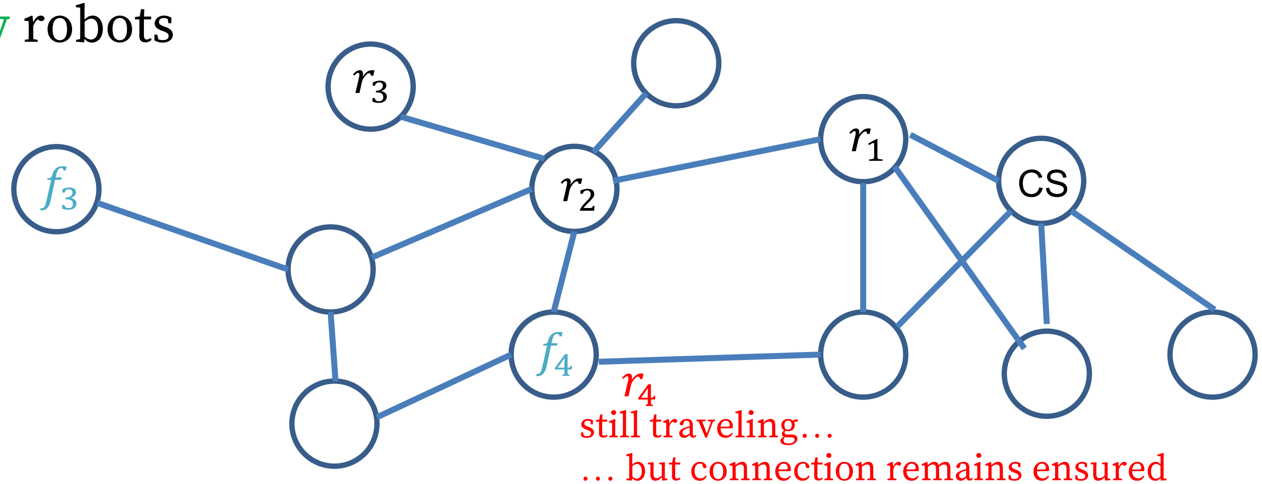

The Need for Communication Maps

- Most of the exploration strategies presented in the literature work with some *a priori* communication model chosen conservatively (e.g. Line-of-Sight) to avoid false positives
  - This ensures robust long-term planning

- Along with such *a priori* model, it could be better to have a subteam of robots building online a communication map based on real samples (two robots are required for each measure)

Related Work

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- **Communication models**: *a priori* knowledge about the possibility of communicating between two given locations
    - usually, chosen conservatively (avoids false positives)

I. None: no assumption is made; coordination is opportunistical (e.g., [Burgard et al., 2005])

II. Line-of-Sight: communication if mutually visible (and, usually, within a given range) (e.g., [Arkin and Diaz, 2002])

III. Circle: communication if within a given range (e.g., [Hollinger and Singh, 2012])

IV. Signal: communication if the estimate of the signal strength is above a given threshold (e.g., [Spirin and Cameron, 2014])

V. Traces: usage of beacons and tags (e.g., [Jensen et al., 2014])

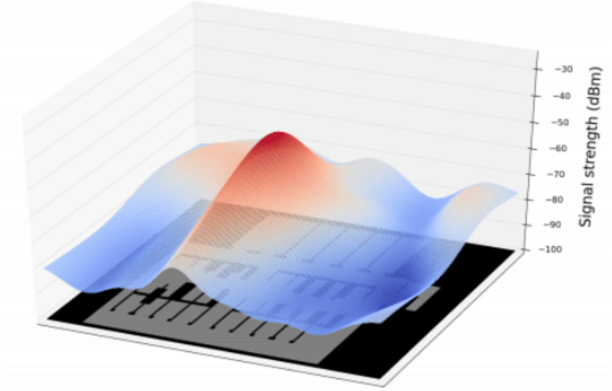
Communication Maps - Problems

- How to represent the map?
  - we need to make predictions about arbitrary location pairs
  - we want to associate each prediction with a confidence value

- How to drive robots around to collect meaningful samples?
  - this is crucial for online applications (like exploration)

Communication Maps - Solutions

- How to represent the map?
  - Gaussian Processes

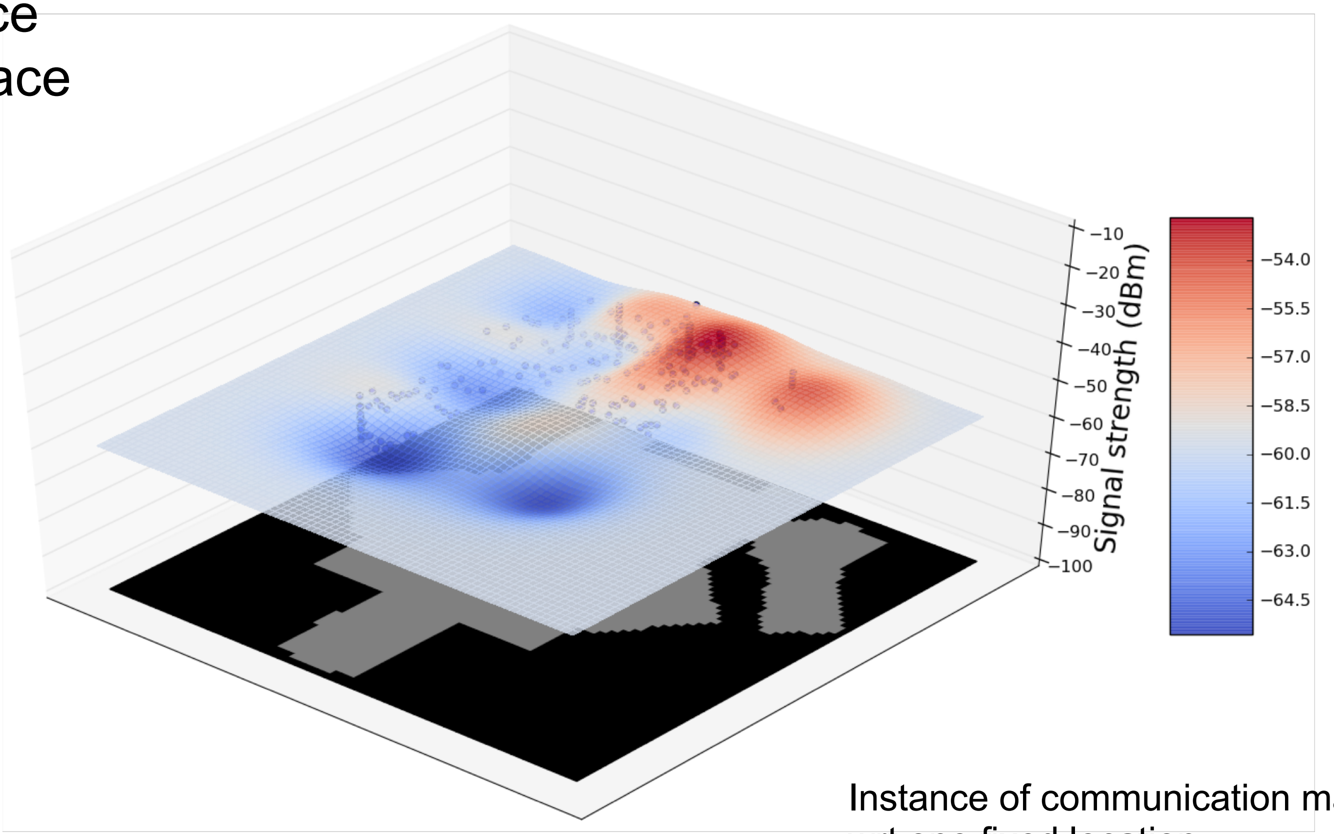


- How to drive robots around to collect meaningful samples?
  - Send the robots to regions of the environment with high uncertainty

Communication Maps - Models

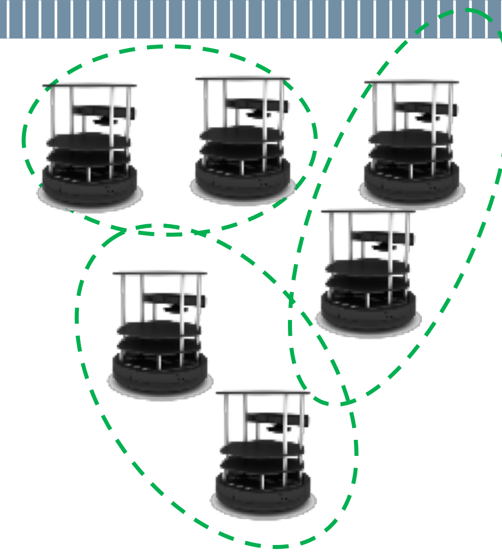
Gaussian Process to model the communication map

- 4d input space
- 1d output space



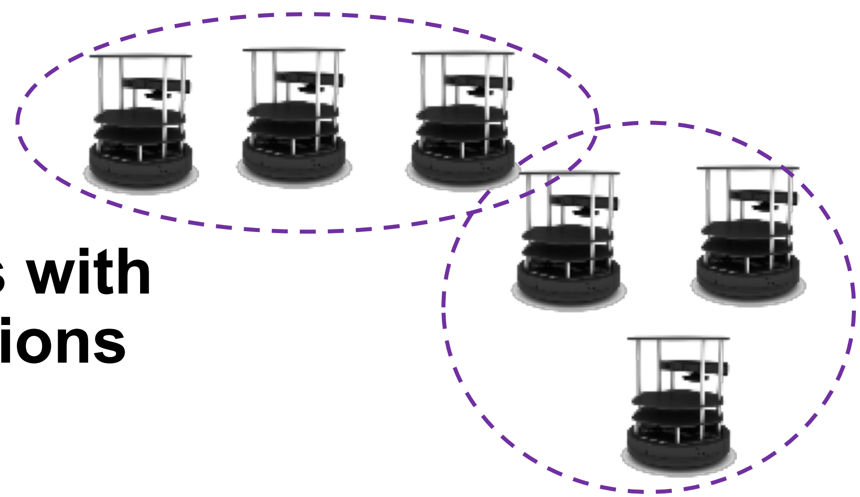
Instance of communication map
wrt one fixed location

Communication Maps - Strategies



Pairwise Mapping (PM)

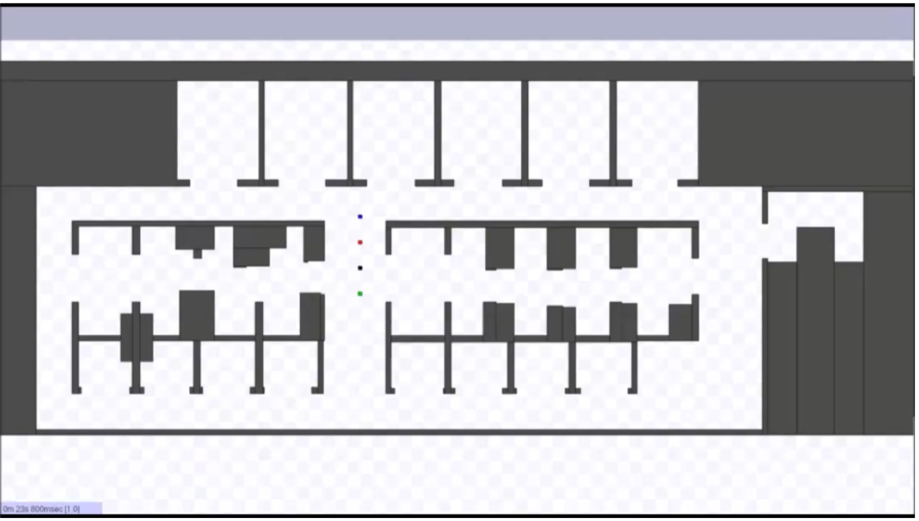
- Focus: robots with same capabilities
- Idea: divide robots in **leader-follower pairs** to go to **locations pair** with high predictive variance



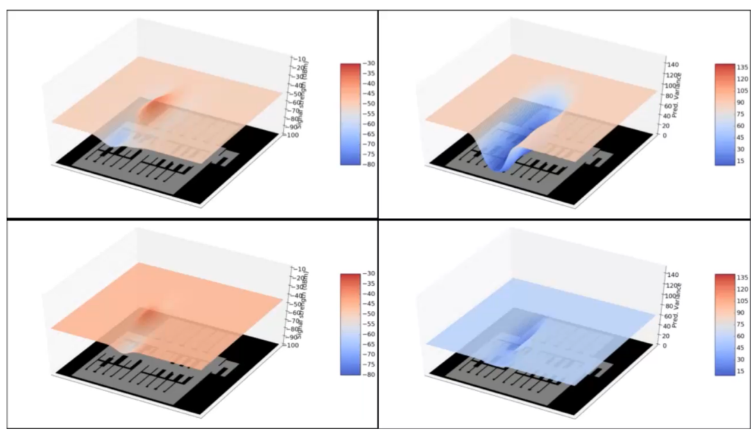
Region Mapping (RM)

- Focus: few robots with more computational power
- Idea: divide robots in **groups with one leader** each to go to **regions** with high predictive variance

Communication Maps - Experiments



Simulations



TurtleBots 2

Cooperation with the University of South Carolina

Multirobot Connected Path Planning

Maintaining **connectivity** among **multiple robots** provides a number of advantages, such as:

- **Sharing information** acquired on the fly
- **Coordination** in carrying out tasks
- Distributed decision making (**more reliability**)

CHALLENGE: A global connectivity could not be available.

IDEA: Planning the robots' paths in such a way they are connected continuously [1] or at discrete steps [2].

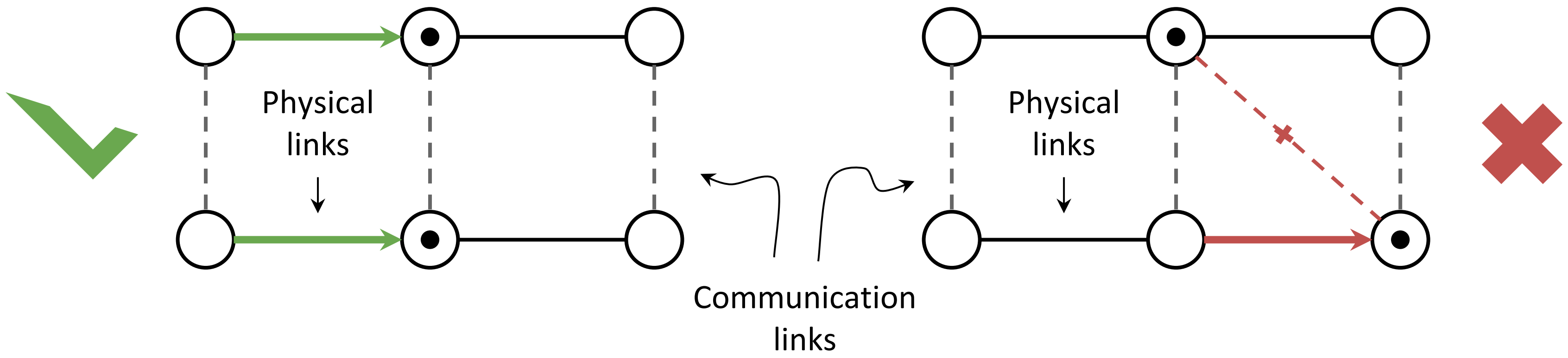
[1] Bhattacharya, S.; Likhachev, M.; and Kumar, V. 2010. Multi-agent path planning with multiple tasks and distance constraints. In Proc. ICRA , 953–959.

[2] Hollinger, G., and Singh, S. 2012. Multirobot coordination with periodic connectivity: Theory and experiments. IEEE T Robot 28(4):967–973.

Multirobot Connected Path Planning

Discrete optimization approach:

- Graph-represented environment
- **Robotic agents** plan a set of start-goal **joint paths** on the graph
- Paths are constrained to **maintain** all the **agents connected** at each step, under some communication model (e.g., distance-based)

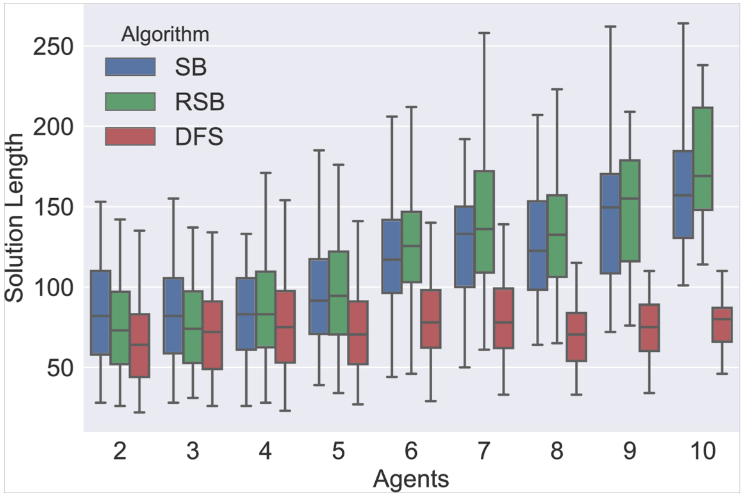


Multirobot Connected Path Planning

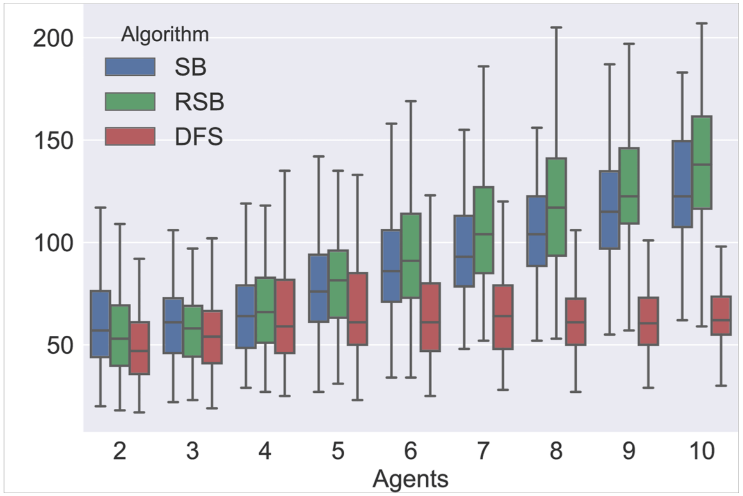
Our contributions

- We proved the **problem** to be **PSPACE-complete**
- We provided **three** different **algorithms** (SB, RSB, DFS)
- Many **realistic-sized** instances can be solved **efficiently**

Office Environment



Open Environment



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