Multi-Robot Exploration

Integrated Seminar: Intelligent Robotics

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What is Exploration?

Perception

Integrate it to the map

SLAM

Exploration

Create a new goal

Planning & Control

Go to the goal location

Perceive and Interpret the Current Environment
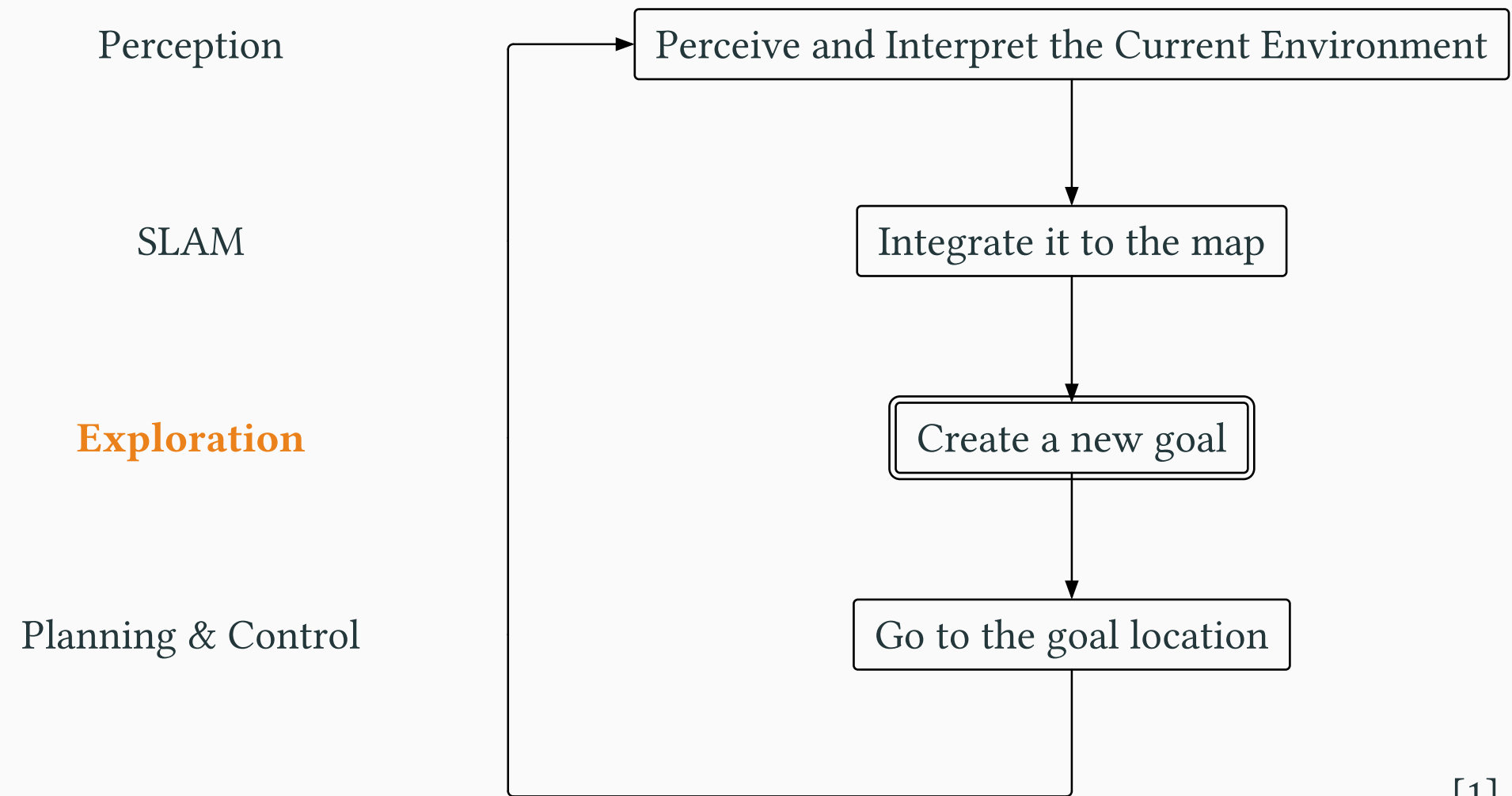
[1], [2]

— What is Exploration?

mobile robot exploration is an iterative process in which the robot integrates its observations into its world model, interprets the world model to determine which parts of the environment are unknown, and plans a path to visit and observe these unknown areas

Formal Definition

"Given a team of m robots $R = \{r_1, r_2, ..., r_m\}$,
deployed in a continuous and bounded environment Env,
the goal for the robots is to select a sequence of poses $Q = \langle Q_0, Q_1, ..., Q_n \rangle$
so that at each pose they perceive features in the environment
through a sensor mounted on-board."

Given a team of m robots $R = \{r_1, r_2, ..., r_m\}$,
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[2]

Motivation

Motivation

- examples: Delivery, Find an Rescue,
- having a map is only the case in veryfew settings
- even if a map exists, the environment might change

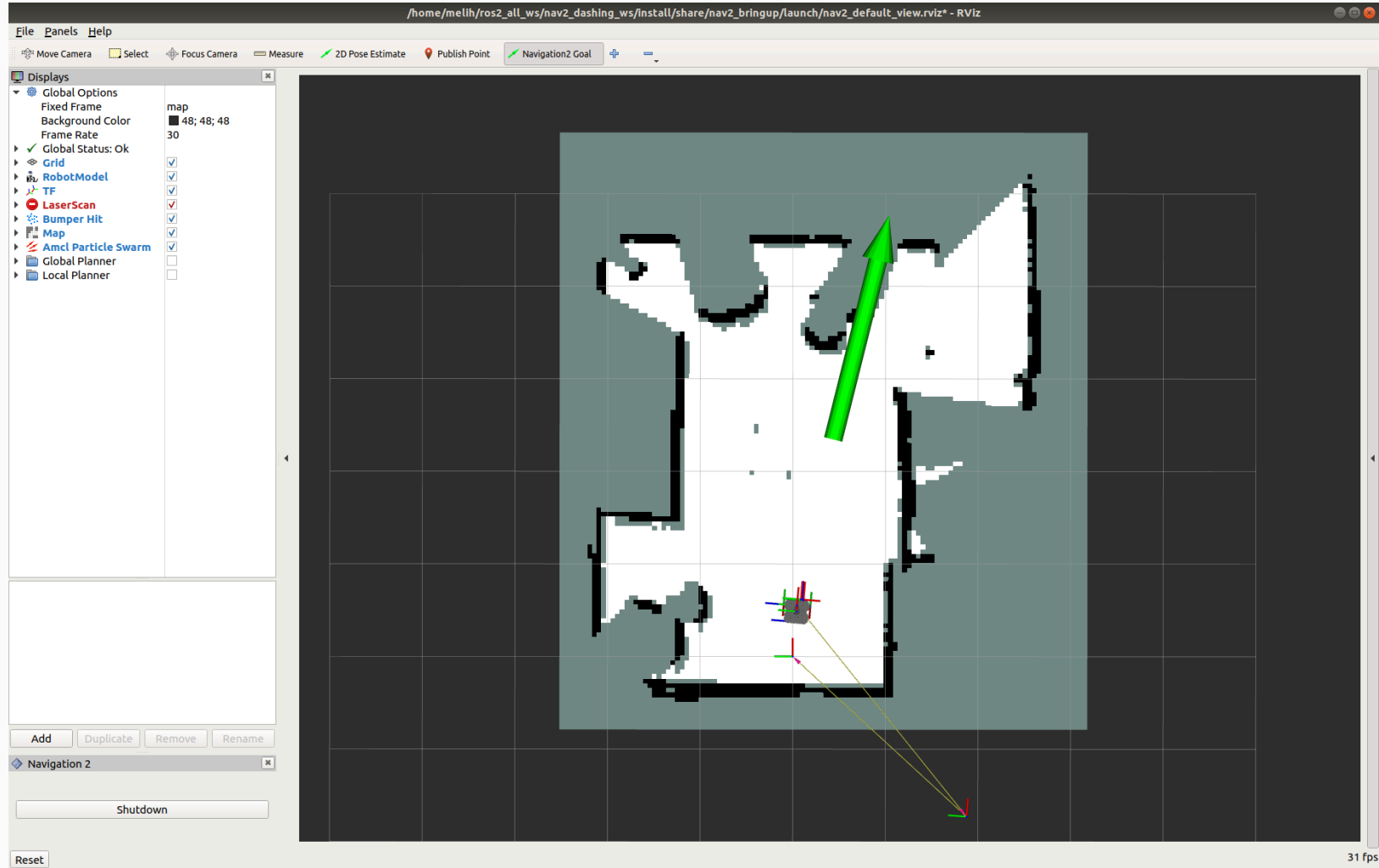**How does Exploration integrate with SLAM and Mapping?**

— Motivation

Coverage

Map every point within a region of interest

Target Localization

Explore a region to find a target of interest

[2]

Coverage: Map every point within a region of interest

- Mapping every point = Coverage by the robot sensor(s)
- Common approach:
  1. Decomposition of the environment into cells
  2. Optimization of the cells' visit order
  3. Generation of a trajectory to visit each cell
- Limiting the number of locations to consider:
  ‣ Term: Frontier
  ‣ Locations between known and unknown portions of the environment

Target Localization: Explore a region to find a target of interest
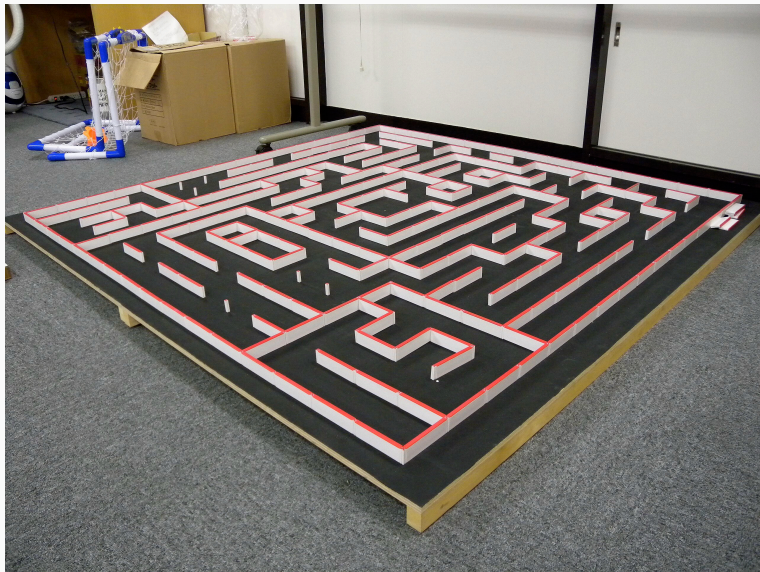- limit the number of locations to consider
- integrates semantic & topology knowledge
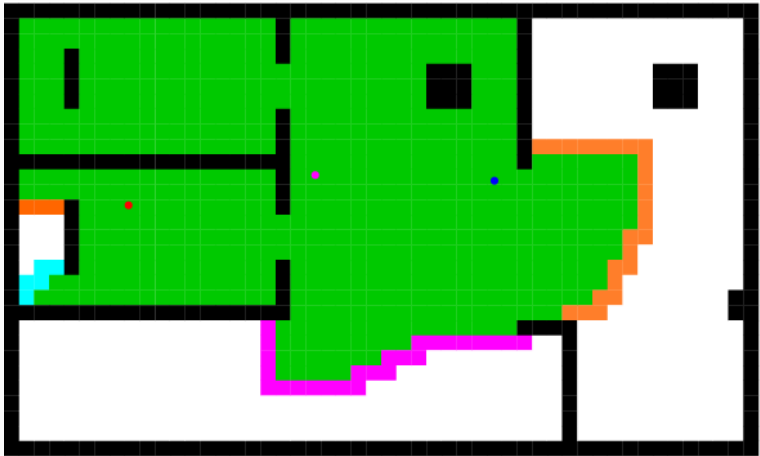
Coverage

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Target Localization

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[2]

— Tasks in Exploration

[3]

[4]

Historical Overview

- End of 1980s, Beginning of 1990s

Prerequisites for Exploration:

- Sensor Data Fusion
- Probabilistic Mapping
- Planning Methods

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- Probabilistic Mapping
- Planning Methods

[1], [5], [6], [7], [2]

Advances over the Years

$$2D \implies 3D$$

$$\text{Without a priori knowledge} \implies \text{Integrating a priori knowledge}$$

$$\text{Constant Environment} \implies \text{Dynamic Environment}$$

$$\text{Indoor Environment} \implies \text{Outdoor Environment}$$

$$\text{Mapping Occupancy} \implies \text{Mapping other Parameters}$$

$$\text{Optimal Robot Conditions} \implies \text{Integrating Robots Health}$$

[2]

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Starting with one robot. What changes if another robot helps with Exploration?

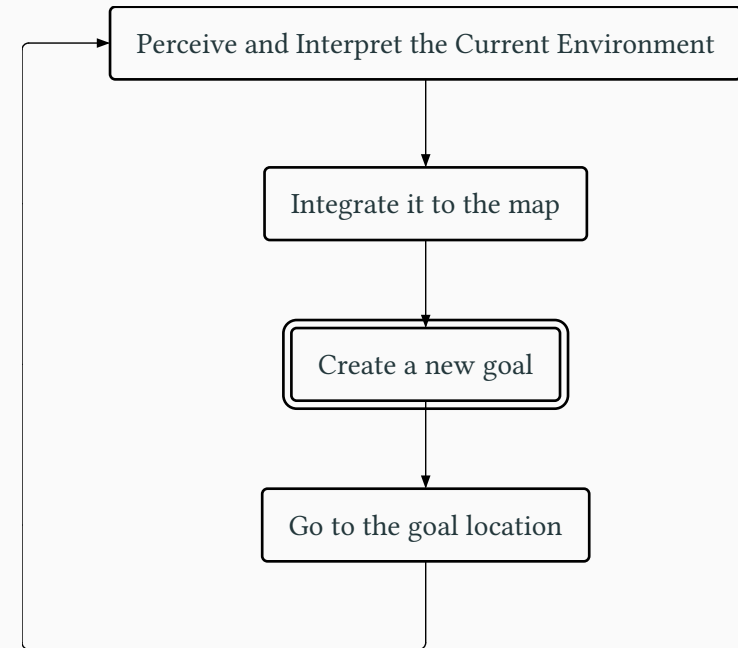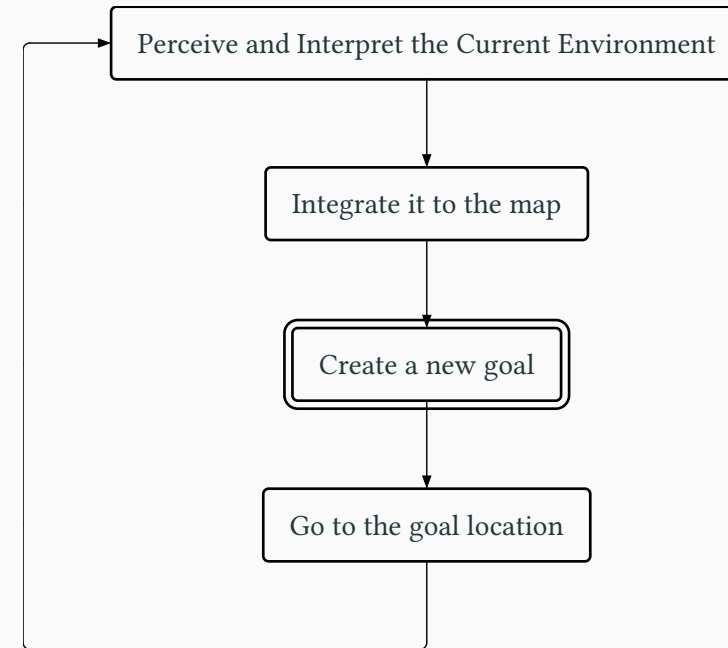**Starting with one robot. What changes if another robot helps with Exploration?**

Perception — Perceive and Interpret the Current Environment

SLAM — Integrate it to the map

Exploration — Create a new goal

Planning & Control — Go to the goal location

[1], [2]

Robot 1

Perceive and Interpret the Current Environment

Integrate it to the map

Create a new goal

Go to the goal location

Robot 2

Perceive and Interpret the Current Environment

Integrate it to the map

Create a new goal

Go to the goal location
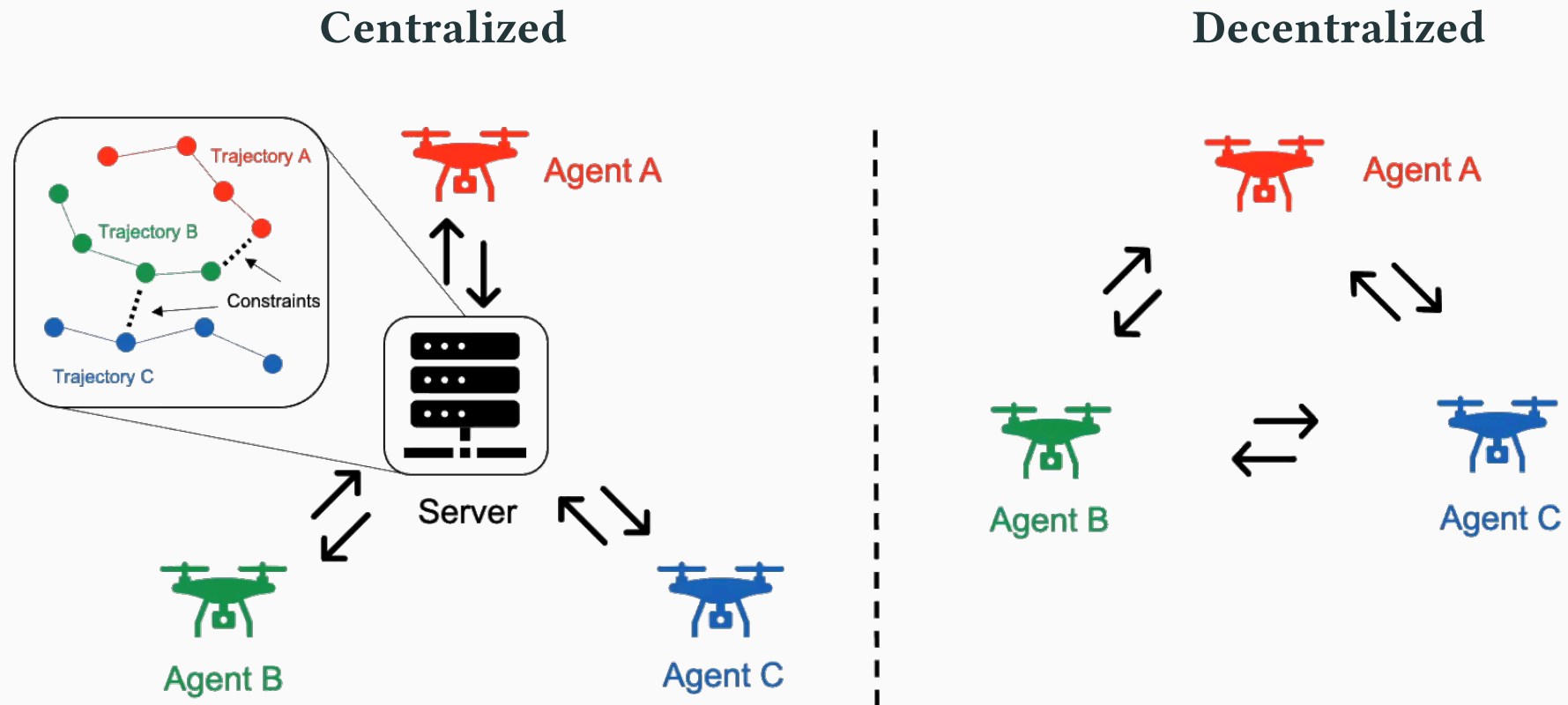
[8], [2]

— Starting with one robot. What changes if another robot helps with Exploration?

- Sensor Data Fusion
- **Shared or Distributed Map:**
  - ▸ Map Merging
  - ▸ Decentralized SLAM
- Multi-Robot Planning
  - ▸ neglecting intersecting paths and let the local controller avoid collisions
  - ▸ *Conflict-based search*

Centralized

Decentralized

[9]

Collaborative SLAM

Centralized	Decentralized

• Agents communicate via server
• server:
  ▸ stores trajectories
  ▸ establishes constraints
  ▸ finds a globally consistent solution
  ▸ server is the bottleneck
	• Agents communicate peer-to-peer
	• computation can be distributed
	• more scalable
	• challenge is to work with the local view of each agent
	• requires a more complex approach to global optimization and finding loop closures

Exploration Techniques

Examples:
1. **Robots work independently of each other; Visited Areas are marked.**
2. Frontier-based exploration

[10], [2]

Exploration Techniques

Examples:

1. Robots work independently of each other; Visited Areas are marked.
2. **Frontier-based exploration**

[10], [2]

Adding Robots with Different Capabilities

Adding Robots with Different Capabilities

- Actuators (one might be able to interact with the environment)
- Sensors
- Velocity limits
- Communication Capabilities
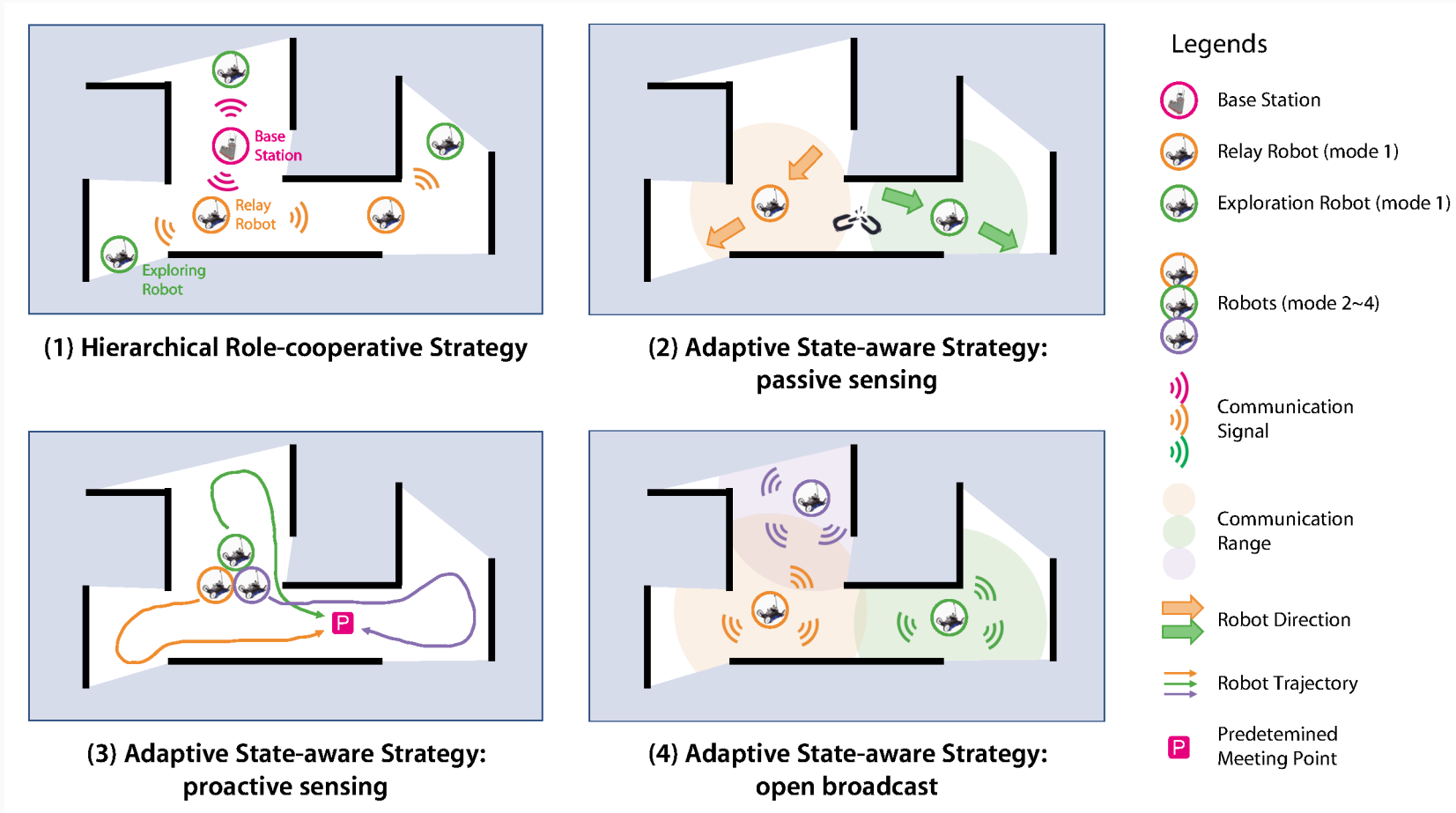- Operating in multiple Domains (e.g. [11])

Exemplory Capabilities
- Actuators (one might be able to interact with the environment)
- Sensors
- Velocity limits
- Communication Capabilities
- Operating in multiple Domains (e.g. [11])

[2]

Approach: Distributing Tasks

(1) Hierarchical Role-cooperative Strategy

(2) Adaptive State-aware Strategy: passive sensing

(3) Adaptive State-aware Strategy: proactive sensing

(4) Adaptive State-aware Strategy: open broadcast

Legends

- Base Station
- Relay Robot (mode 1)
- Exploration Robot (mode 1)
- Robots (mode 2~4)
- Communication Signal
- Communication Range
- Robot Direction
- Robot Trajectory
- P — Predetemined Meeting Point

[10]

Application Example

— Adding Robots with Different Capabilities

https://vimeo.com/893930171

Exploring Unstructured Environments using Minimal Sensing on Cooperative Nano-Drones

Pedro Arias-Perez[1], Alvika Gautam[2], Miguel Fernandez-Cortizas[1], David Perez-Saura[1], Srikanth Saripalli[2] and Pascual Campoy[1]

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Scenario

- Task: Covering
- Variable Swarm Sizes
- Variable Obstacle Densities
- Nano Drones

[12]

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Approach

"ExploreBug, a novel hybrid frontier range bug algorithm"

"an intra-swarm collision avoidance system is integrated"

[12]

Conclusion

1. **What is Exploration?**

   > Generation of a pose target suitable for exploring the environment.

2. **What do we need to consider for multi-robot Exploration**

   > How do we share current knowledge about the environment and each generate a new pose target?
   > Robot Capabilities, Tasks, Multiple Domains

3. **Example:** Exploration with Nano-Drones

Sources

https://drive.proton.me/
urls/0W2WAQHM58#J7
LByzUsANy7

Sources

[1]   J. M. Santos, T. Krajník, and T. Duckett, "Spatio-Temporal Exploration Strategies for Long-Term Autonomy of Mobile Robots," *Robotics and Autonomous Systems*, vol. 88, pp. 116–126, Feb. 2017, doi: 10.1016/j.robot.2016.11.016.

[2]   A. Quattrini Li, "Exploration and Mapping with Groups of Robots: Recent Trends," *Current Robotics Reports*, vol. 1, no. 4, pp. 227–237, Dec. 2020, doi: 10.1007/s43154-020-00030-5.

[3]   M. Andries and F. Charpillet, "Multi-Robot Taboo-List Exploration of Unknown Structured Environments," in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sep. 2015, pp. 5195–5201. doi: 10.1109/IROS.2015.7354109.

[4]   "Micromouse." Oct. 21, 2025. Accessed: Nov. 27, 2025. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Micromouse&oldid=1318037617

[5]   A. Cassandra, L. Kaelbling, and J. Kurien, "Acting under Uncertainty: Discrete Bayesian Models for Mobile-Robot Navigation," in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS '96*, Nov. 1996, pp. 963–972. doi: 10.1109/IROS.1996.571080.

[6]   H. P. Moravec, "Sensor Fusion in Certainty Grids for Mobile Robots," *Sensor Devices and Systems for Robotics*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 253–276, 1989. doi: 10.1007/978-3-642-74567-6_19.

[7]   S. Thrun, "Exploration and Model Building in Mobile Robot Domains," in *IEEE International Conference on Neural Networks*, Mar. 1993, pp. 175–180. doi: 10.1109/ICNN.1993.298552.

[8]   G. Sharon, R. Stern, A. Felner, and N. R. Sturtevant, "Conflict-Based Search for Optimal Multi-Agent Pathfinding," *Artificial Intelligence*, vol. 219, pp. 40–66, Feb. 2015, doi: 10.1016/j.artint.2014.11.006.

[9]   P. Bänninger, "ICRA 2023 - Cross-Agent Relocalization for Decentralized Collaborative SLAM," 2023. Accessed: Nov. 26, 2025. [Online]. Available: https://youtu.be/GZjKrLsQJ5c?si=xELeB0Q7qcnfn79s

[10]   C. Wang *et al.*, "Multi-Robot System for Cooperative Exploration in Unknown Environments: A Survey."

[11]   J. Delmerico, E. Mueggler, J. Nitsch, and D. Scaramuzza, "Active Autonomous Aerial Exploration for Ground Robot Path Planning," *IEEE Robotics and Automation Letters*, vol. 2, no. 2, pp. 664–671, Apr. 2017, doi: 10.1109/LRA.2017.2651163.

[12]   P. Arias-Perez, A. Gautam, M. Fernández-Cortizas, D. Pérez-Saura, S. Saripalli, and P. Campoy, "Exploring Unstructured Environments Using Minimal Sensing on Cooperative Nano-Drones," *IEEE Robotics Autom. Lett.*, vol. 9, no. 12, pp. 11202–11209, 2024, doi: 10.1109/LRA.2024.3486212.