# Towards a communication free coordination for multi-robot exploration

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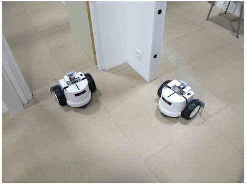
# Exploration of unknown environment



## Multi-robot advantages

Minimize exploration time

- explore distinct part of the environment simultaneously
- redundancy of information increases accuracy
- robustness

# Outline

1. Problem Statement
   - Specification
   - Notations
   - Assignation criteria
2. State of the art : Frontier allocation techniques
   - Closest Frontier
   - Greedy allocation
3. Proposition : Min Position allocation
   - Description
   - Algorithm
   - Cost Matrix computation
4. Simulation Results
5. Conclusion

# Assumptions

## Robot fleet Assumptions

- Homogeneous robots
- Communication ability (maps, location)

## Robot abilities

- localization and mapping
- map fusion

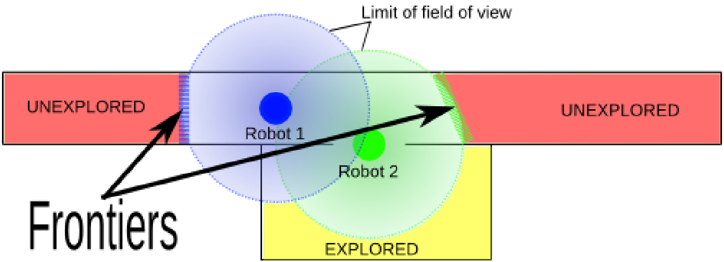
$\Longrightarrow$ remains to define a **multi-robot exploration strategy**

# Frontiers

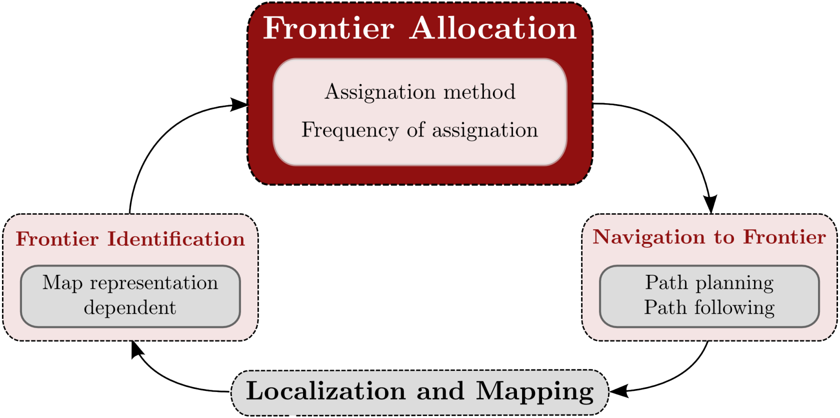
- Finite environment
- Exploration → increase explored part of the environment

**Frontier definition [Yamauchi97]**

Boundary between unexplored and empty/accessible areas



# Problem Statement



# Notations

## Definition

- $\mathcal{R}$ is the set of robots, $\mathcal{R} : \{\mathcal{R}_1 ... \mathcal{R}_n\}$ with $n = |\mathcal{R}|$ the number of robots
- $\mathcal{F}$ is the set of frontiers, $\mathcal{F} : \{\mathcal{F}_1 ... \mathcal{F}_m\}$ with $m = |\mathcal{F}|$ the number of frontiers
- $\mathcal{C}$ a cost matrix with $\mathcal{C}_{ij}$ the cost associated with assigning robot $\mathcal{R}_i$ to frontier $\mathcal{F}_j$
- $\mathcal{A}$ an assignation matrix with $\alpha_{ij} \in [0, 1]$ computed as follows :

$$\alpha_{ij} = \begin{cases} 1 & \text{if robot } \mathcal{R}_i \text{ is assigned to } \mathcal{F}_j \\ 0 & \text{otherwise} \end{cases}$$

# Frontier allocation constraints

## One frontier per robot

$$\forall i \sum_{j=1}^{m} \alpha_{ij} = 1$$

## Balanced distribution of robots among frontiers

$$\lfloor n/m \rfloor \leq \forall j \sum_{i=1}^{n} \alpha_{ij} \leq \lceil n/m \rceil$$

Number of robots per frontier is roughly equal with a maximum difference of one.

# Optimization Criteria 1

## Minimize of the sum of cost at each assignation

Minimize the exploration cost by minimizing the sum of cost (typically distance to reach the frontiers)

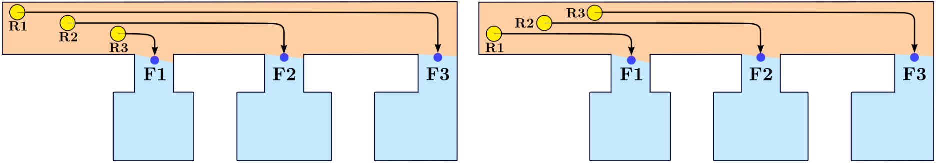
$$C(\mathcal{A}) = \sum_{i=1}^{n} \sum_{j=1}^{m} \alpha_{ij} \;\; \mathcal{C}_{ij}$$

# Optimization Criteria 2

## Minimum of the frontier exploration maximum cost

Time for all frontiers to be explored is determined by the maximum exploration time among all frontiers.

$$C_{max}(\mathcal{A}) = \max_{\forall i} \sum_{j=1}^{m} \alpha_{ij} \, \mathcal{C}_{ij} \quad (1)$$



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# Closest Frontier

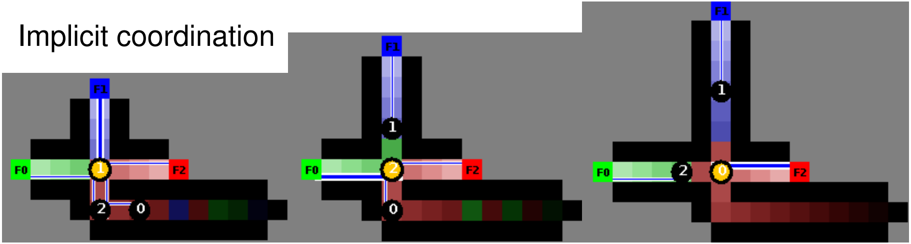
**Algorithm** Complexity : $O(n)$

**Input**: $\mathcal{C}_i$ cost vector of robot $i$ to each frontier
**Output**: $\mathcal{A}_i$ robot $i$ assignation
**begin**

$\alpha_{ij} = 1$ such that $j = \min \mathcal{C}_{ij} \quad \forall j \in \mathcal{F}_j$

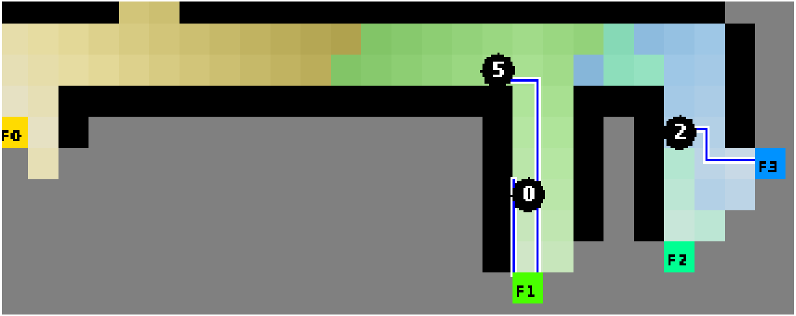
**end**

Implicit coordination



# Closest Frontier

Problem : robots assigned to the same frontiers



# Greedy allocation

**Algorithm** Complexity : $O(n^2 m)$

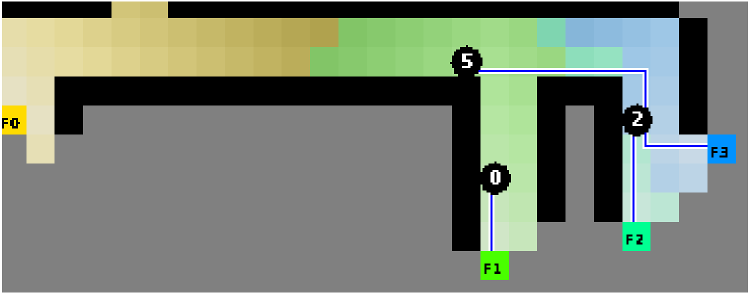
**while** $\mathcal{R}_i$ *has no frontier assignated* **do**

  Find i, j = argmin $\mathcal{C}_{ij}$ $\forall \mathcal{R}_i \in \mathcal{R}, \forall \mathcal{F}_j \in \mathcal{F}$

  $\alpha_{ij} = 1$ , $\mathcal{R} = \mathcal{R} \setminus \mathcal{R}_i$ , $\mathcal{F} = \mathcal{F} \setminus \mathcal{F}_j$

  IF $\mathcal{F} = \varnothing$ THEN $\mathcal{F} = \mathcal{F}_{init}$

**end**



# Limits

## Coordination-complexity

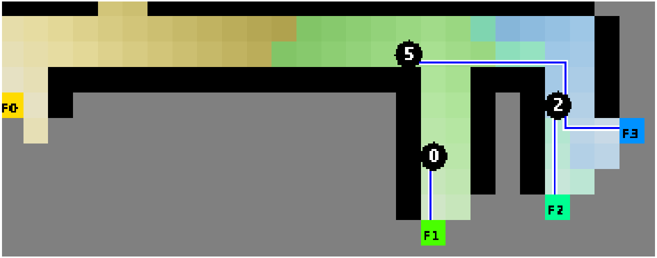
- Closest Frontier allocation : $O(n)$ but low performance
- Greedy Frontier allocation : $O(n^2 m)$ good cooperation
- Frontier-based methods are inherently simplier than utility based (estimated information gain)
  - market-based [Zlot et al. 02], greedy + extra communication
  - without communication, extra computation

# Outline

# Our approach

## Idea

"Go towards the frontier having the less robots closer"

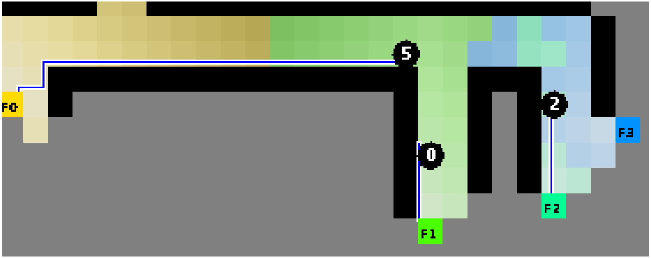


# Our approach : Min Position

**Position of a robot towards a frontier**

Number of robots closer to the frontier + 1

Robots are assigned to the frontier where its position is minimum



# Min Position

**Algorithm** Complexity $O(nm)$

**Input**: $\mathcal{C}$ cost matrix
**Output**: $\alpha_{ij}$ assignation of robot $\mathcal{R}_i$

**foreach** $\mathcal{F}_j \in \mathcal{F}$ **do**

$$\mathcal{P}_{ij} = \sum_{\forall k \in \mathcal{R}_k,\ k \neq i,\ \mathcal{C}_{kj} < \mathcal{C}_{ij}} 1$$

**end**

$\alpha_{ij} = 1$ such that $j = \underset{\forall \mathcal{F} j \in \mathcal{F}}{\text{argmin}}\ \mathcal{P}_{ij}$

*In case of equality choose the minimum cost among min* $\mathcal{P}_{ij}$

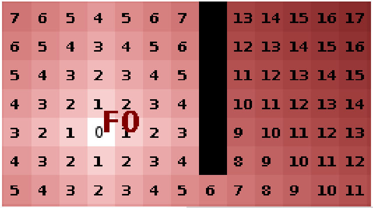
# How to compute the Cost Matrix without communication

## Standard approach

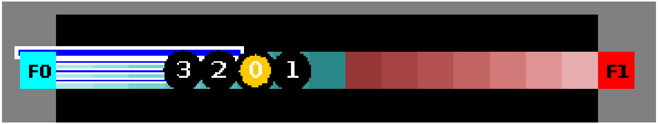
A* algorithm : depth-first search

## Wave-front propagation from every frontier

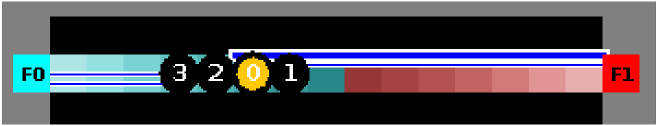
Wave-front propagation : breadth-first search [Barraquand & Latombe 91]
→ shortest path from all accesible points in the environment
→ cost for every robot



# Min Position




Closest Frontier allocation




Min Position Frontier allocation

# Outline

# Test Environments

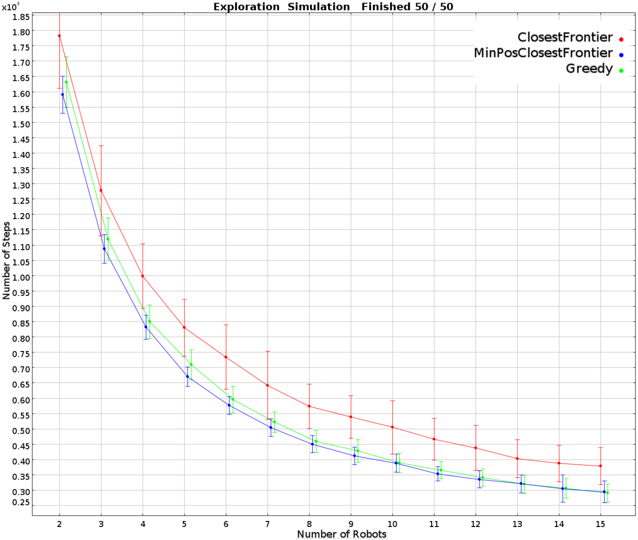
Maze environment

Player/Stage Project [Gerkey et al. 03] - Hospital section

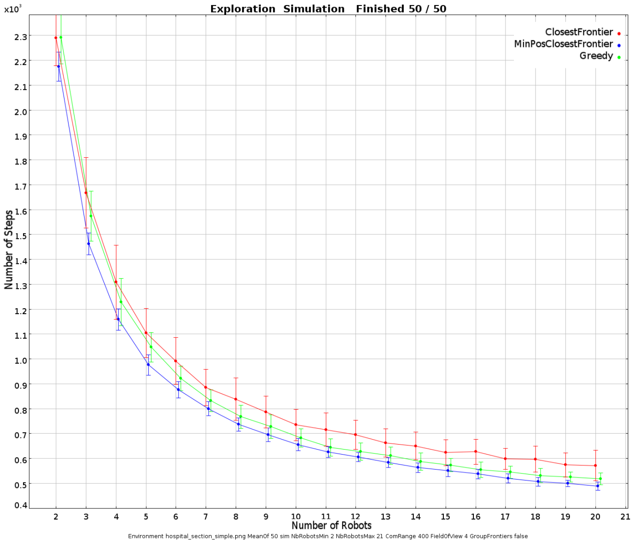
# Min Position in action

video

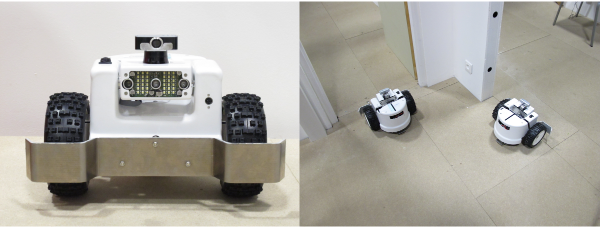
# Results on the maze environment



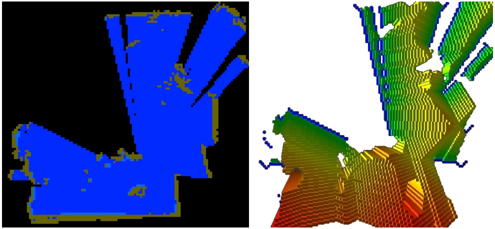
# Results on the hospital environment



# Towards a real implementation



MiniPekee - Cartomatic Team participating in CAROTTE Challenge



Occupancy grid and potential field grid

# Outline

# Conclusion

Novel frontier assignation algorithm :

- based on the concept of **position** towards a frontier
- **outperforms Closest Frontier** exploration performance
- **lower complexity** than standard Greedy approaches
- **decentralized**, **asynchronous** featuring implicit coordination (without communication)**.**