9 – Multi-Robot Planning

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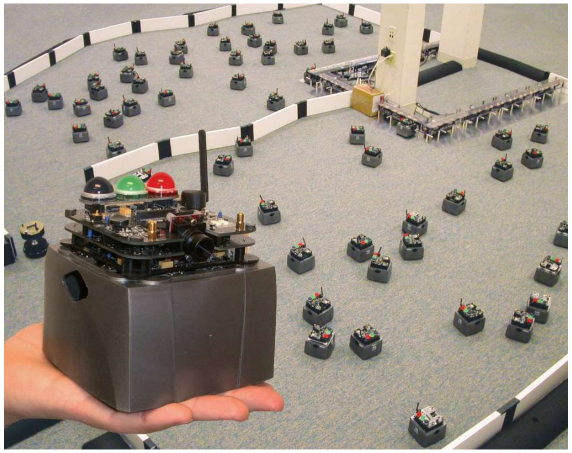
Multi-Robot Systems

- A set of robots which can cooperate and communicate with each other to accomplish certain tasks

Environmental monitoring

Shelving



Construction

https://spectrum.ieee.org/robotics/robotics-software/three-engineers-hundreds-of-robots-one-warehouse
http://people.seas.harvard.edu/~jkwerfel/morpheng.pdf

Single-Robot vs. Multi-Robot

- Advantages:
  - Better spatial distribution
  - Improved robustness
  - Potentially lower cost
  - Diverse range of applications
- Disadvantages:
  - Computational complexity
  - Communication
  - Interference
  - Maintenance

Taxonomy

- **Collective** behaviour
  - Cooperative: Robots work together to complete a task
  - Competitive: Robots compete against each other for self-interest or have conflicting utility functions
- **Communication** methods
  - Explicit: Robots use communication media
  - Implicit: Robots infer information through the environment

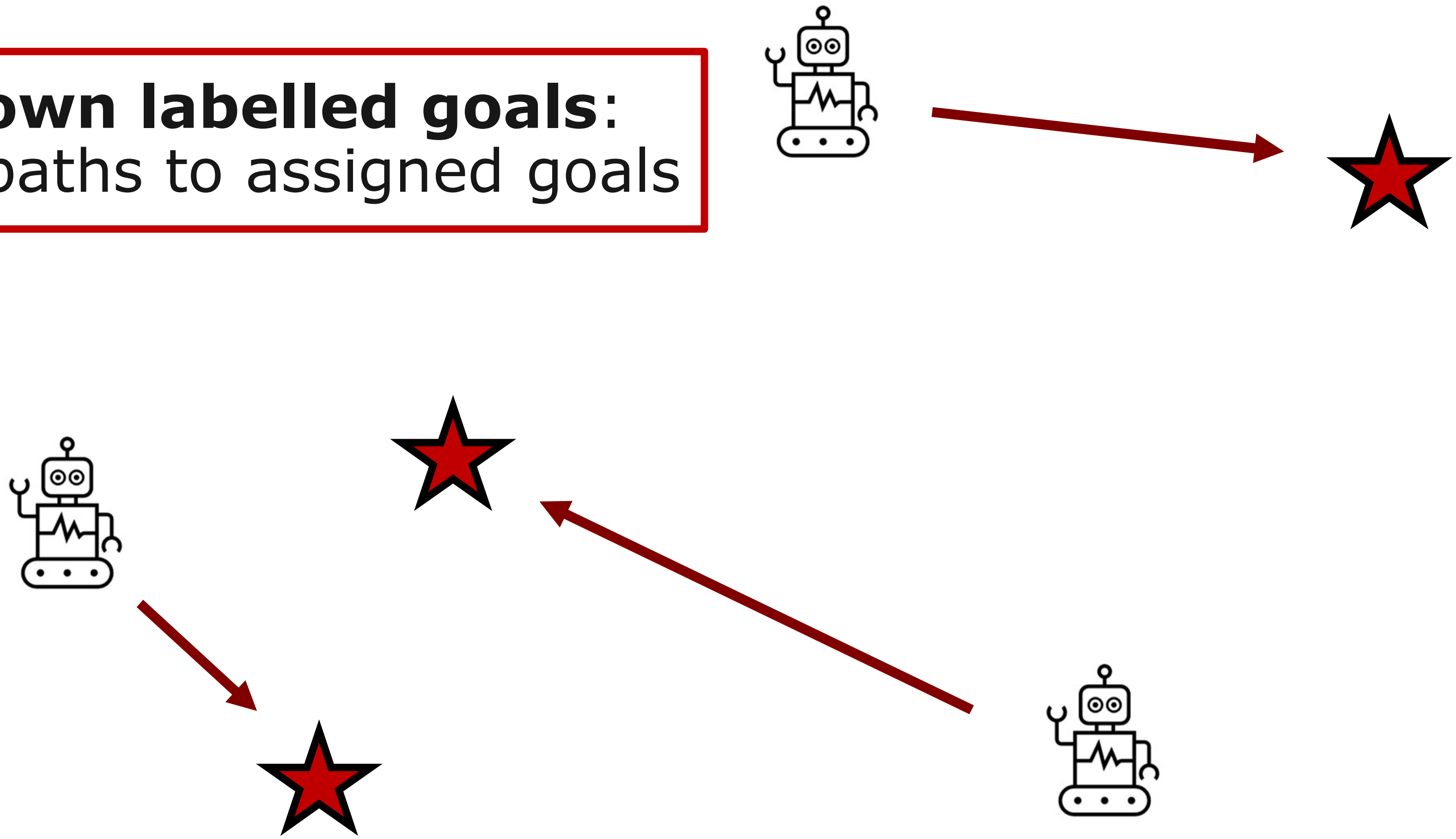
Taxonomy

- **Decision-making** approach
  - Centralised: Central control agent with global information that can communicate to robots
  - Decentralised: No central control agent – can be hierarchical or distributed

- **Problem formulation**
  - Discrete vs. continuous
  - Known vs. unknown goals
  - Labelled vs. unlabelled problem
  - Coupled vs. decoupled state representation

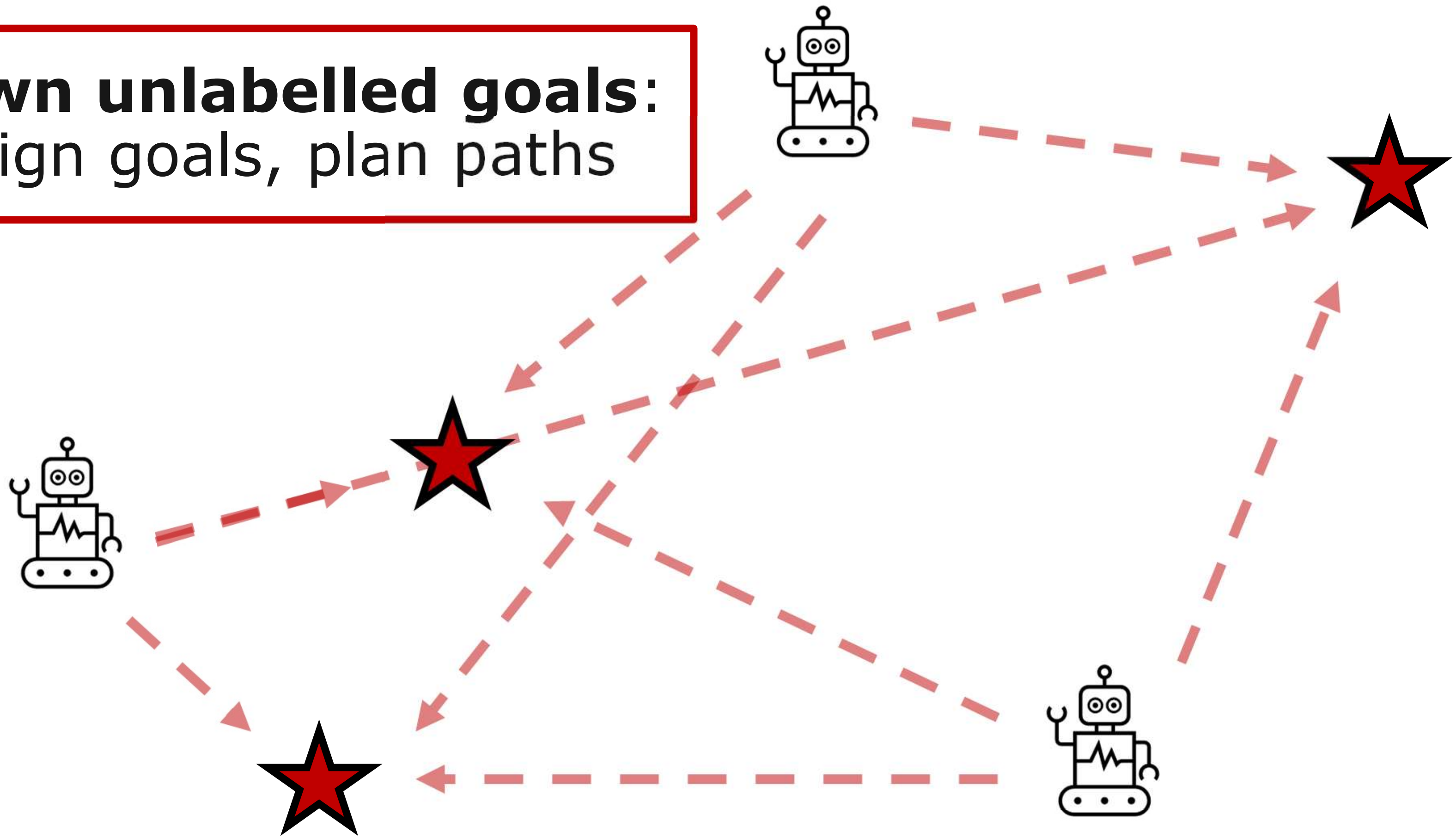
Problem Variations

Known labelled goals:
Plan paths to assigned goals



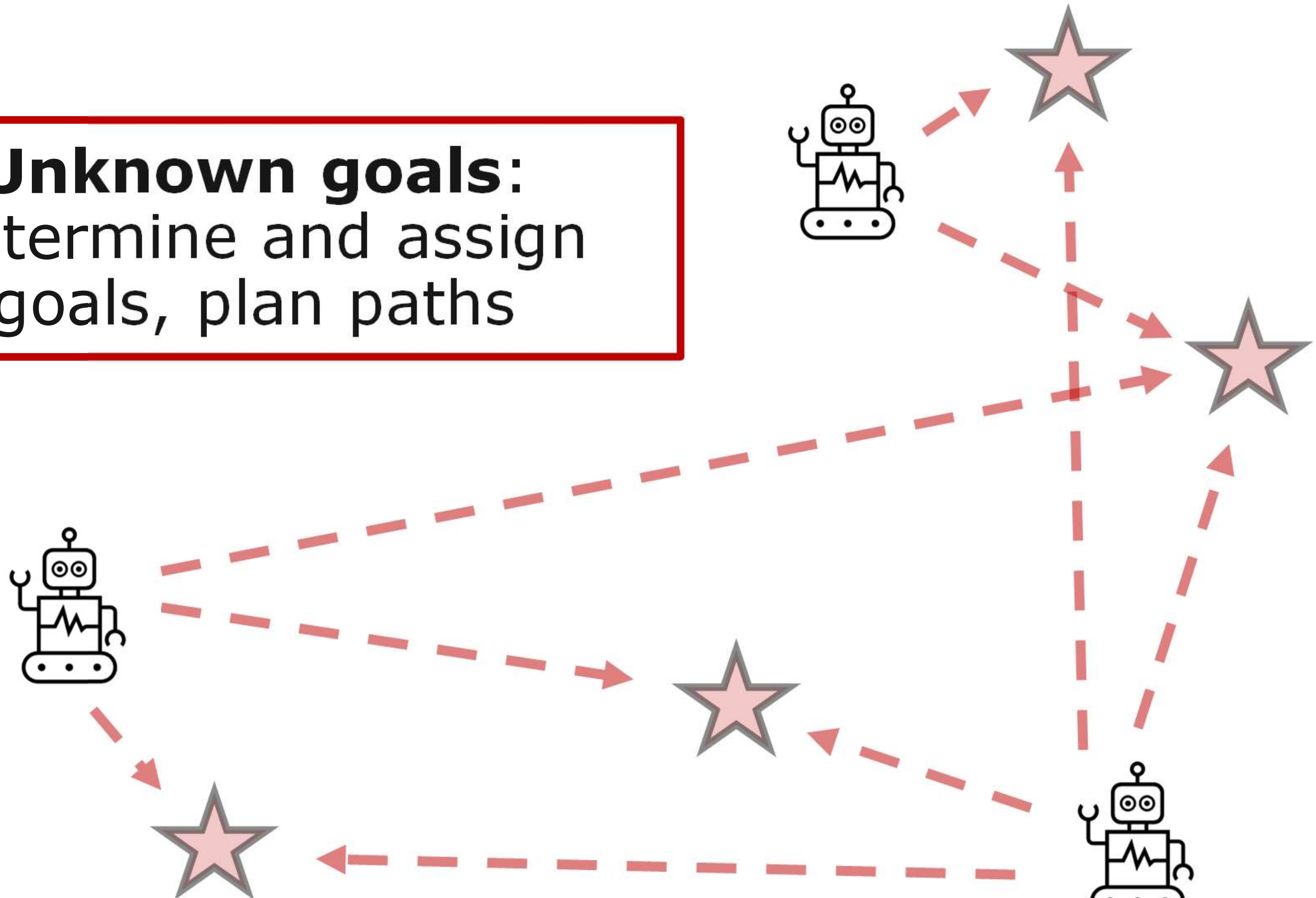
Problem Variations

Known unlabelled goals:
Assign goals, plan paths



Problem Variations

Unknown goals:
Determine and assign
goals, plan paths



Reward: Explore environment, find targets, maximise map accuracy, collect measurements, etc.

Multi-Robot Planning Strategies

Centralised vs. Decentralised

- **Centralised**: One entity plans for the entire robot team
  - Coupled planning: joint configuration space
  - Decoupled planning: each path planned separately
- **Decentralised**: Robots are completely independent and plan their own paths individually
- **Hybrid**

Centralised Planning: Coupled

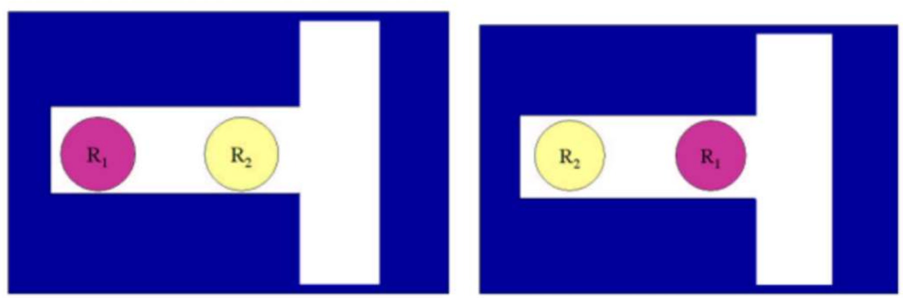
- Plan directly in **joint** configuration space
- For K robots:

  $\mathcal{C} = \mathcal{C}_1 \times \mathcal{C}_2 \times \ldots \times \mathcal{C}_K$
- Use standard planning methods, e.g. A*, to find a **complete** solution

- Problem space dimensions grow linearly with number of robots
- Computationally intractable even with small teams

Centralised Planning: Decoupled

- First, plan for each robot **separately**
- Then, **coordinate** individual plans
  - Resolve conflicts and avoid collisions
  - Online or offline
- Not complete, not optimal



(a) Initial configuration (b) Goal configuration

Figure 6: A "bad" example for decoupled planning.

Sanchez and Latombe (2002). "Using a PRM Planner to Compare Centralized and Decoupled Planning for Multi-Robot Systems," in: IEEE ICRA.

Centralised Planning: Decoupled

- First, plan for each robot **separately**
- Then, **coordinate** individual plans
  - Resolve conflicts and avoid collisions
  - Online or offline
- Not complete, not optimal

- Coordination strategies:
  - Priority schemes
  - Scheduling techniques

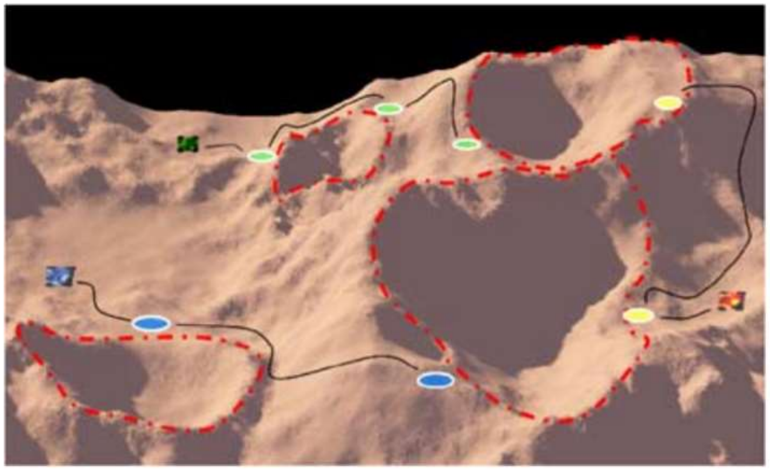
Decentralised Planning

- Information processed locally - computationally efficient and robust
- Suboptimal
- Implicit or explicit communication
- Coordination strategies for collision avoidance, e.g. local replanning

Bähnemann et al. (2017). "A decentralized multi-agent unmanned aerial system to search, pick up, and relocate objects," in: IEEE SSRR.

Hybrid Planning: Market-based

- **Market-based**: Auction protocol to coordinate between different robots
- Assemble team information to allocate limited shared resources
- Robots bid based on utility/cost
- Subteam coordination possible

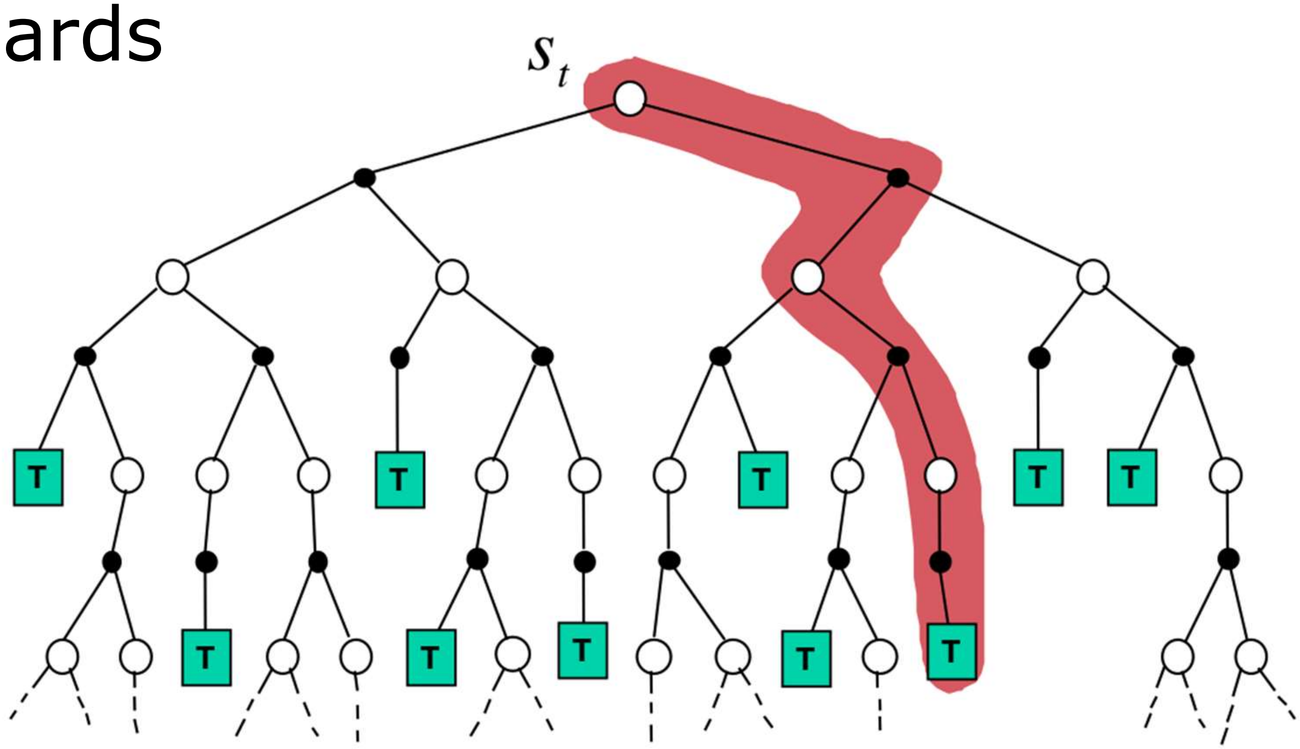


Bernardine Dias, M. et al. (2006). "Market-Based Multirobot Coordination: A Survey and Analysis", in: Proceedings of the IEEE. 1257-1270.

Decentralised MCTS

Monte Carlo Tree Search (MCTS)

- **Completely observable** MDP
- Build search tree of state-action sequences
- **Rollout**: simulate episodes and collect rewards



Decentralised MCTS

- **Idea**: Execute a decentralised MCTS wrt. a belief over the other agents' future action sequences
  - Best et al. (2018). "Dec-MCTS: Decentralized planning for multi-robot active perception," in: IJRR. 38(2): 316-337.

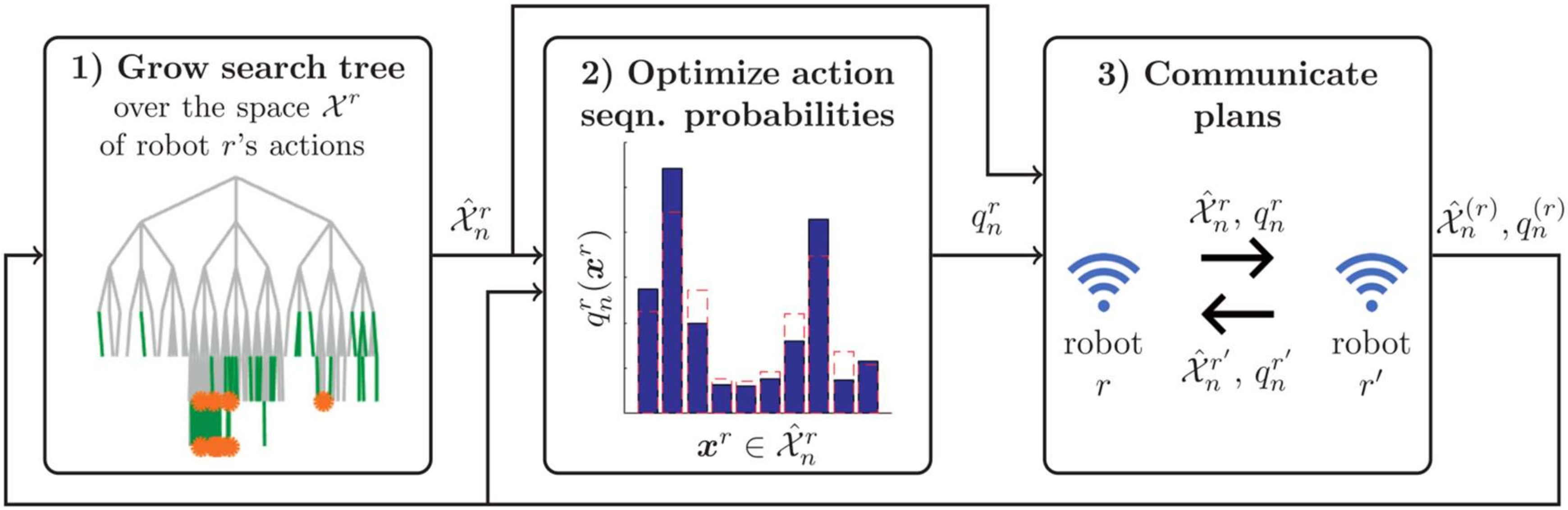
- **Advantages**:
  - Applicable with any objective function
  - Anytime planning
  - Robust
  - Scalable to large robot teams

Decentralised MCTS

- **Idea**: Execute a decentralised MCTS wrt. a belief over the other agents' future action sequences
  - Best et al. (2018). "Dec-MCTS: Decentralized planning for multi-robot active perception," in: IJRR. 38(2): 316-337.

- **Procedure**:
  1. Grow MCTS search tree wrt. other robots' plans
  2. Update prob. distribution over next actions
  3. Communicate prob. distribution over next actions to other robots
  4. Receive prob. distributions from other robots over their next actions

Algorithm



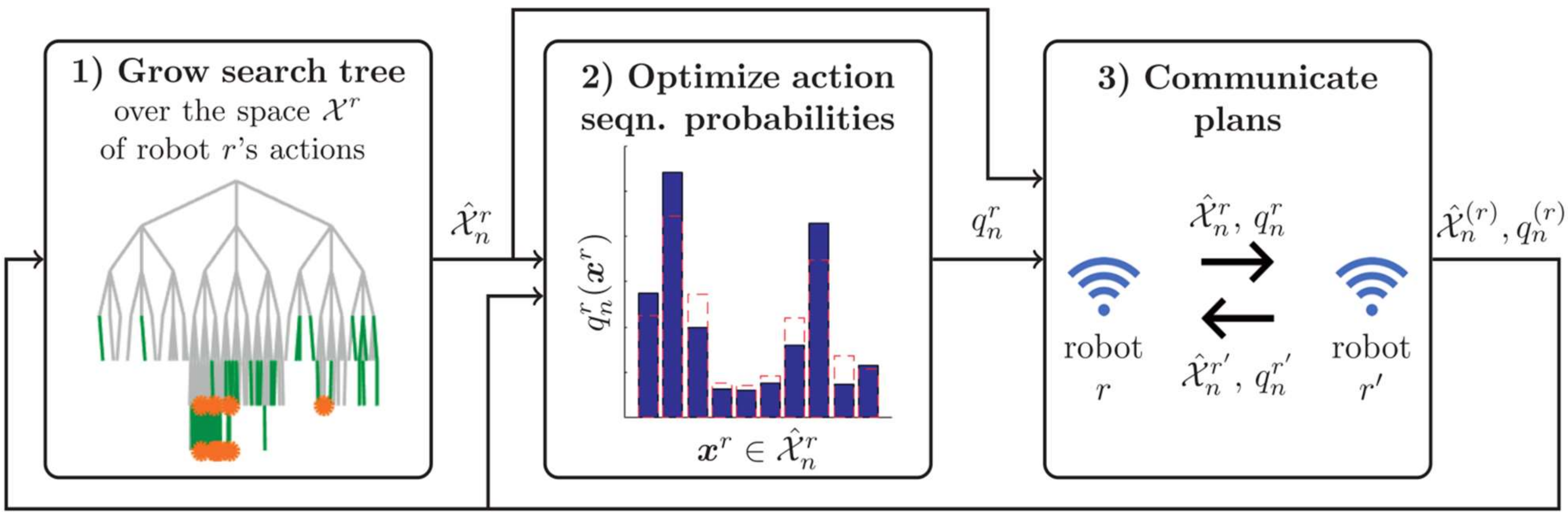
Robot's utility function

$$f^r(\boldsymbol{x}) := g(\boldsymbol{x}^r \cup \boldsymbol{x}^{(r)}) - g(\boldsymbol{x}^r_\emptyset \cup \boldsymbol{x}^{(r)})$$

Robot r takes action

Other robots

Algorithm



Robot's utility function

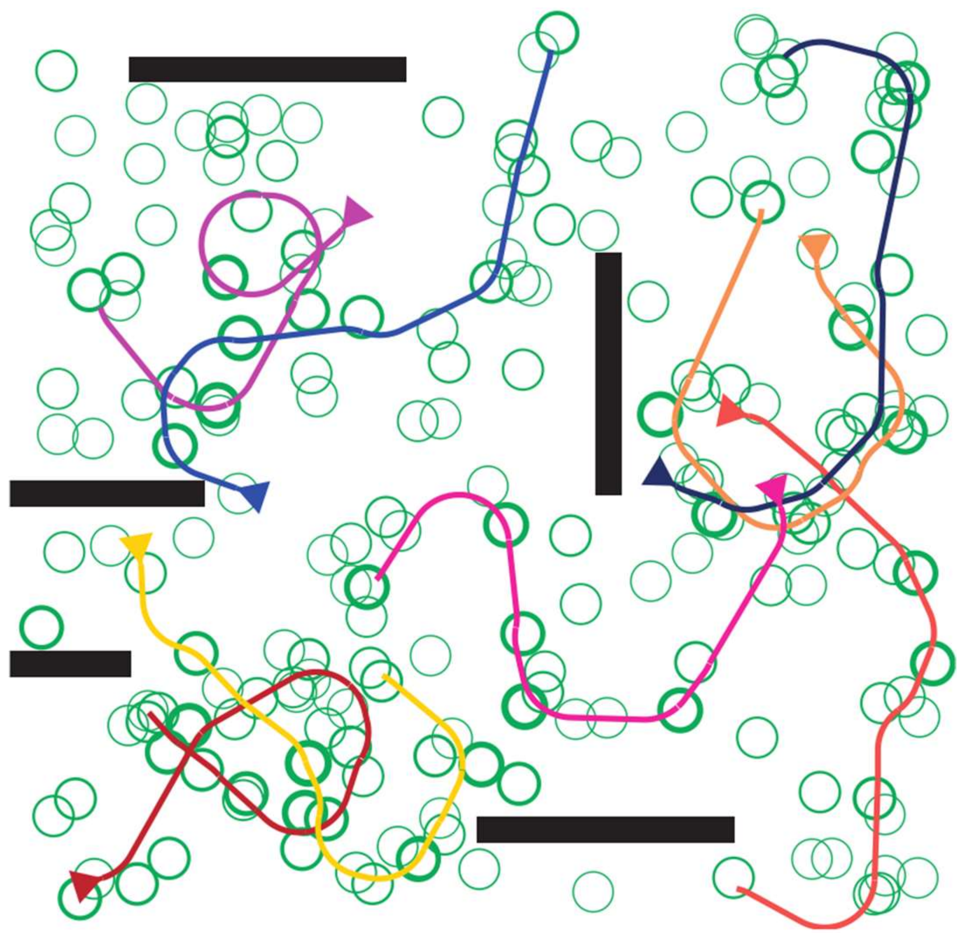
$$f^r(\boldsymbol{x}) := g(\boldsymbol{x}^r \cup \boldsymbol{x}^{(r)}) - g(\boldsymbol{x}_\emptyset^r \cup \boldsymbol{x}^{(r)})$$

Robot r stays idle

Other robots

Results

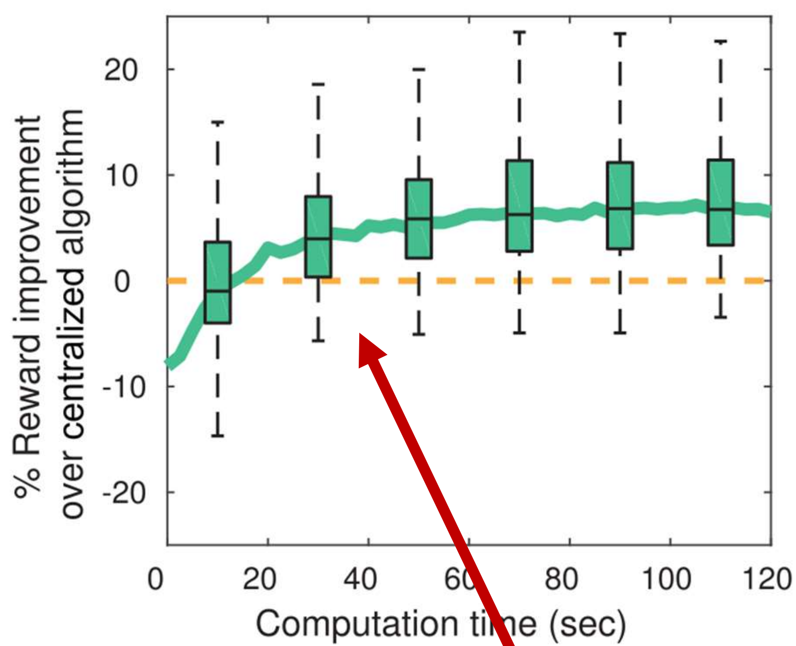
- Generalised team orienteering problem



Results

- 100 trials

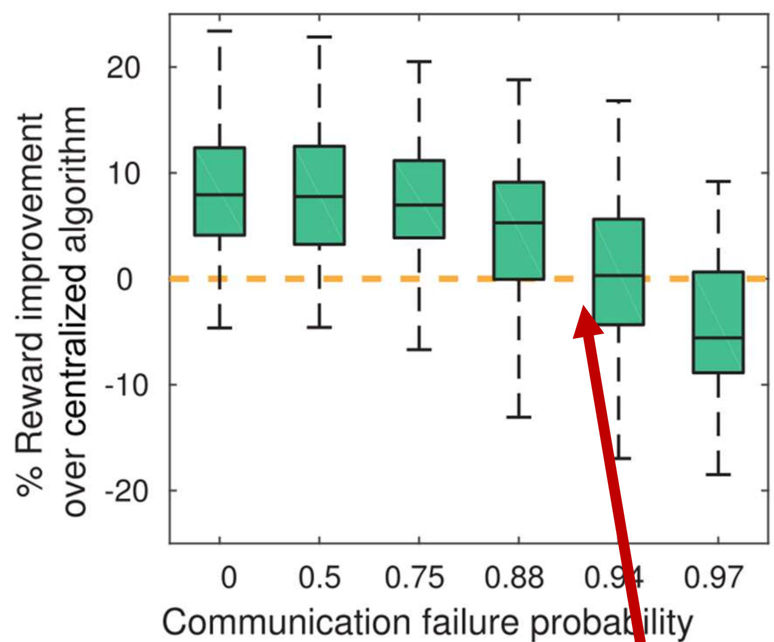
Performance



(a)

Higher rewards

Communication Robustness



(b)

Higher rewards with limited comm.

Summary

- Multi-agent systems
- Decision-making approaches
  - Centralised
  - Decentralised
  - Hybrid (market-based)
- Decentralised MCTS
  - General multi-robot planning algorithm

Further Reading

- Yan et al. (2013), “A Survey and Analysis of Multi-Robot Coordination,” in: Artificial Intelligence. 10(12).
- Lifeng and Tokekar (2021), “Multi-Robot Coordination and Planning in Uncertain and Adverserial Environments,” in: Current Robotics Reports.
- Parker, L.E. (2009). “Multiple Mobile Robot Teams, Path Planning and Motion Coordination”, in: Encyclopaedia of Complexity and Systems Science.
- Bernardine Dias, M. et al. (2006). “Market-Based Multirobot Coordination: A Survey and Analysis”, in: Proceedings of the IEEE. 1257-1270.
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Thank you for your attention