# Multi-Robot Perception and Action: World Modeling and Task Allocation

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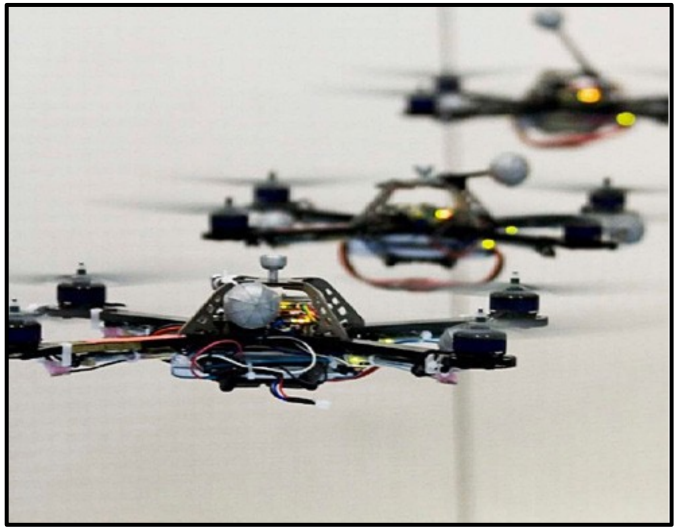
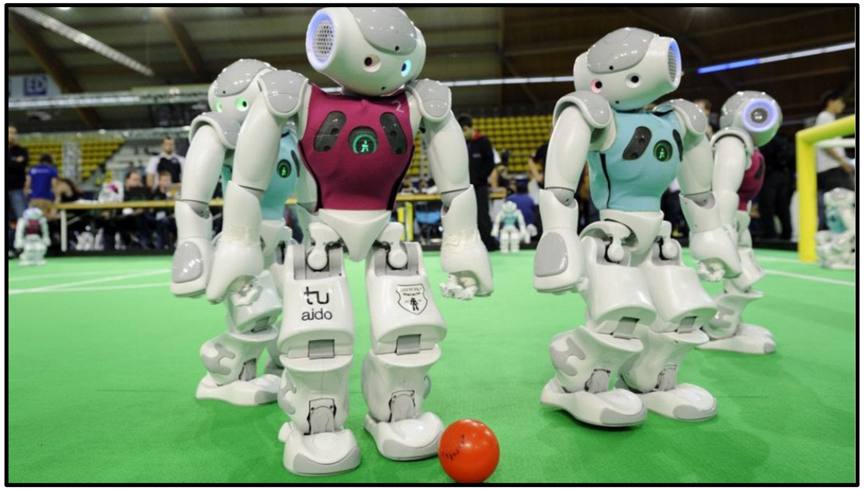
# Multi-Robot Systems (MRSs)





# Multi-Robot Applications

- Foraging
- Observation
- Box-pushing/manipulation
- Exploration
- RoboCup

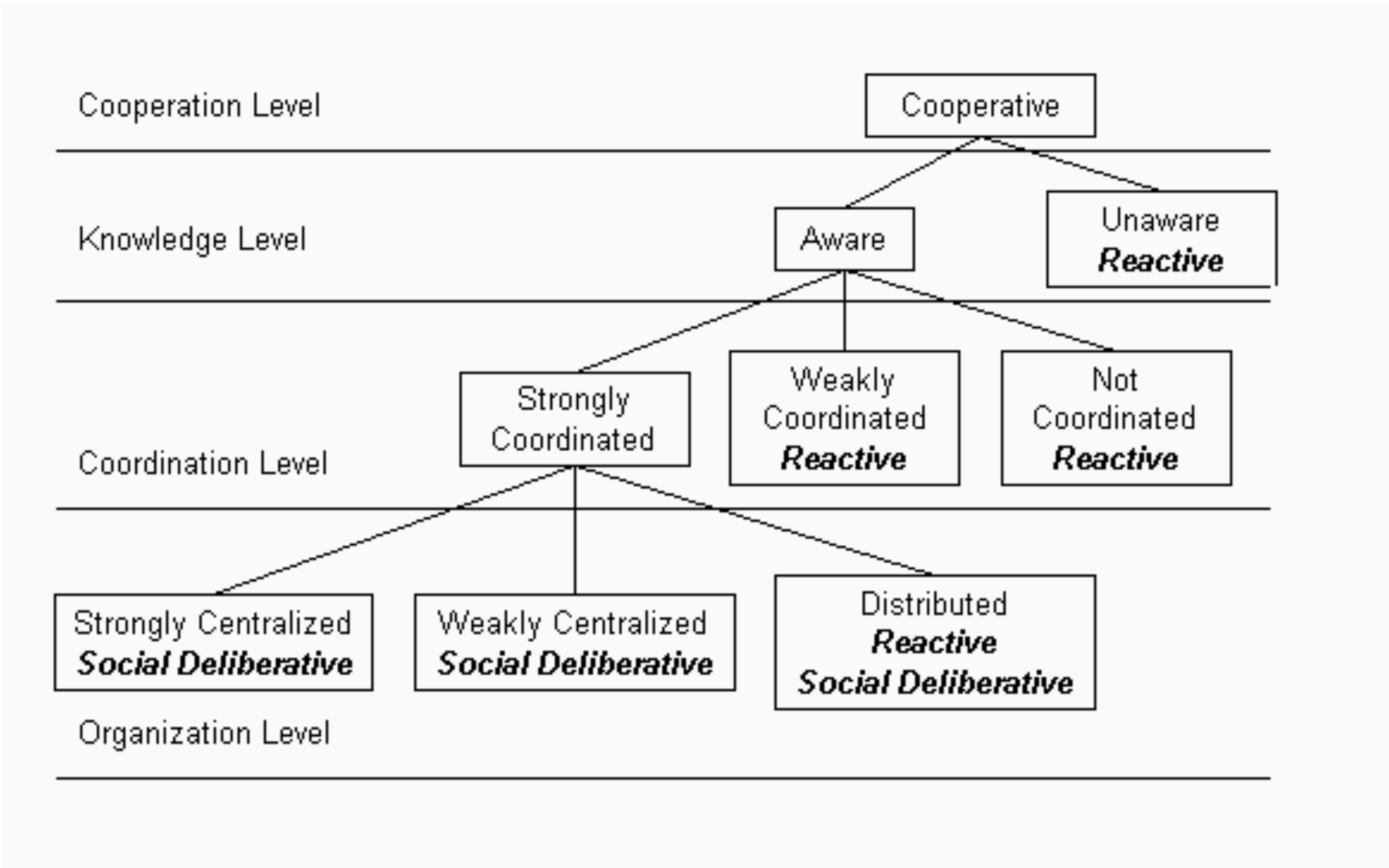
# Multi-Robot Systems

A MRS cannot be simply regarded as a generalization of the single robot case.

Nor a MRS can be simply regarded as an instance of a multi- agent system.

Cooperation implies autonomy (al least to some degree).

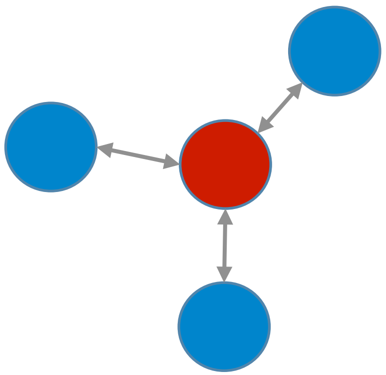
# Multi-Robot Systems: our old taxonomy



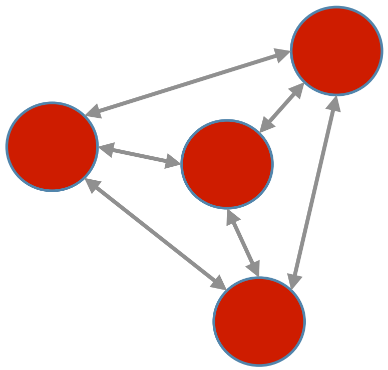
# Multi-Robot Systems

## Structure

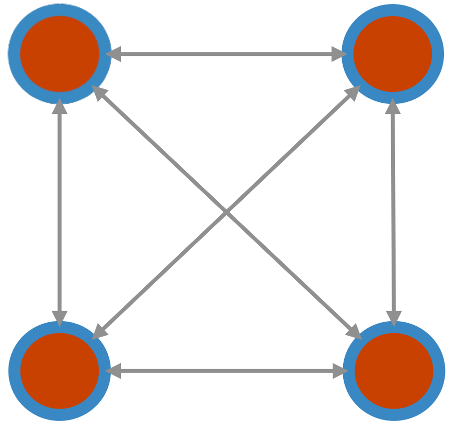
- **Centralized:**



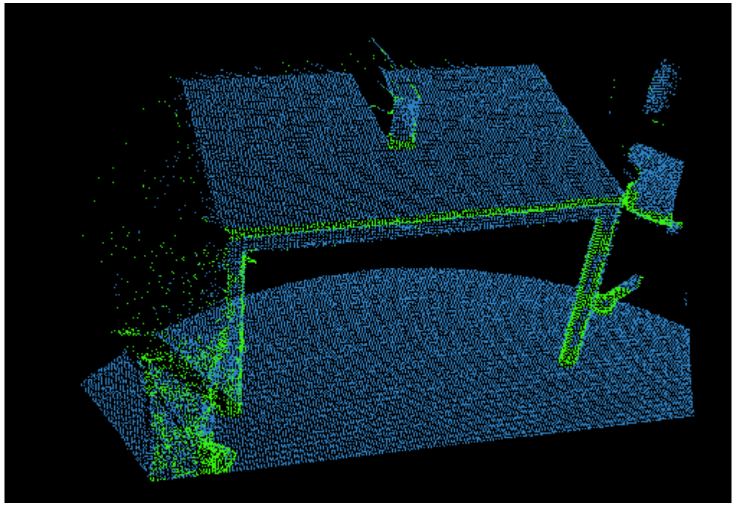
- **Decentralized:**

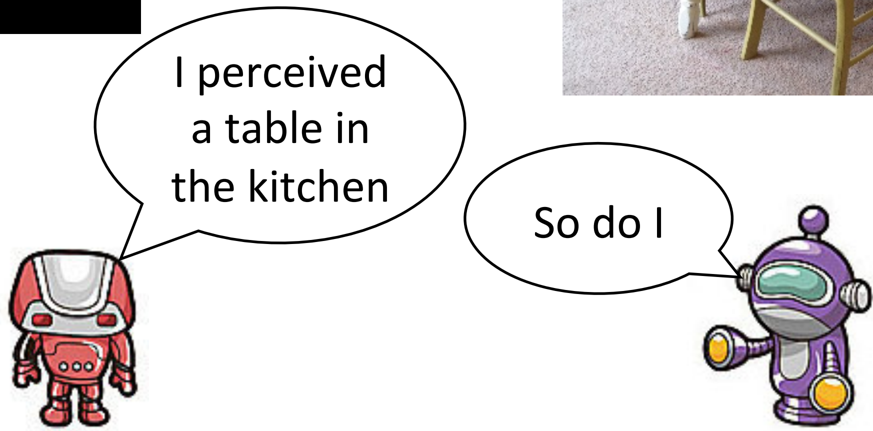


- **Distributed:**

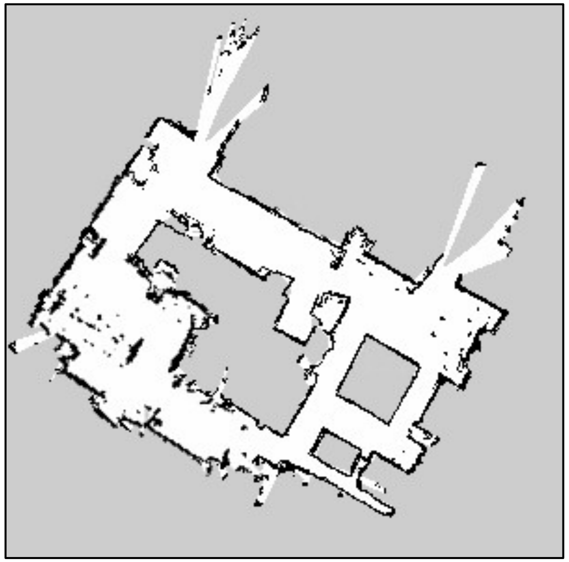


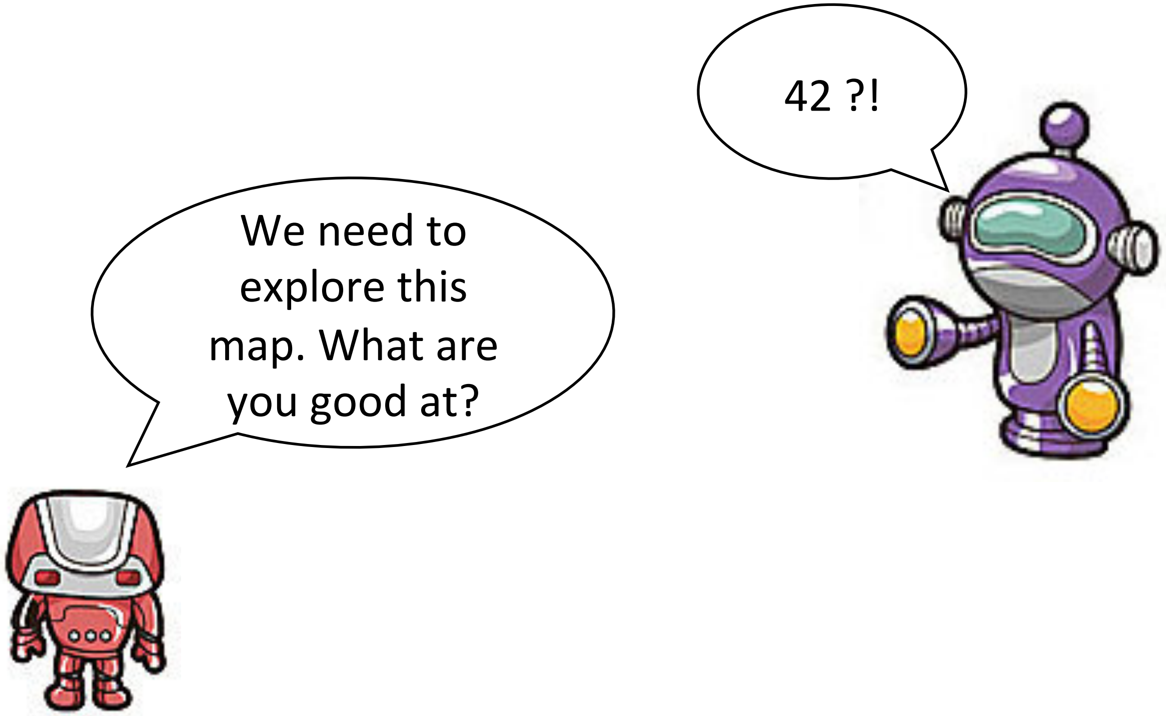
# World representation: cooperative perception



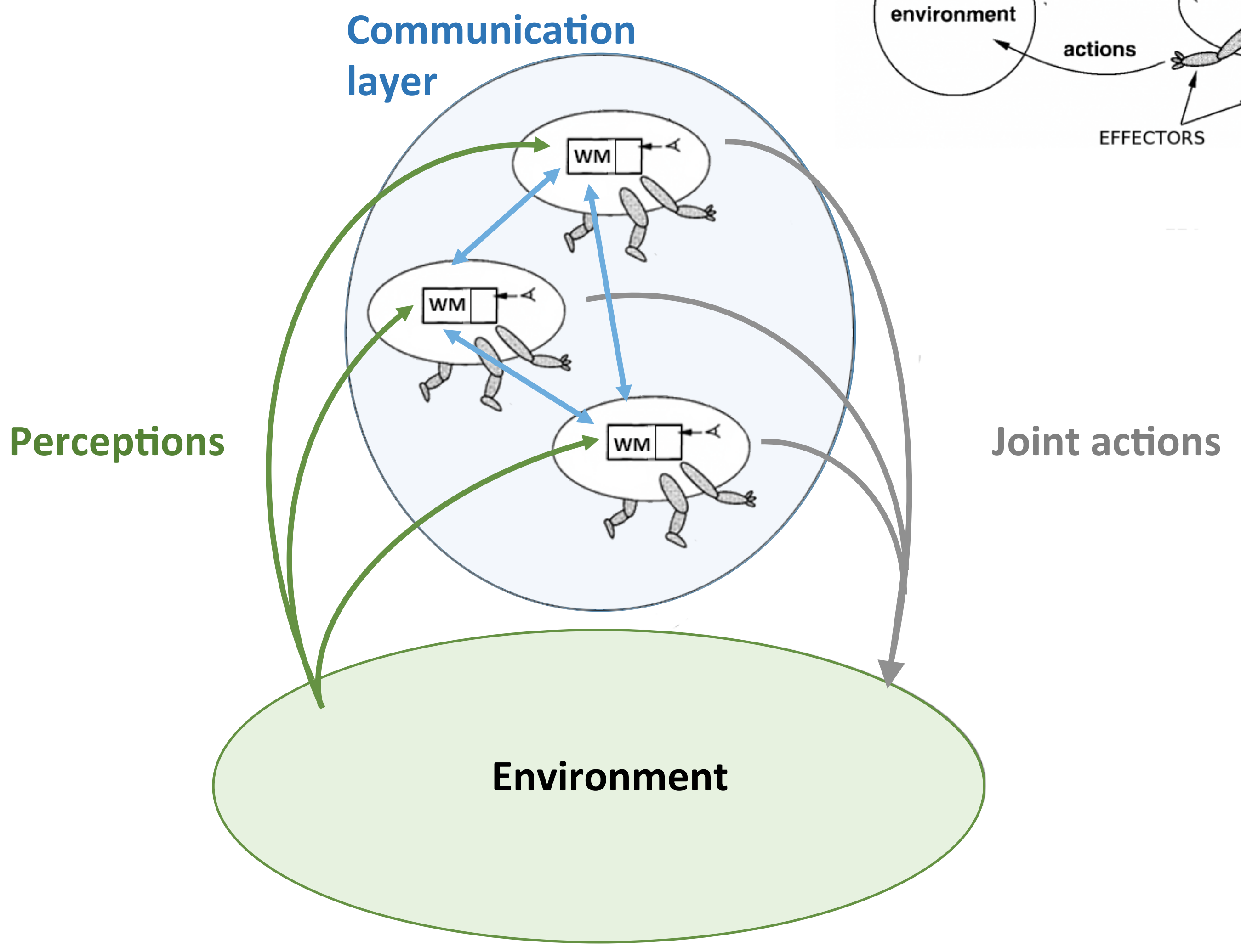


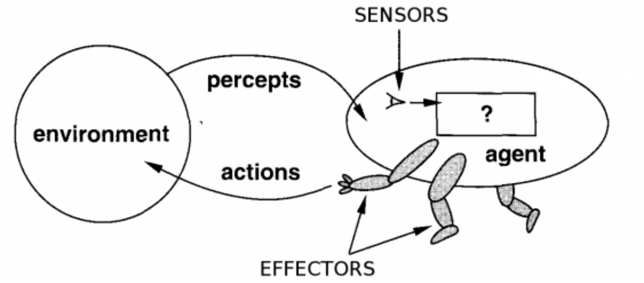
# Robot coordination: cooperative action





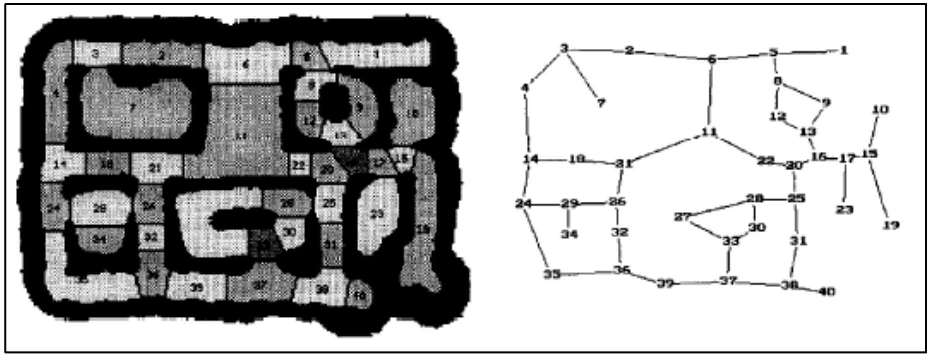
# Multi-Robot Systems

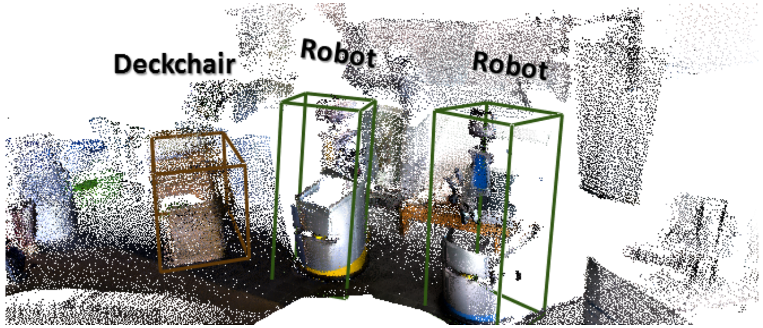


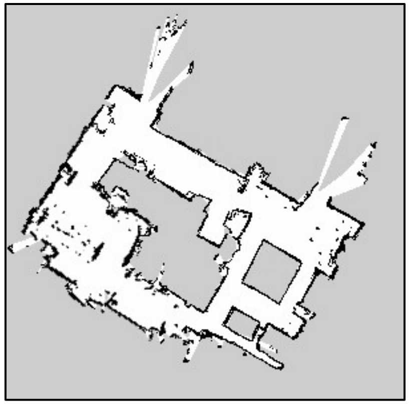



# World modeling

## Environment representation





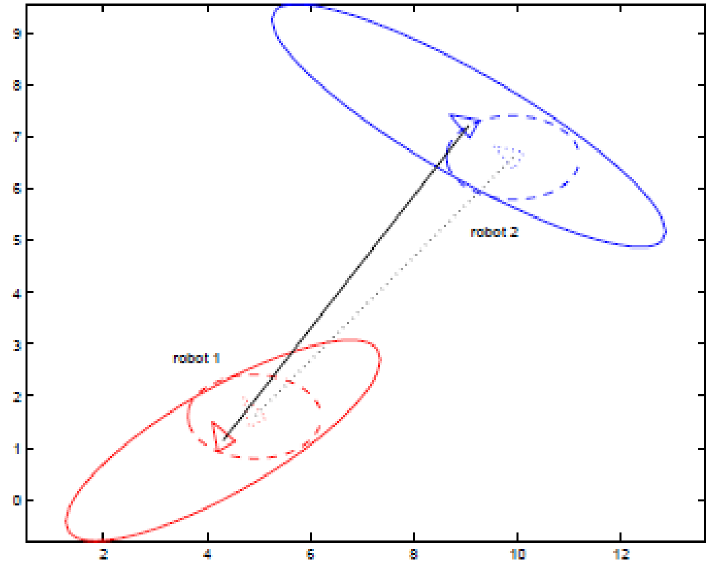



# Cooperative perception:
## Distributed multi-robot localization

Distributed EKF approach for **multi-robot localization**.

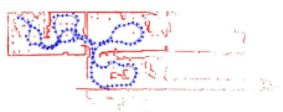
Each robots carries the joint state vector of the team, and any time it receives a teammate measurement it updates its own state.

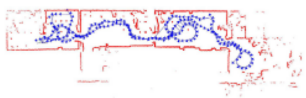
A decentralized Kalman filter requires the exchange of information only when the robots see each other.

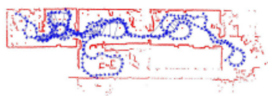


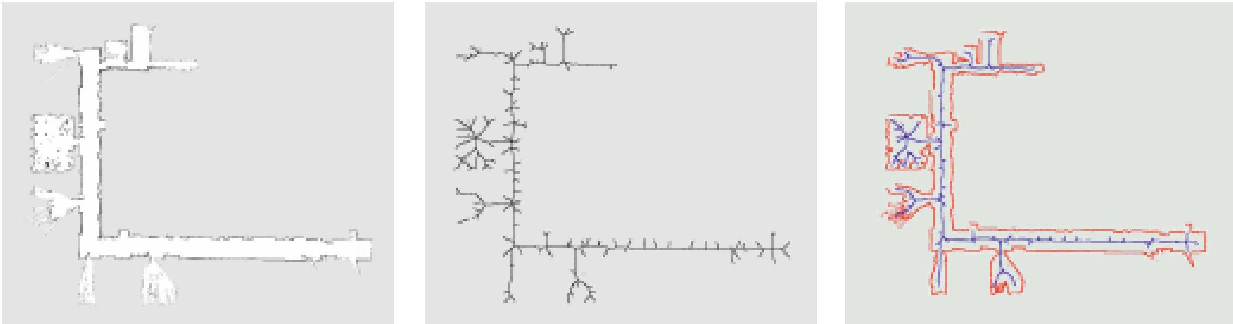

S. Roumeliotis and G. Bekey, "Distributed multi-robot localization," IEEE Transactions on Robotics and Automation, vol. 18, no. 5, pp. 781–795, Oct. 2002.

# Cooperative Mapping:
## Merging partially consistent maps (topological)


Robot 1


Robot 2


Merged map



Bonanni et al. merge partially consistent maps through a **topological representation**.

In a multi-robot context it can be use to fuse partial world knowledge

T. Bonanni, G. Grisetti, and L. Iocchi, "Merging partially consistent maps," in Simulation, Modeling, and Programming for Autonomous Robots, ser. Lecture Notes in Computer Science, D. Brugali, J. Broenink, T. Kroeger, and B. MacDonald, Eds. Springer International Publishing, 2014, vol. 8810, pp. 352–363.

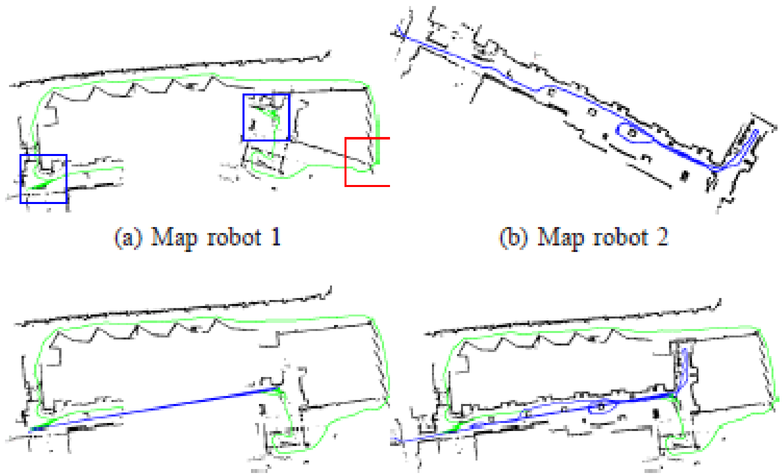
# Cooperative SLAM:
## Fusing maps (metric)

- EIFs
- EKFs
- Particle Filters
- Graph based

# Multi-robot SLAM:
## using condensed measurements

Mapping the environment using a **distributed graph-based SLAM** approach.

The robots augment their local maps using **meaningful compressed information** coming from their teammates in a given range which allows to satisfy communication constraints in real scenario.



(a) Map robot 1 (b) Map robot 2

(c) Map robot 1 + condensed graph from robot 2 (d) Final global map

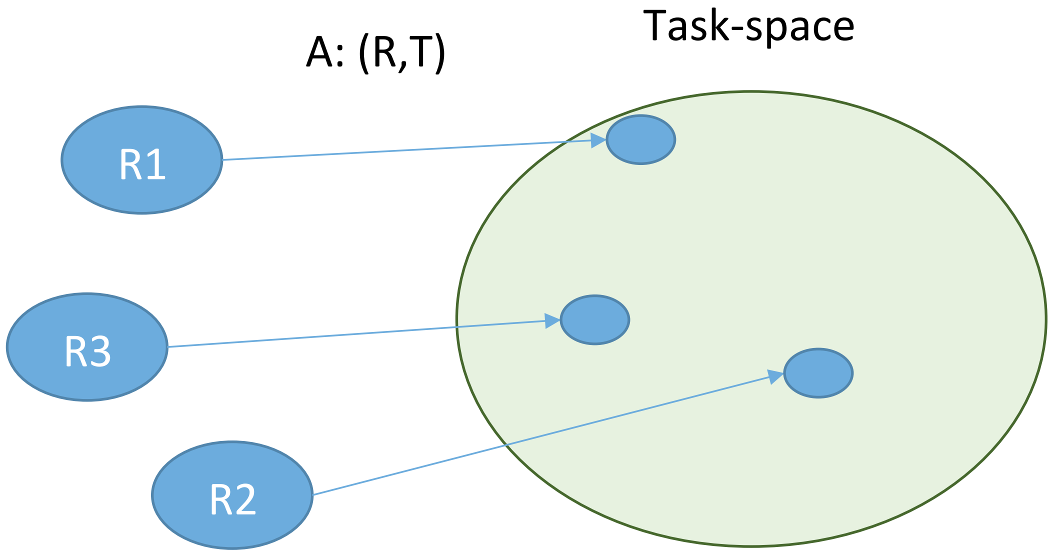
M. T. Lázaro, L. M. Paz, P. Pini´es, J. A. Castellanos, and G. Grisetti, "Multi-robot SLAM using condensed measurements," in IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, Nov 3-8 2013.

# Cooperative action

- Joint coordinated behaviors (e.g. synchronization)

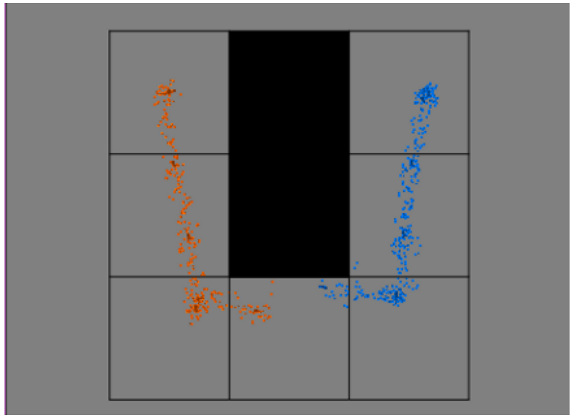
Focus on socially deliberative cooperation

- Task Assignment




- Cooperation without pre-defined protocols

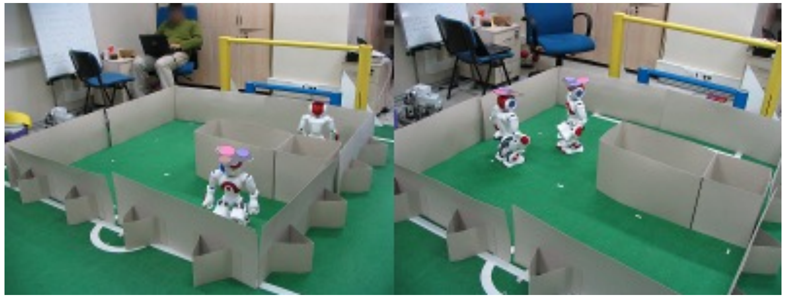
# Joint Coordinated Behaviours as task learning in dec-pomdp



**Decentralized POMDP** can be adopted to learn policies that implement cooperative behaviours.

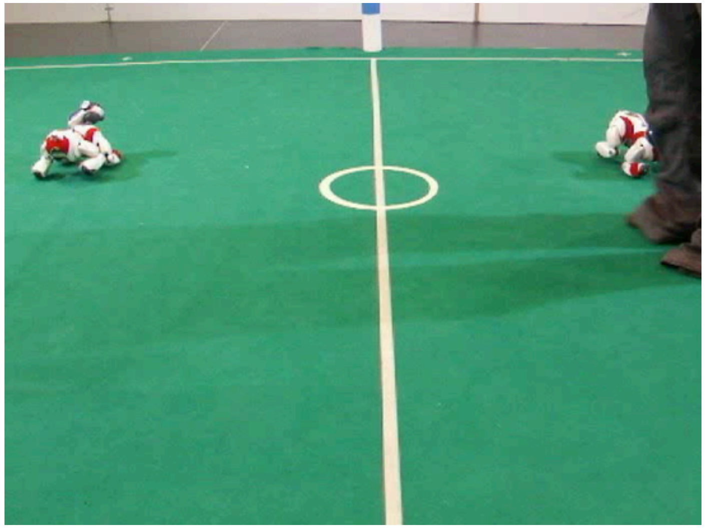
Evolutionary strategies are used to generate policies and learn joint actions for two robots in a grid-world.

Common goal and "global" World Representation.

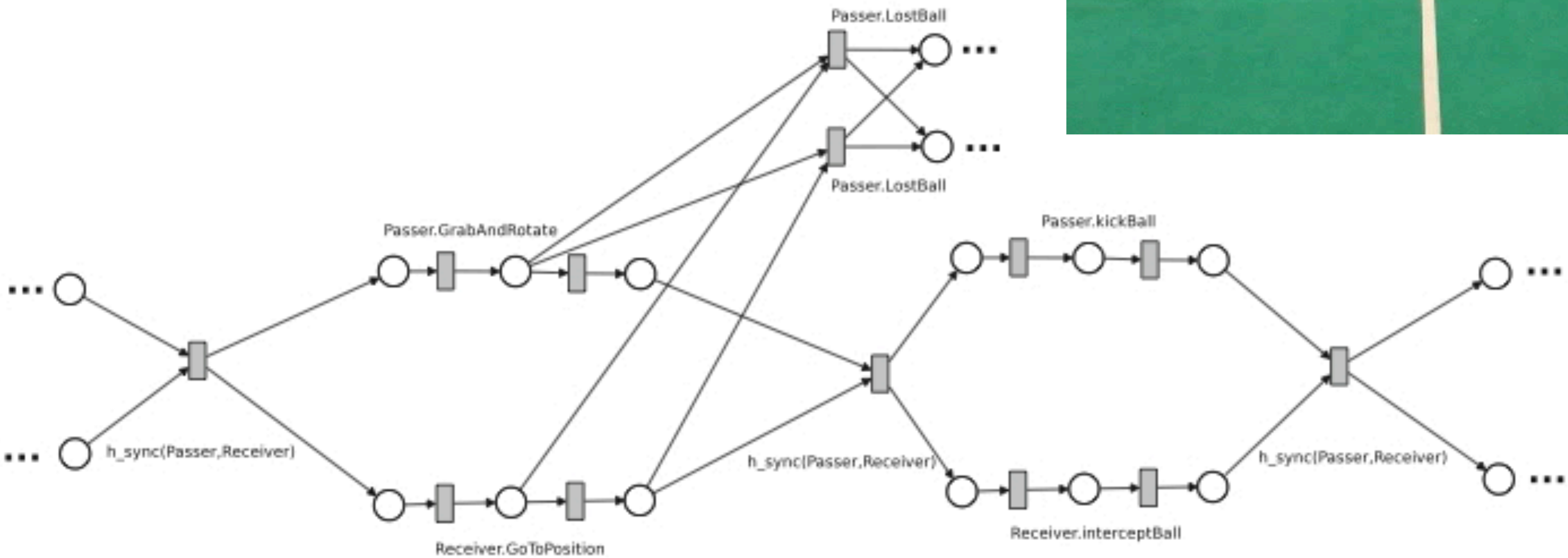


B. Eker, E. O¨ zkucur, C. Meric¸li, T. Meric¸li, and H. L. Akin, "A finite horizon dec-pomdp approach to multi-robot task learning," in Application of Information and Communication Technologies (AICT), 2011 5th International Conference on. IEEE, 2011, pp. 1–5.

# Joint Coordinated Behaviours as Joint Intentions in PNPs

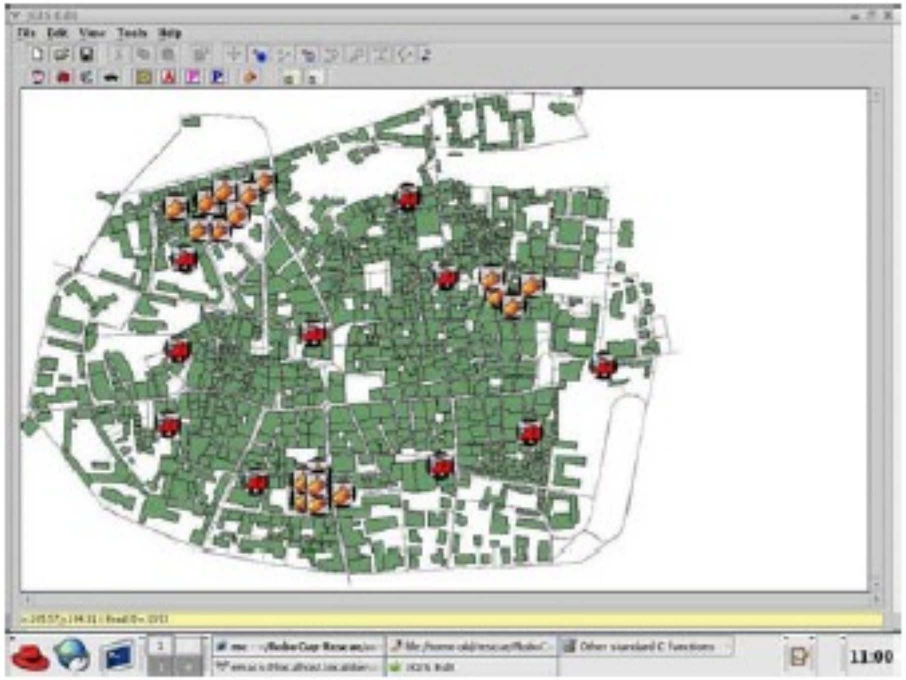


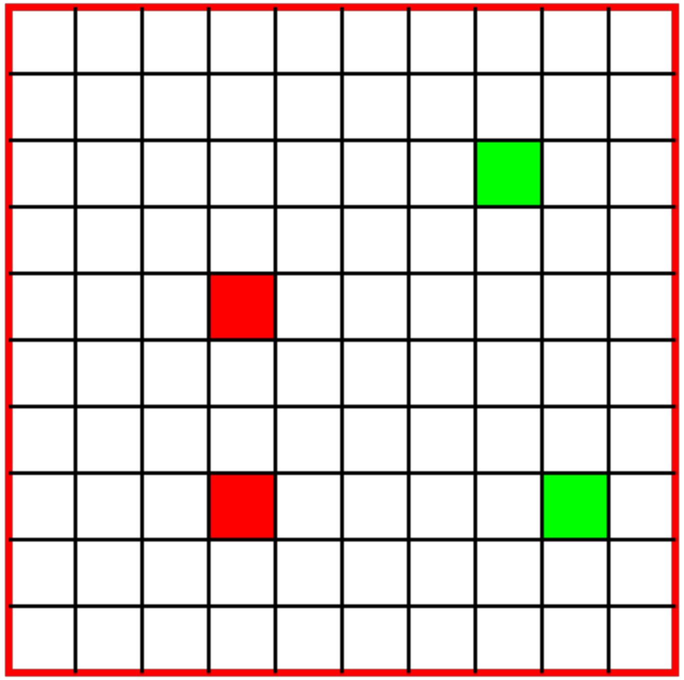
- Action Synchronization
- Joint Intentions Theory




V. A. Ziparo, L. Iocchi, P. U. Lima, D. Nardi, P. F. Palamara, "Petri Net Plans - A framework for collaboration and coordination in multi-robot systems", *In Autonomous Agents and Multi-Agent Systems*, vol. 23, no. 3, pp. 344-383, 2011.

# Task assignment as
## Distributed Constraint Optimization





Scerri, Paul,A. Farinelli et al. "Allocating tasks in extreme teams. " *Proceedings of the fourth international joint conference on Autonomous agents and multiagent systems*. ACM, 2005.

S. Okamoto, N. Brooks, S. Owens, K. Sycara, and P. Scerri, “Allocating spatially distributed tasks in large, dynamic robot teams,” Autonomous Agents and Multiagent Systems, 2011.

# Task assignment as
## Reactive Distributed Protocol

Alliance is a **Multi-Robot architecture** developed to enable heterogeneous teamwork.

Robots decide to act based on **impatience** updated also with the exchange of sensory data.

There is not a distributed consciousness of the world state nor of the tasks performed by other robots

Parker, Lynne E. "ALLIANCE: An architecture for fault tolerant, cooperative control of heterogeneous mobile robots." *Intelligent Robots and Systems' 94.'Advanced Robotic Systems and the Real World', IROS'94. Proceedings of the IEEE/RSJ/GI International Conference on*. Vol. 2. IEEE, 1994.

# Task assignment as auction based allocation

TraderBot is a **market-based** Multi-Robot architecture.

It allows a team of robots to bid for a task in a distributed fashion.

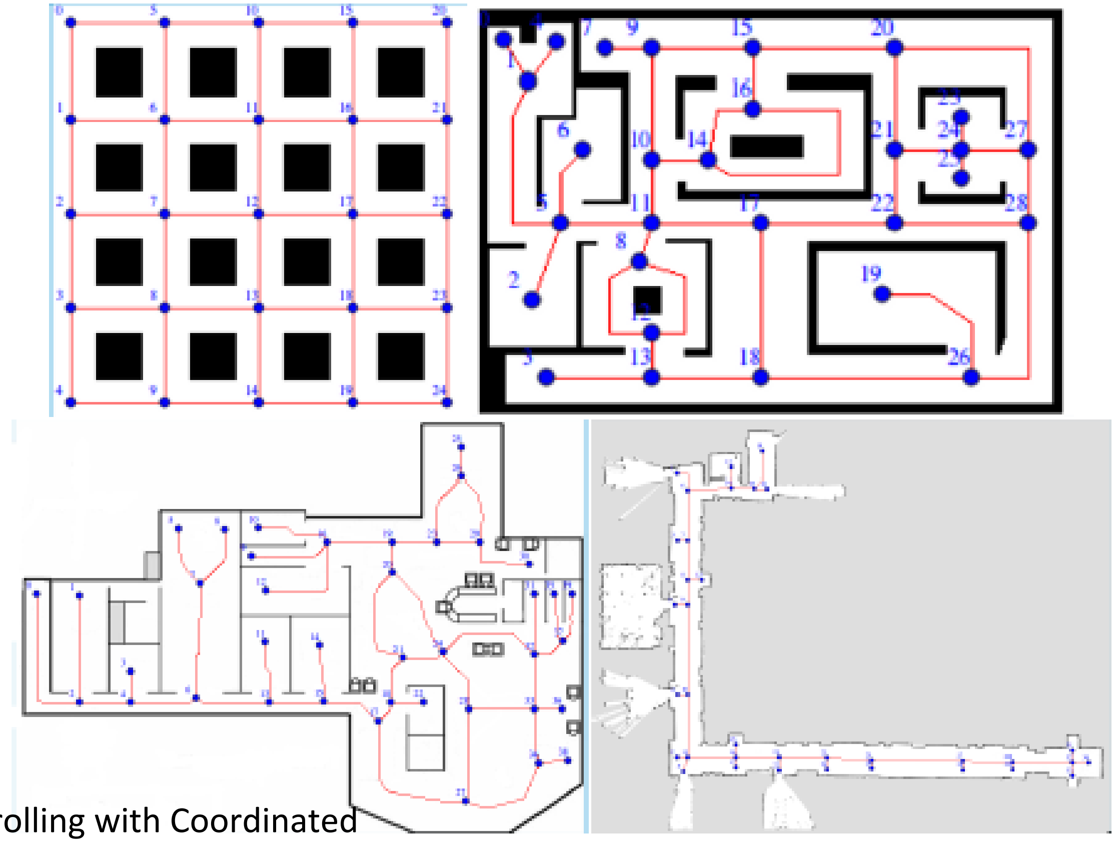
The robots self-organize in sub-groups and allocate resources/ tasks through auctions.

Dias, M. Bernardine, and Anthony Stentz. "Traderbots: A market-based approach for resource, role, and task allocation in multirobot coordination.", Tech. ReportCMU-RI-TR-03-19, Pittsburg, PA (2003).

# Task Assignment as
## Distributed On-Line Coordination for Multi-Robot Patrolling

**Dynamic TA** compared with offline approaches showing that the uncertainties arising from execution on robots is must be taken into account.

Later, **sequential single-item auctions** are compared with several on-line and offline approaches.



L. Iocchi, L. Marchetti, D. Nardi, "Multi-Robot Patrolling with Coordinated Behaviours in Realistic Environments", *In Proceedings of the International Conference on Intelligent Robots and Systems (IROS)*, pp. 2796-2801, 2011.

# Provably-good distributed algorithm for constrained multi-robot task assignment for grouped tasks

Luo et al. propose an **auction-based task allocation** algorithm.

Their algorithm associates a given **payoff** to groups of tasks that the robots receive when performing them.

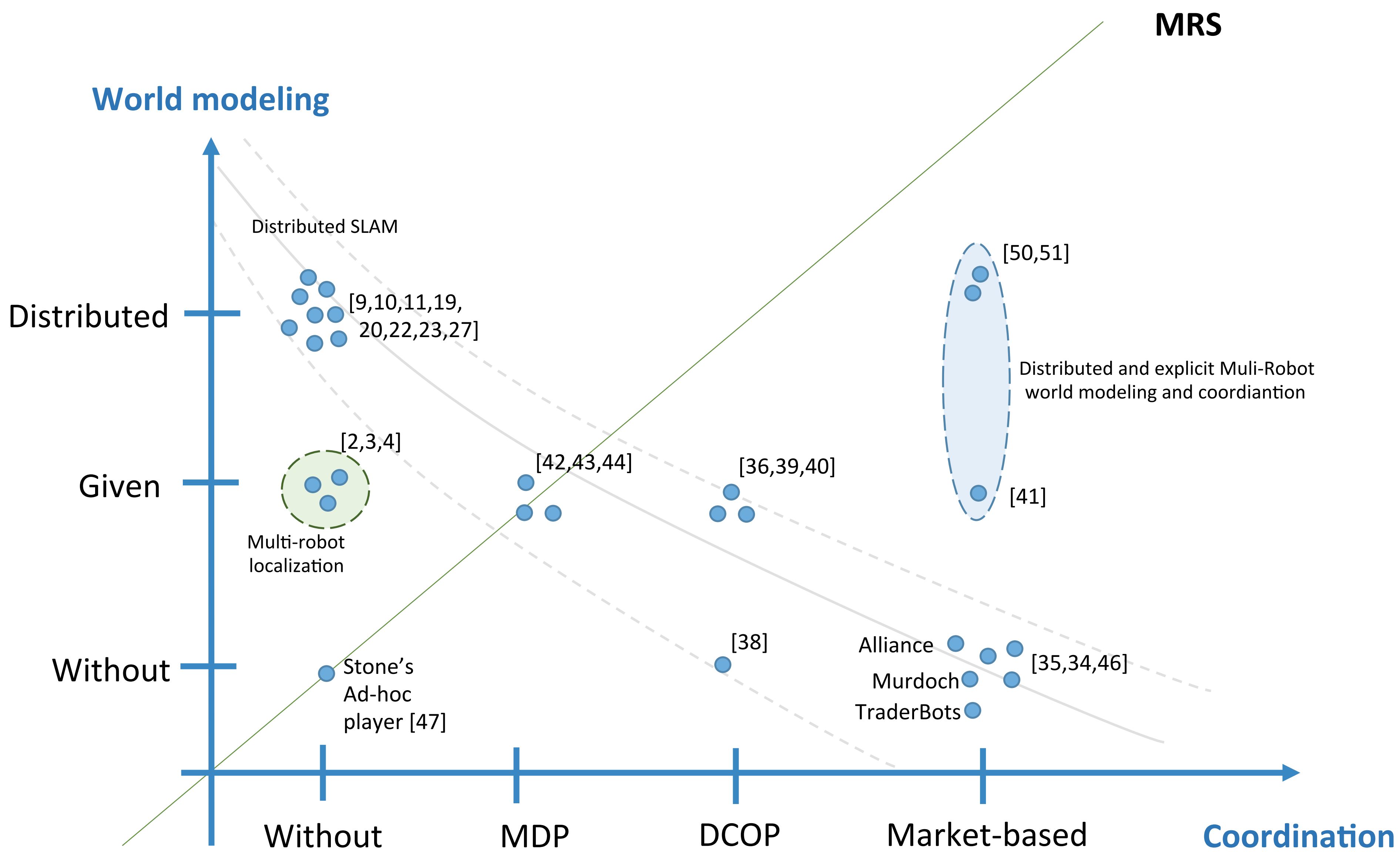
The authors evaluate their solution by simulating a cooperative **Package Transport** scenario.

L. Luo, N. Chakraborty, and K. Sycara, "Provably-good distributed algorithm for constrained multi-robot task assignment for grouped tasks," IEEE Transactions on Robotics, vol. 31, no. 1, pp. 19–30, 2015.

# Ad hoc autonomous agent teams

**Ad-hoc challenge**: building a single agent able to cooperate with other unknown agents that are not necessarily programmed by the same team.

P. Stone, G. A. Kaminka, S. Kraus, J. S. Rosenschein, et al., "Ad hoc autonomous agent teams: Collaboration without pre-coordination." in AAAI, 2010.

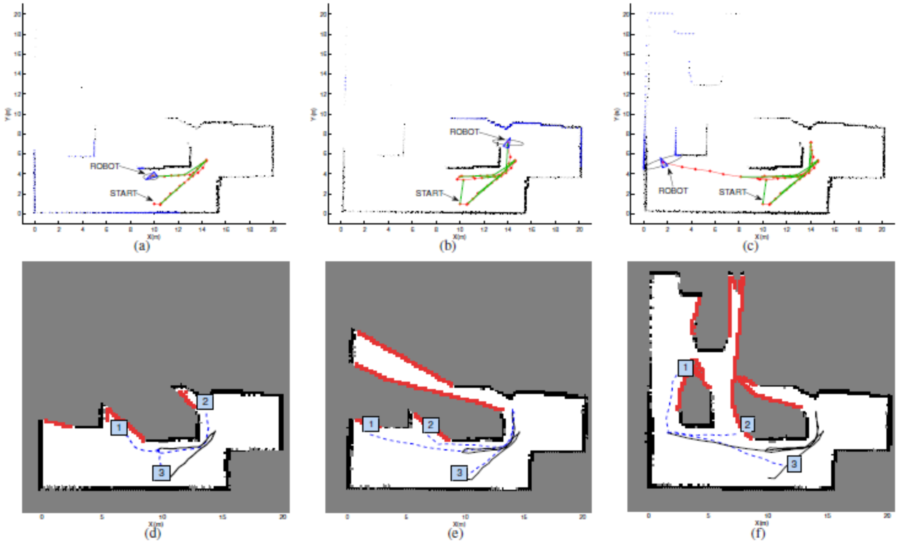

MRS
World modeling
Distributed
Given
Without
Distributed SLAM
[9,10,11,19,
20,22,23,27]
[2,3,4]
Multi-robot
localization
[42,43,44]
[36,39,40]
[50,51]
Distributed and explicit Muli-Robot
world modeling and coordiantion
[41]
[38]
Alliance
Murdoch
TraderBots
[35,34,46]
Stone's
Ad-hoc
player [47]
Without
MDP
DCOP
Market-based
Coordination

# Active pose SLAM

Valencia et al. combine the exploration and map-building process, also known as **Active SLAM**.

The goal of the exploration strategy is to minimize the overal map error. When the robot has a high uncertainty about its localization, it backtracks to known mapped areas.

In a multi-robot case, a team of robots can co-work to reduce teammates uncertainty and enhance the performance.

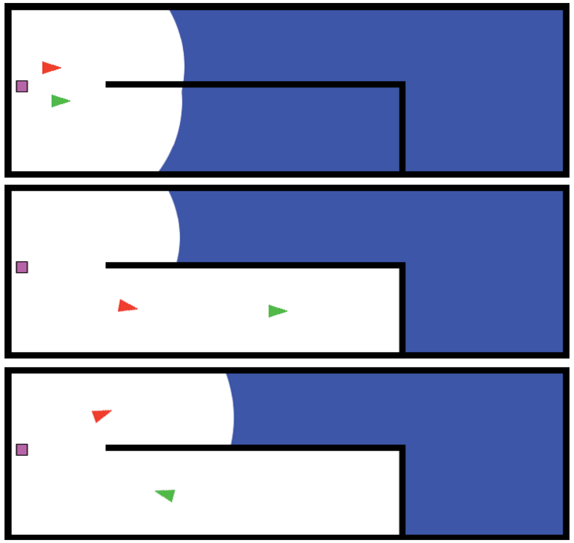


Valencia, Rafael, et al. "Active pose SLAM." *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012.

# Autonomous multi-robot exploration in communication-limited environments

De Hoog et al. employ a **role hierarchy** for multi-robot exploration.

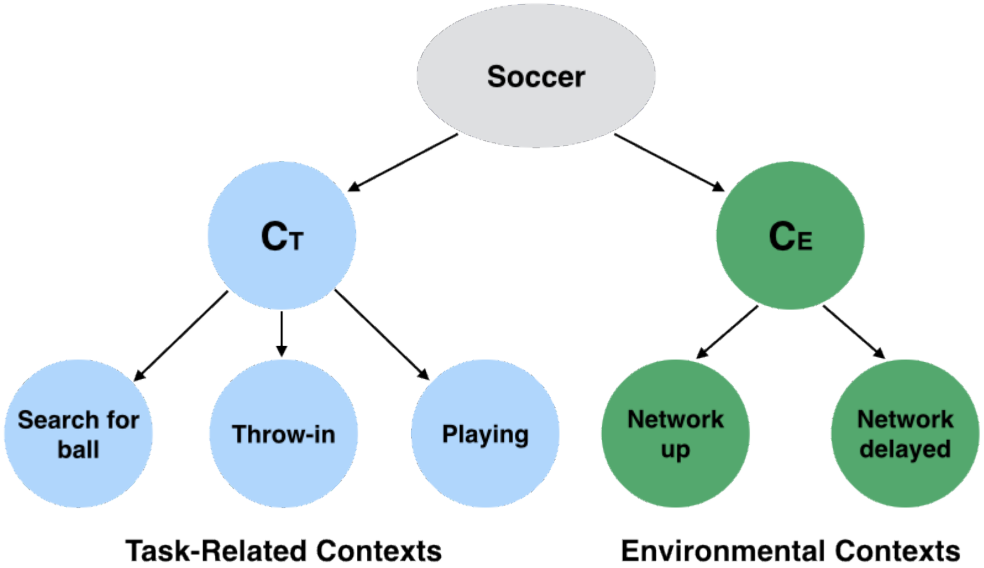
They perform a **frontier-based** exploration **dynamically** reassigning task to the active robots



J. De Hoog, S. Cameron, and A. Visser, "Autonomous multi-robot exploration in communication-limited environments," in Proc. of the 11th Conference Towards Autonomous Robotic Systems. University of Plymouth, School of Computing and Mathematics, 2010.

# Context-based coordination for a multi-robot soccer team

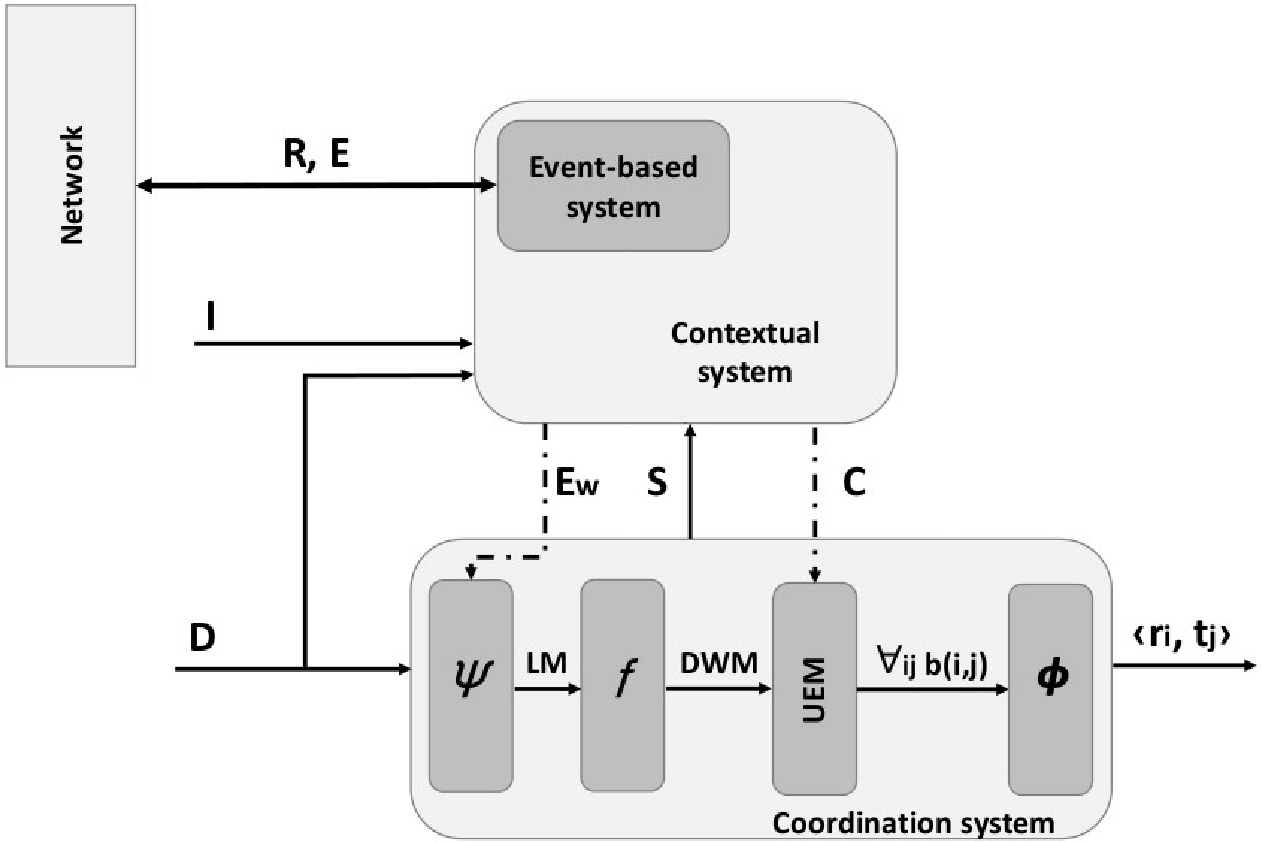
Riccio et al. exploit **contextual knowledge** to distributively update robots' world model and coordinate accordingly in a soccer scenario.



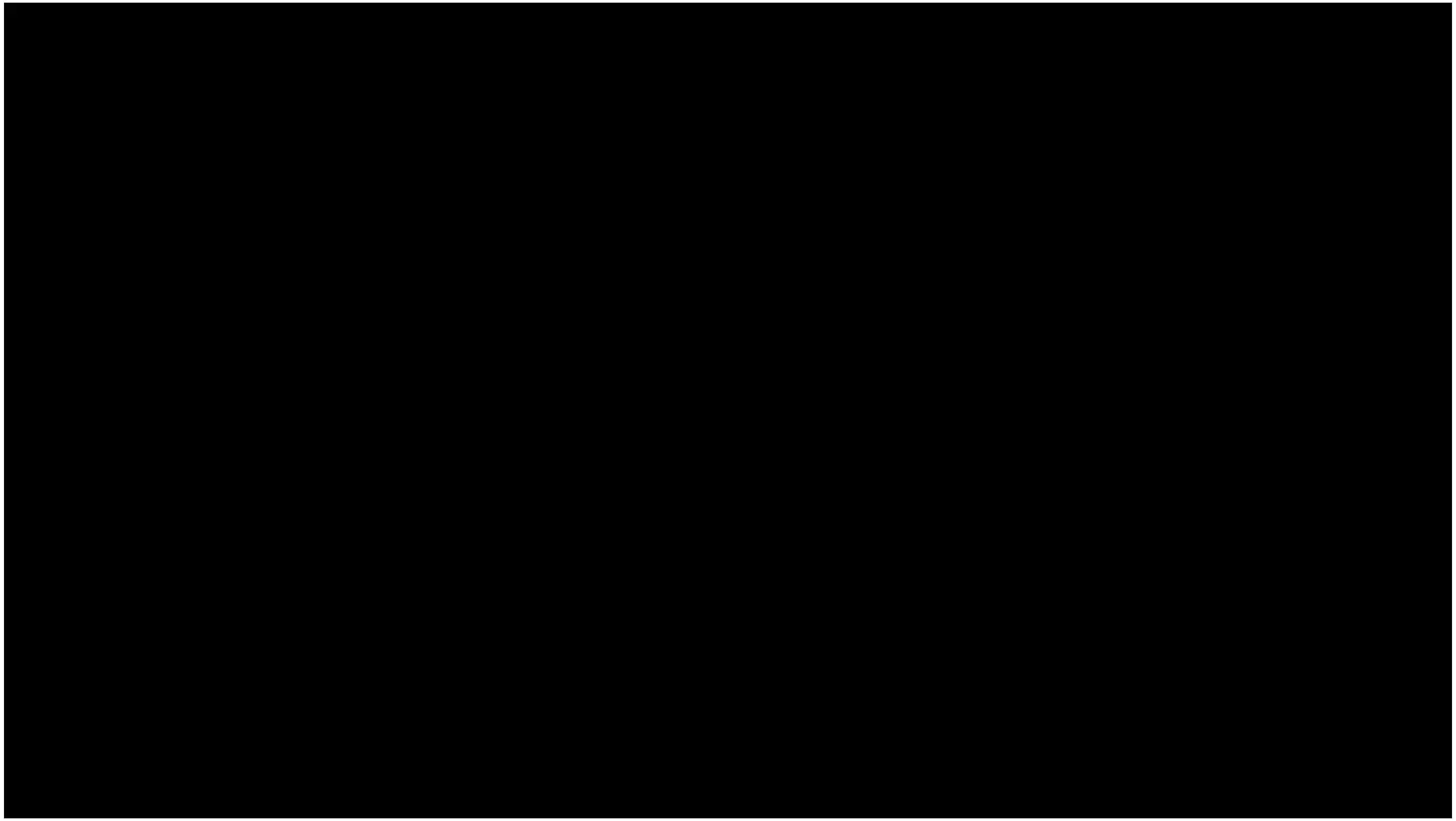


F. Riccio, E. Borzi, G. Gemignani, and D. Nardi, "Context-based coordination for a multi-robot soccer team," RoboCup Symposium, 2015.

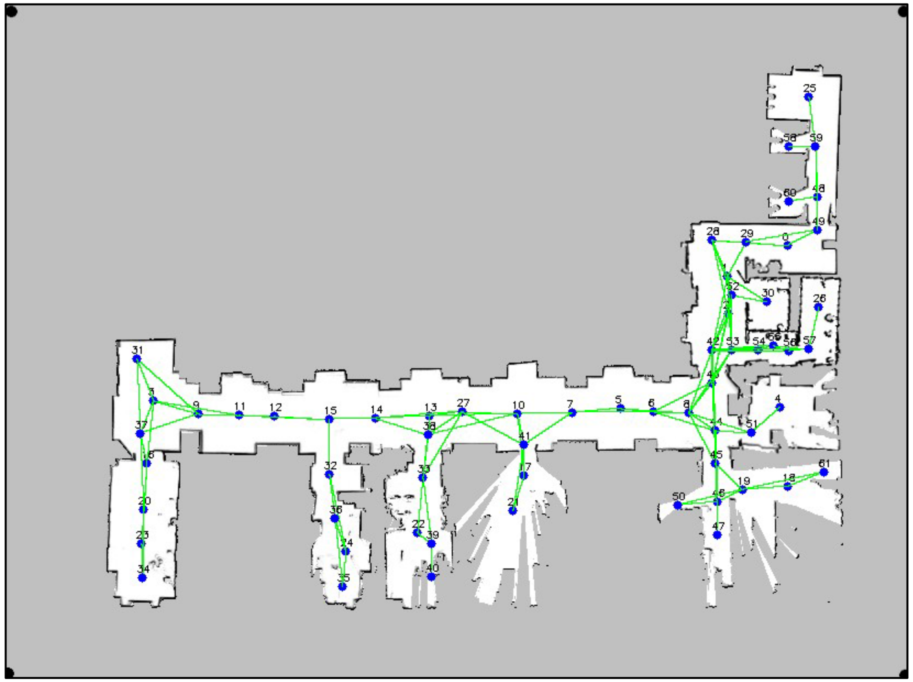
# Context-aware coordination in a soccer scenario



# Context-aware coordination in a soccer scenario



# Context-aware cooperation in multi-robot target localization



# Context-aware cooperation in multi-robot target localization

# Summary and Conclusions

Cooperative perception and cooperative action are two sides of **Multi-Robot Systems** that have been addressed largely independently.

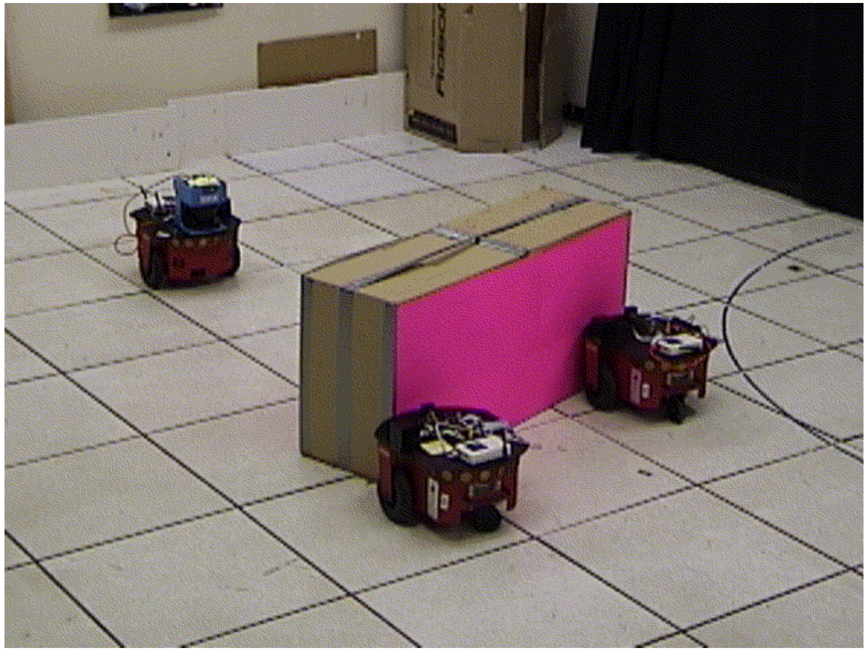
A challenging research stream aims at investigating MRS including both components of the perception-action loop.

Better methods for performance evaluation are needed!!

# MURDOCH: Publish/Subscribe Task Allocation for Heterogeneous Agents

Gerkey and Mataric implement a **pusblish/subscribe** system able to allocate task among a team of heterogeneous robots.

The robots evaluate their **metric functions** to bid for a given task and win their assignment



Gerkey, Brian P., and Maja J. Matarić. "Murdoch: Publish/subscribe task allocation for heterogeneous agents." *Proceedings of the fourth international conference on Autonomous agents*. ACM, 2000.