Communication-Constrained Multirobot Exploration: Short Taxonomy and Comparative Results

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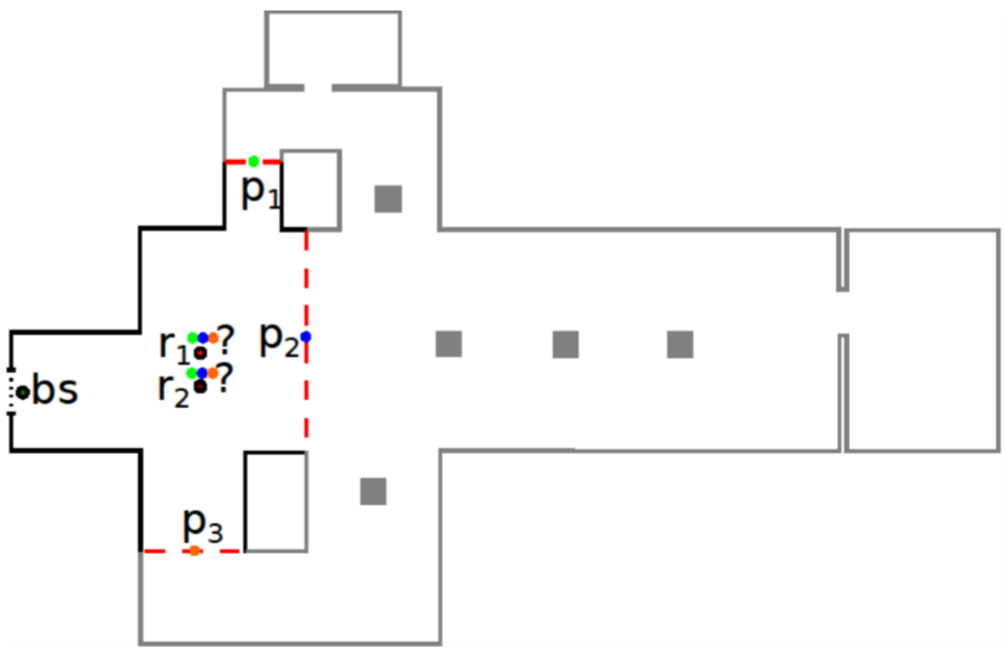
Robot exploration

- *Multirobot exploration* is fundamental for map building, search and rescue, …
- *Exploration strategies* are fundamental to drive robots to the next candidate locations

Source: robocup.org



Exploration strategies

- Several exploration strategies have been proposed in literature (e.g., [Yamauchi, 1998, CIRA], [Wurm et al., 2008, IROS], [Basilico and Amigoni, 2011, Auton Robot])

- Typical assumption: robots can always communicate with each other with high-bandwidth and are always connected

- Some exploration strategies have been proposed requiring that robots are able to communicate with a base station under realistic communication models

Purpose of the work

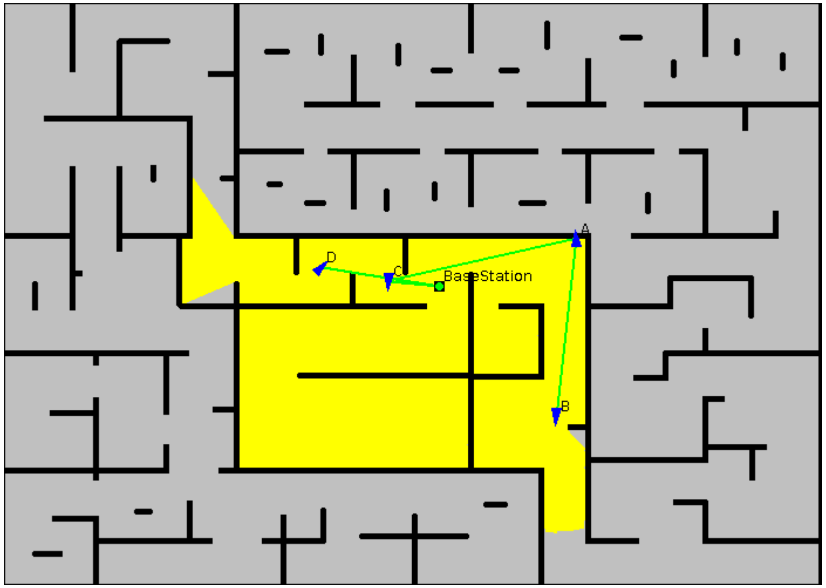
- Provide a short taxonomy of exploration strategies **with communication constraints to a base station**
- Comparatively evaluate different strategies with different types of communication constraints
  - How do they affect the exploration performance?

Short taxonomy

- **Continuous** connection with BS (e.g., [Rooker and Birk, 2007, Control Eng Pract])
  - Application: Search and Rescue
- **Connectivity at deployment positions** (e.g., [Stump et al., 2011, ICRA])
  - Application: Search and Rescue, Map building
- **Periodic reconnection**: communicate discoveries under a more or less strict regime (e.g., [Spirin et al., 2013, TAROS])
  - Application: Map building, precision agricolture

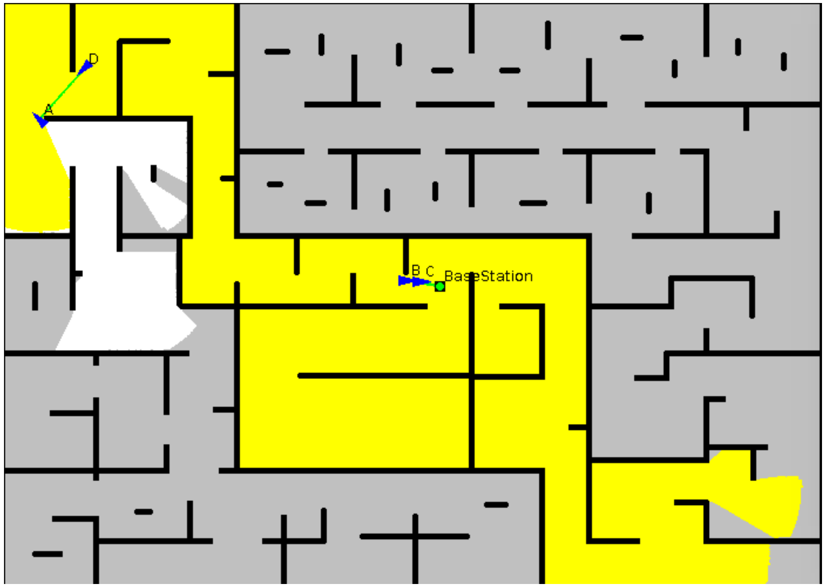
Hard vs soft constraints

- *Communication constraints are said to be **hard** if (i) when a robot acquires some information at some location, it must be able to forward it to the BS from that same location, and (ii) before any new plan is computed, the whole team (robots and BS) must be globally connected*



Hard vs soft constraints

- *Communication constraints are said to be* ***soft*** *if the communication between the BS and the robots, despite being a desired condition, needs not to be maintained on a regular basis*



Assumptions

- Two-dimensional environments to explore represented with occupancy grids
- One fixed base station (BS)
- m differential drive mobile robots equipped with a 180° laser range scanner
- Limited line-of-sight communication model (conservative approach, as the environment is unknown)

Hard constraints - exact formulation

$$\text{maximize} \sum_{a \in A} \sum_{v \in V^{t+1}} (g(v) - \alpha d(q_a^t, v)) z_{av} \qquad (1)$$

subject to

$$\sum_{a \in A \setminus \{BS\}} z_{av} = y_v \qquad \forall v \in V^{t+1} \setminus \{b\} \qquad (2)$$

$$\sum_{v \in V^{t+1} \setminus \{b\}} z_{av} = 1 \qquad \forall a \in A \setminus \{BS\} \qquad (3)$$

$$\sum_{(i,j) \in \mathcal{C}^-(v)} x_{ij} = y_v \qquad \forall v \in V^{t+1} \setminus \{b\} \qquad (4)$$

$$\sum_{(i,j) \in \delta^-(S)} x_{ij} \geq y_v \qquad v \in S, b \notin S, \ \forall S \subseteq V^{t+1} \qquad (5)$$

- Compute new deployment on graph $G = (V^{t+1}, C^{t+1})$
- $z_{av} = 1$ iff agent a in vertex v, in this case collect utility proportional to information gain and distance to v
- Constraints (5) exponential in number, but model can be solved optimally

Selected exploration strategies

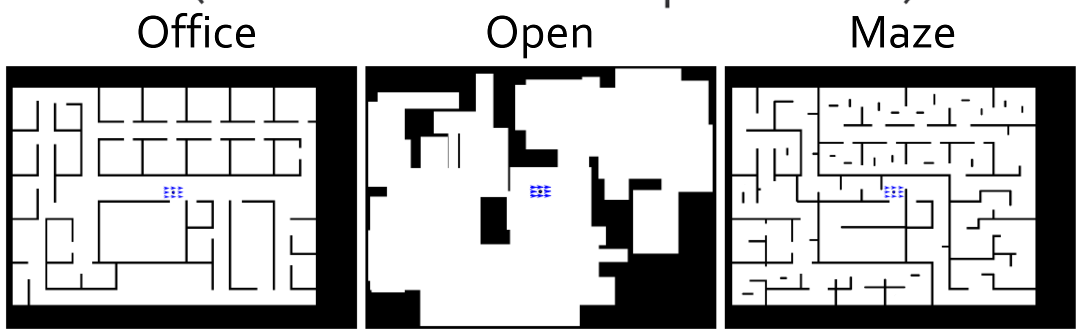
Method	Communication constraints	Coordination
Optimal Hard	Hard	Centralized
Stump [Stump et al., 2011, ICRA] (adapted)	Hard	Centralized
Rooker [Rooker and Birk, 2007, Control Eng Pract]	Hard (continuous)	Centralized
Utility [Spirin et al., 2013, TAROS] r → 0 greedy, r → 1 quasi-hard r=0.1,0.5,0.9	Soft	Decentralized

Simulator

- MRESim [de Hoog et al., 2009, COGNITIVE]
  - Focuses on communication aspects
  - Used to test other exploration strategies (e.g., [de Hoog et al., 2010, TAROS], [Spirin et al., 2013, TAROS]) and to look at the effect of different communication models [Tuna et al., 2012, Ad Hoc Netw]
  - Enabling comparison and reproduction of results [Amigoni et al., 2009, Auton Robot]

Experimental setting

- Environments (size about 800 x 600 pixels each)



- Teams of 2, 4, 6, and 8 robots
- For each environment, team, exploration strategy, we execute 5 runs of 500 time steps (robot speed: 4px/step)
- Metrics measured
  - Traveled distance by the robots
  - Time robots are not in communication with the BS
  - Amount of explored area known by the BS
  - Replan time

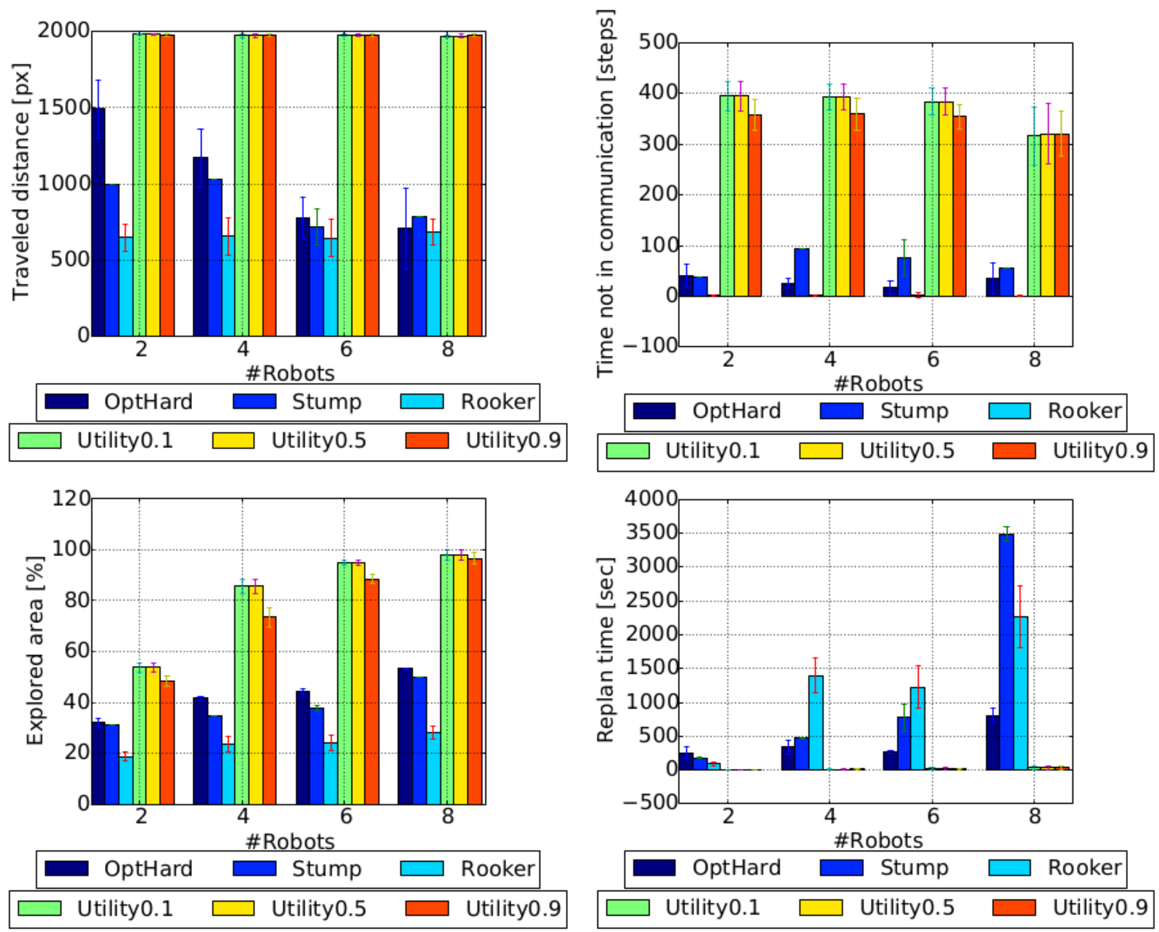
Experimental results

- The stricter the communication constraint, the less traveled distance and explored area

- The looser the communication constraint, the higher the time robots are not in communication with the BS

- Replan time is higher for centralized methods with hard communication constraints

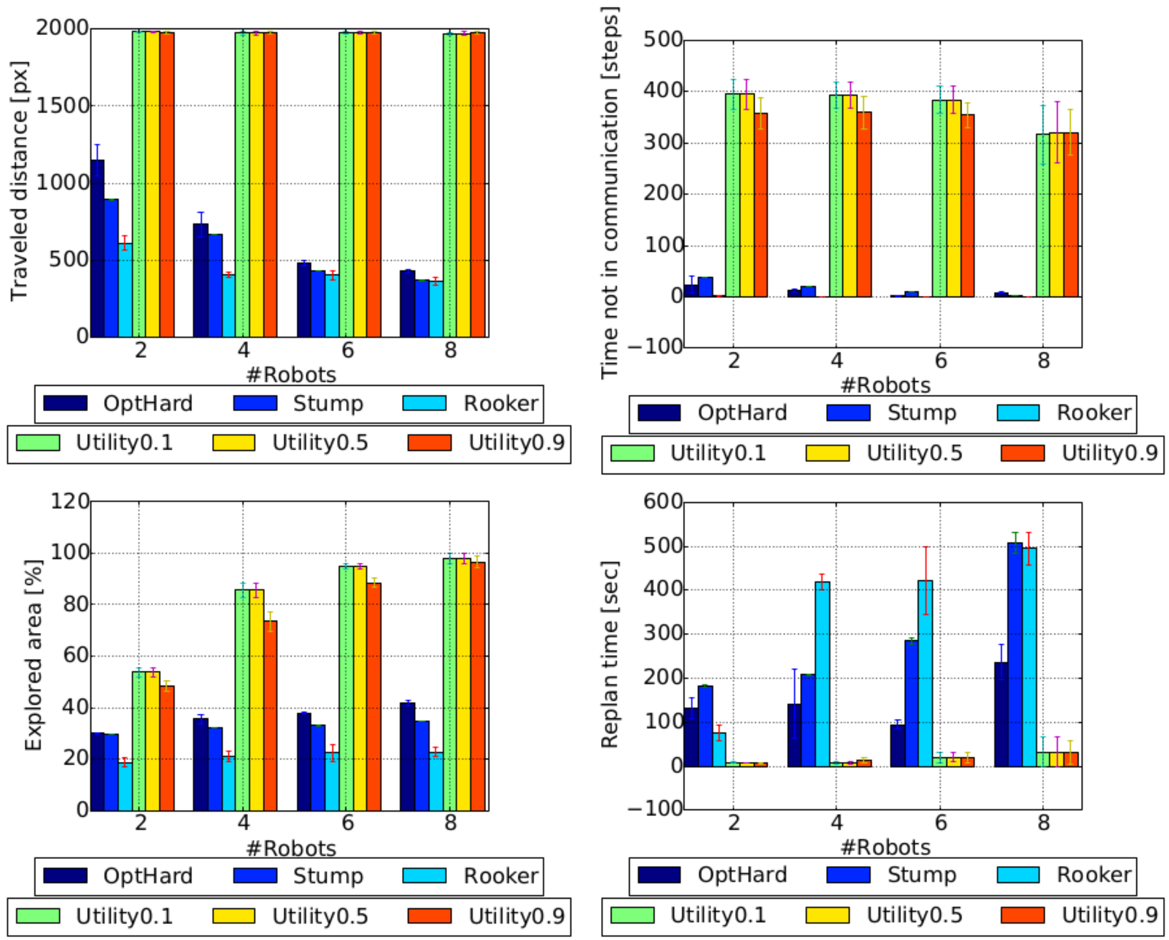
Office – instant replan



Experimental results

Office – with repl. time (1 step = 2 seconds)

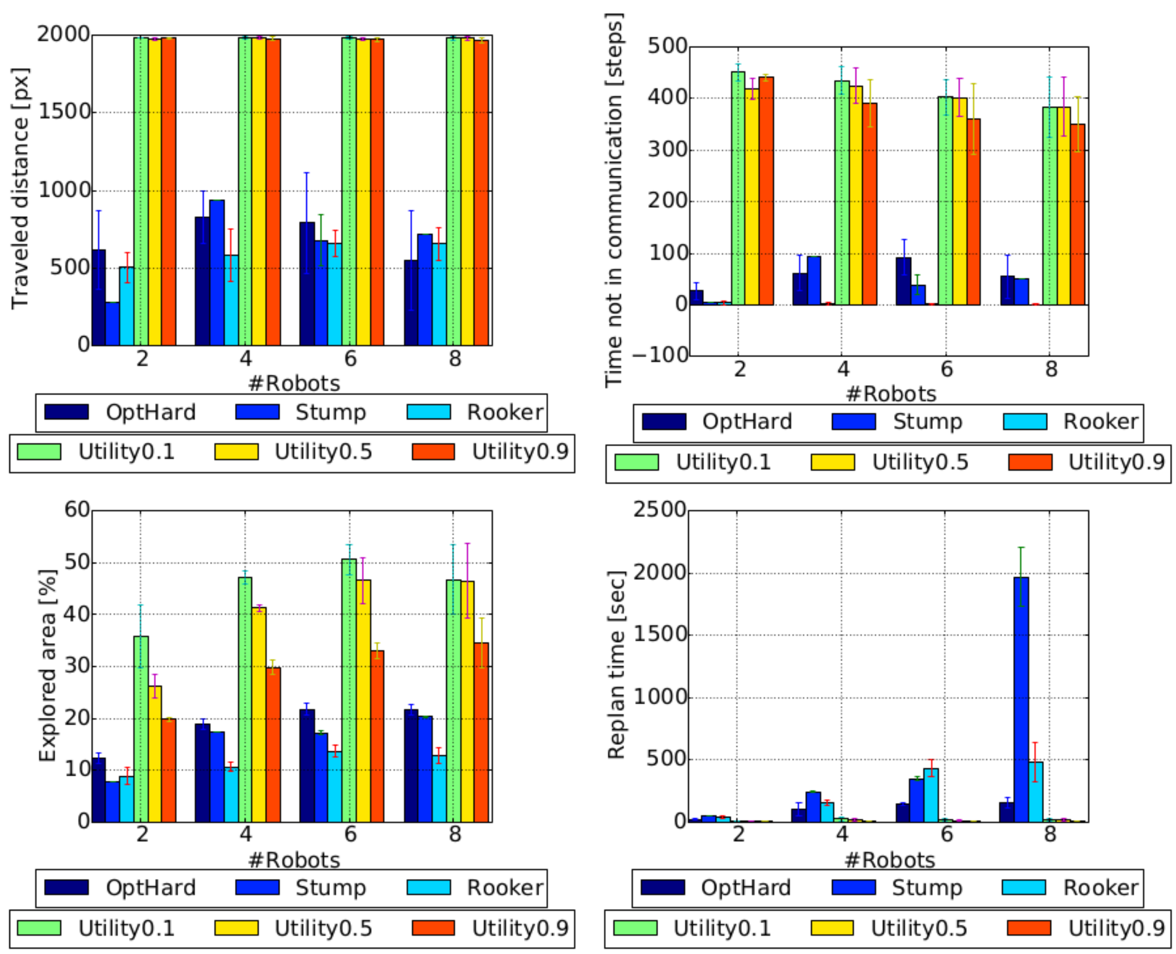
- → Explored area reduced up to 15% for best hard constraint method (planning time starts to be high at the end of the simulation)



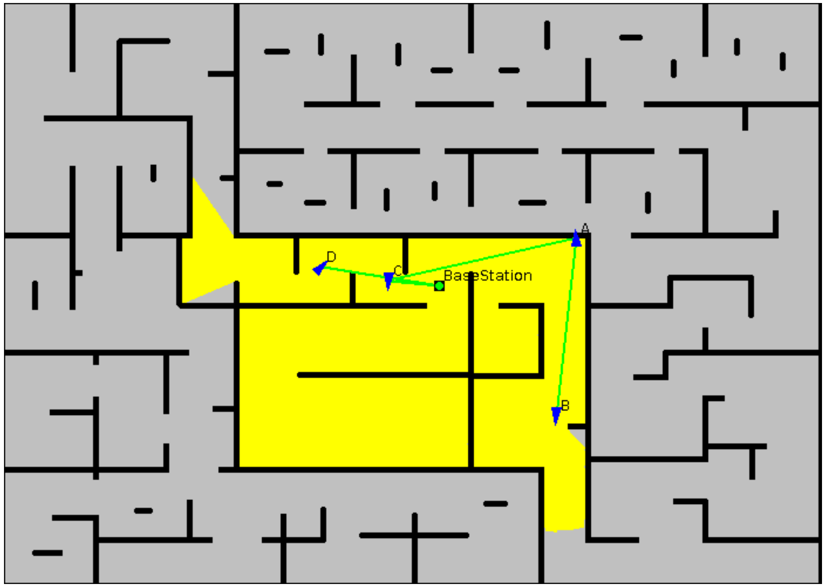
Experimental results

Maze – instant replan

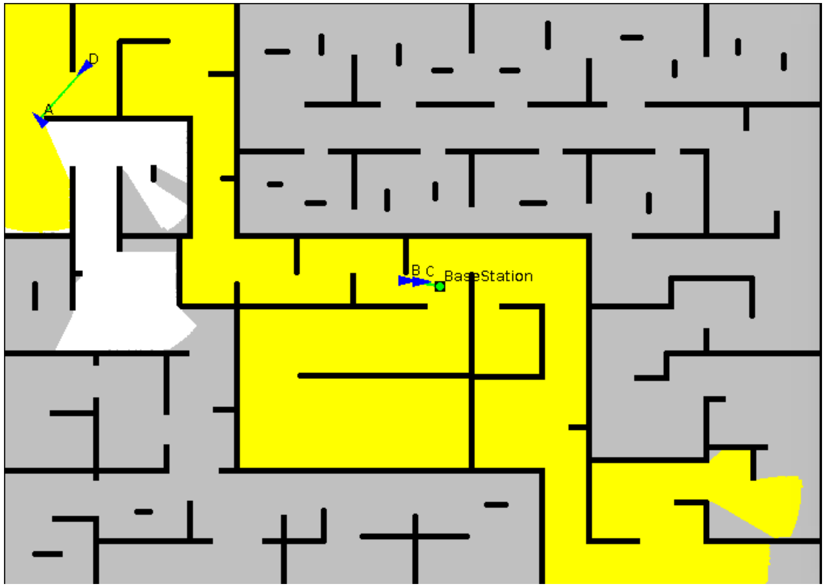
- → Similar trends to those in the office environment
- → The more complex structure of the environment leads methods enforcing soft communication constraints to make robots travel over already explored area



Experimental results



Optimal Hard

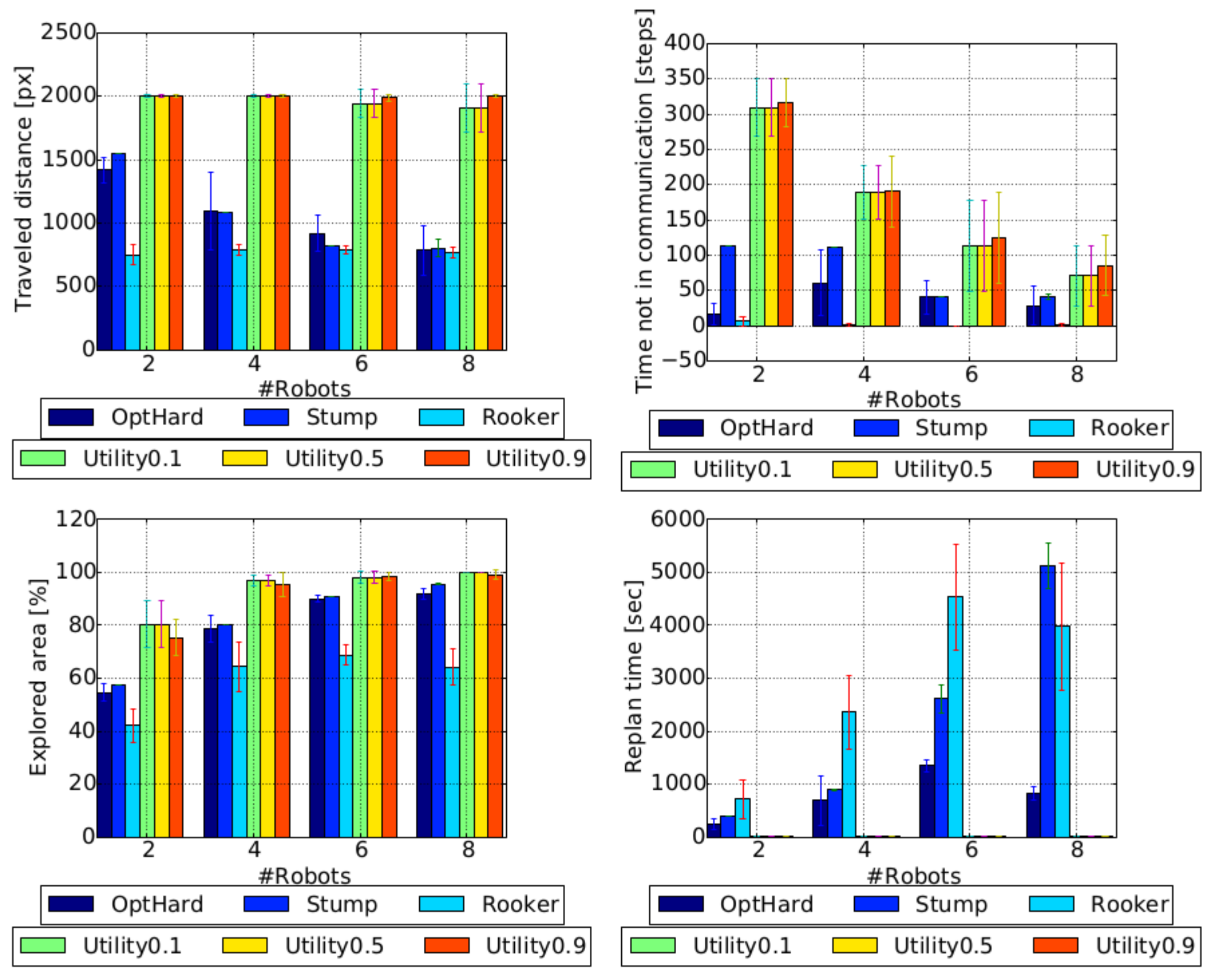


Utility 0.5

Experimental results

Open – instant replan

- In more unstructured environments, it is easier:
  - to explore the environment also for exploration strategies with hard constraints
  - to maintain communication also for strategies that consider soft communication constraints



Conclusions

- Results provide some interesting insights about the trade-off between efficiency/connectivity but are not yet definitive
- Future works include:
  - Exploring asynchronicity in hard communication constraints
  - Real robots

Thank you!

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