Introduction to Mobile Robotics

Lecture 11: Multi-robot Systems

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From One to Many

So far, we have focused on the single robot:

- How **it** sees the world (perception).
- How **it** decides where to go (decision-making).
- How **it** gets there (control).

Multi-Robot Systems (MRS)

What happens when we put robots in the same environment and ask **them** to cooperate?

$$\text{System Utility} > \sum_{i=1}^{N} \text{Individual Utility}_i$$

The whole should be greater than the sum of its parts.

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Why MRS?

Advantages:

- **Parallelism:** Tasks can be done faster (e.g., exploring a building).
- **Robustness:** If one robot fails, others can take over (redundancy).
- **Specialization:** Heterogeneous teams (e.g., a drone for view, a UGV for heavy lifting).

Challenges:

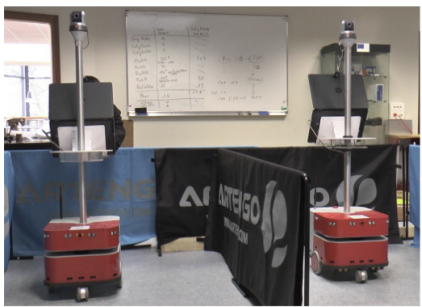
- **Interference:** Robots physically blocking each other.
- **Communication:** Bandwidth limits, packet loss, latency.
- **Uncertainty:** We now have uncertainty in N poses and the state of other agents.
- **Complexity:** State space grows exponentially with N.

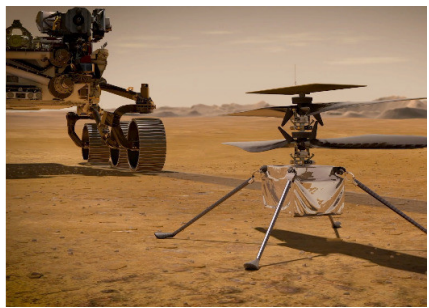
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Team Composition

Homogeneous vs. Heterogeneous

- **Homogeneous:** All robots have the same capabilities (physical structures do not need to be the same, e.g., two robots with different locomotion but the same speed, load capacity, field of view, etc.).
- **Heterogeneous:** Different capabilities (e.g., Mars Rover + Helicopter).





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Decision-making Mechanism

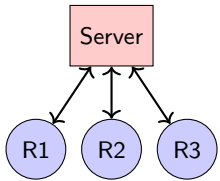
Centralized vs. Decentralized

- **Centralized:** One "God node" plans for everyone. $\Longrightarrow$ *Optimal but fragile (single point of failure).*
- **Decentralized:**
  - **Distributed:** Each robot makes its own decisions based on local info. $\Longrightarrow$ *Robust but sub-optimal.*
  - **Hierarchical:** one or more "team leaders" which organize robots into clusters. $\Longrightarrow$ *A form between centralized and distributed.*

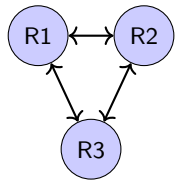
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Decision-making Mechanism

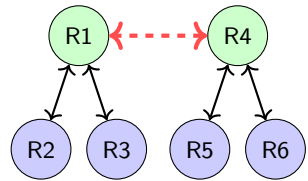
Centralized vs. Decentralized



Centralized (Star)



Distributed (Mesh)



Hierarchical (Clusters)

In ROS 2, DDS (Data Distribution Service) facilitates a **distributed** discovery system, but bandwidth usage scales poorly (communication complexity $\mathcal{O}(N^2)$) if everyone talks to everyone.

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Communication Mode

Explicit vs. Implicit

- **Explicit:** Robots send data packets (messages) to specific recipients or broadcast them.
  - *Example:* Robot A sends "I am at (x,y)" to Robot B via WiFi / ROS 2 DDS.
  - *Pros:* Precise, high bandwidth.
  - *Cons:* Limited range, infrastructure required.
- **Implicit:** Communication through the environment.
  - *Example:* Robot A leaves pheromone trails (like ants).
  - *Pros:* Robust, scalable to hundreds / thousands of robots.
  - *Cons:* Slow propagation of information.





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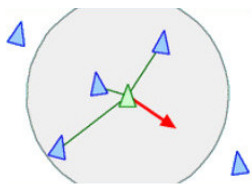
Motion Coordination

Avoid congestion / collisions while moving together.

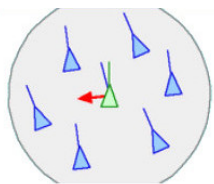
Swarm Intelligence: Reynolds' Boids

How do thousands of birds flock without a leader?

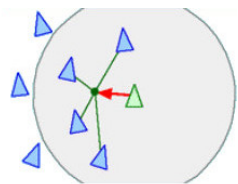
Craig Reynolds (1986) proposed three simple local rules:



1. Separation
Steer to avoid crowding



2. Alignment
Steer towards average heading



3. Cohesion
Steer to avg. position

$\Longrightarrow$ Complex global behavior emerges from simple local rules.

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Formation Control

Maintaining a strict geometric shape (e.g., for carrying a object).

Strategy 1: Virtual Structure

- The entire formation is treated as a single rigid body.
- Reference points are calculated for each robot.
- Robots track these virtual points.

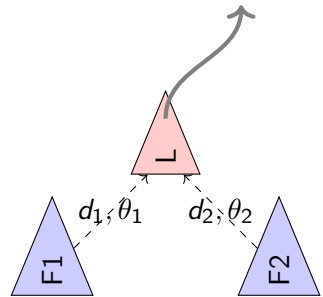


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Formation Control

Strategy 2: Leader-Follower

- One robot navigates. $\Longrightarrow$ Leader
- Others maintain a relative distance (d) and bearing (θ) to the leader.
- **Pros:** Simple to implement.
- **Cons:** No feedback to leader (if follower gets stuck, leader keeps going).



We will implement a basic Leader-Follower controller in the project.

Task Coordination

Who does what.

The Problem

- A set of robots: $\mathcal{R} = \{r_1, r_2, \ldots, r_m\}$
- A set of tasks: $\mathcal{T} = \{t_1, t_2, \ldots, t_n\}$
- A utility function: $U(r_i, t_j) \implies$ the quality of robot r_i performing task t_j (often calculated as $\mathit{Utility} = -\mathit{Cost}$, e.g., negative distance)

Objective: Find the mapping $\mathcal{A} : \mathcal{R} \to \mathcal{T}$ that maximizes total system utility:

$$\max \sum_{i=1}^{m} \sum_{j=1}^{n} \alpha_{ij} U(r_i, t_j)$$

subject to specific constraints (e.g., each robot does at most one task).

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The Gerkey & Matarić Taxonomy (2004)

Classifying "Multi-Robot Task Allocation" problems along three axes:

Robot Type

- **ST (Single-Task):** Robot can do 1 thing at a time.
- **MT (Multi-Task):** Robot can do parallel tasks.

Task Type

- **SR (Single-Robot):** Task needs 1 robot.
- **MR (Multi-Robot):** Task needs N robots (e.g., moving a heavy table).

Allocation

- **IA (Instantaneous):** Allocate now, no planning.
- **TA (Time-extended):** Schedule tasks over time.

Example: ST-SR-IA

Taxi dispatch: One car, one passenger, allocated now. Solved optimally via the "Hungarian algorithm".

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Centralized Approach: The Assignment Problem

ST-SR-IA:

- Formulate as a **Cost Matrix** (C_{ij}).
- Row = Robot, Column = Task.
- **Goal:** Select exactly one element per row/column to minimize total cost.

The Hungarian algorithm:

- Combinatorial optimization algorithm.
- Complexity: $\mathcal{O}(N^3)$.
- Guarantees optimal assignment.

$$\begin{pmatrix} 10 & \mathbf{5} & 9 \\ \mathbf{4} & 8 & 7 \\ 6 & 12 & \mathbf{3} \end{pmatrix}$$

Selecting minimal cost unique mapping.

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Decentralized 1: Market-Based

Borrowing from economics. $\Longrightarrow$ A very popular decentralized approach.

Contract Net Protocol:

1. **Auctioneer** (or Task Manager) announces a task: "Who can explore Room A?"
2. **Bidders** (Robots) calculate their cost (e.g., path length to Room A) and submit a bid.

$$\text{Bid} = \text{Revenue} - \text{Marginal Cost}$$

3. **Auctioneer** awards the contract to the lowest cost bidder.

Pros: Robust and handles failure naturally (re-auction).
Cons: Communication heavy.

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Decentralized 2: Threshold-based

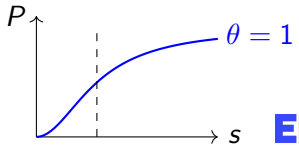
Bio-inspired: How do bees decide to forage or nurse?

- **Stimulus (s):** Level of demand (e.g., number of unvisited frontiers).
- **Threshold (θ):** Internal resistance of the robot to perform the task.
- **Response probability:**

$$P(\text{act}) = \frac{s^2}{s^2 + \theta^2}$$

Result:

- Low θ robots start first (Specialists).
- If demand s rises, High θ robots join (Redundancy).

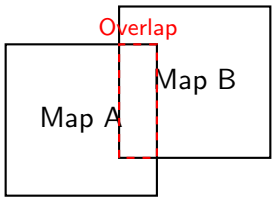


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Case Studies

Multi-robot Exploration: The Map Merging Problem

Robot A maps the kitchen, while Robot B maps the hallway. How do we combine them?



Challenge: The relative transformation T_{AB} between Robot A's start frame and Robot B's start frame is unknown.

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Multi-robot Exploration: Map Merging Strategies

- **Known initial poses:** If we know start positions, T_{AB} is trivial. $\Longrightarrow$ Simply overlay occupancy grids.
- **Rendezvous:** Robots must meet each other. When they detect each other (LiDAR / camera), they calculate relative pose and lock the maps together.
- **Scan matching:**
  1. Extract features from Grid A and Grid B (e.g., corners, long walls).
  2. Try to find a transformation that maximizes feature overlap.
  3. Similar to "Loop Closure" in single-robot SLAM, but across two robots.

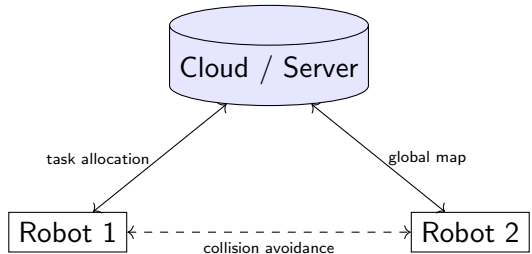
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Intralogistics: Amazon Kiva Systems

- **Setup:** Hundreds of orange robots lifting pods.
- **Environment:** Structured (QR codes on floor).
- **Navigation:** Centralized Traffic Control (CTC). $\Longrightarrow$ The server tells every robot exactly which path to take to avoid gridlock.
- **Key Lesson:** If you control the environment, centralized planning beats decentralized.

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Intralogistics: Cloud vs. Edge Architecture



- **Cloud layer:** Heavy computation (global optimization, long-term storage, fleet management).
- **Edge layer (Robot):** Real-time safety (collision avoidance, local control).
- This is the standard industry model. $\Longrightarrow$ A hybrid approach.

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Summary

1. **MRS** increases utility but adds complexity (interference, comms).
2. The key lies in **coordination** including motion and task.

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Questions?

Next: Practical Work 11 - ROS 2 Namespaces and DDS

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