Comparison of exploration strategies for multi-robot search

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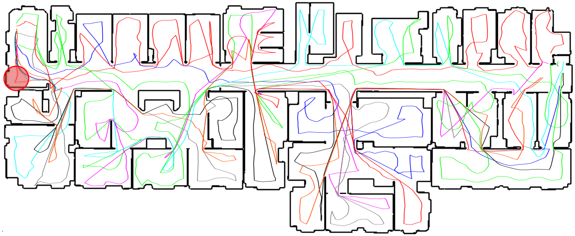
Content

- Problem definition (exploration x search)
- Goal-selection strategies
- Experimental evaluation
- Conclusion



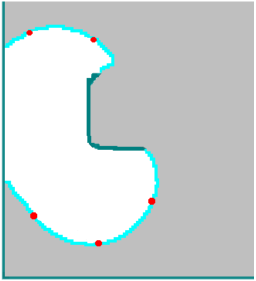
Problem definition

Search

A process of autonomous navigation of a team of mobile robots in an unknown environment in order to find an object of interest (placed randomly) with minimal resources used.

Frontier based algorithm (Yamauchi)

while *the object not found* **do**
- read current sensor information
- update the map with the obtained data
- determine new goal candidates
- assign the goals to the robots
- plan paths for the robots
- move the robots towards the goals



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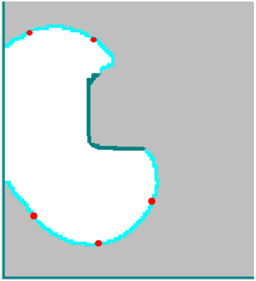

Problem definition

- The robots are equipped with a sensor with a limited range able to detect an object.
- Finding the object: the object is firstly detected by the sensor.
- Goal: to minimize the expected time T_f when this occurs:

$$T_f = \mathbb{E}(T|\mathcal{R}) = \int_0^{\infty} tp(t)\,\mathrm{d}t,$$

- where $p(t) = \frac{A_t^R}{A_{total}}$ is the probability of finding the object at time t.
- $A_t^{\mathcal{R}}$ is the area newly sensed at time t when the robots follow the trajectory $\mathcal{R}$
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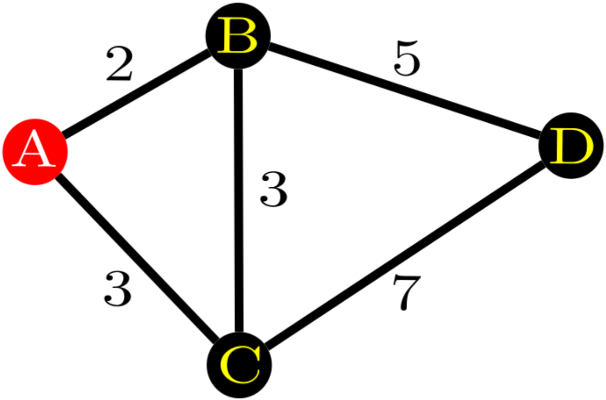
- The objective is to find trajectories $\mathcal{R}^{opt}$ minimizing $\mathbb{E}(T|\mathcal{R})$:

$$\mathcal{R}^{opt} = \arg\min_{R} \mathbb{E}(T|\mathcal{R}) = \arg\min_{\mathcal{R}} \sum_{t=0}^{\infty} tA_t^{\mathcal{R}}$$

Objectives of exploration and search are not the same



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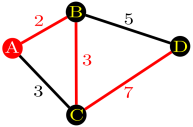
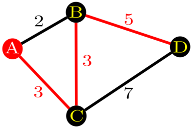
Exploration



$T = 2 + 3 + 7 = \mathbf{12}$



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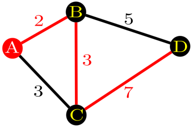

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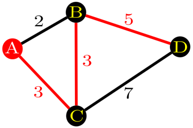

$T = 3 + 3 + 5 = \mathbf{11}$

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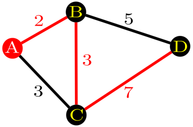

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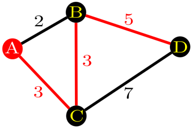

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ACBD is better

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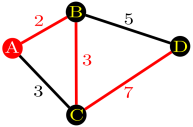
Exploration **Search**



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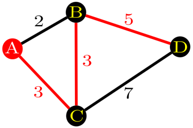

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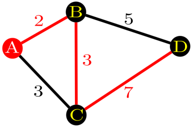

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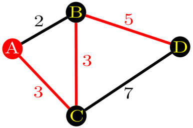


$T = 3 + 3 + 5 = \mathbf{11}$

ACBD is better

Search

$B = 2$

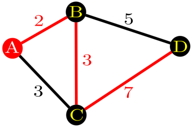
$C = 2 + 3 = 5$

$D = 2 + 3 + 7 = 12$

$\mathbb{E}(T) = \frac{2+5+12}{3} = \mathbf{6.33}$

Objectives of exploration and search are not the same

Exploration | **Search**



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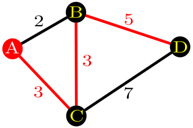
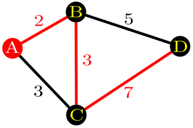
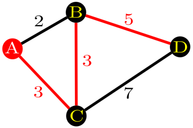


$$T = 3 + 3 + 5 = \mathbf{11}$$

$$C = 3$$
$$B = 3 + 3 = 6$$
$$D = 3 + 3 + 5 = 11$$
$$\mathbb{E}(T) = \frac{3+6+11}{3} = \mathbf{6.66}$$

ACBD is better

Objectives of exploration and search are not the same

	Exploration	**Search**
	$T = 2 + 3 + 7 = \mathbf{12}$	$B = 2$ $C = 2 + 3 = 5$ $D = 2 + 3 + 7 = 12$ $\mathbb{E}(T) = \frac{2+5+12}{3} = \mathbf{6.33}$
	$T = 3 + 3 + 5 = \mathbf{11}$	$C = 3$ $B = 3 + 3 = 6$ $D = 3 + 3 + 5 = 11$ $\mathbb{E}(T) = \frac{3+6+11}{3} = \mathbf{6.66}$
	ACBD is better	ABCD is better

Goal Assignment Strategies for Exploration

1. **Greedy Assignment**

   Yamauchi B, Robotics and Autonomous Systems 29, 1999

   - Randomized greedy selection of the closest goal candidate

2. **Broadcast of Local Eligibility**

   Werger B, Mataric M, Distributed Autonomous Robotic Systems 4, 2001

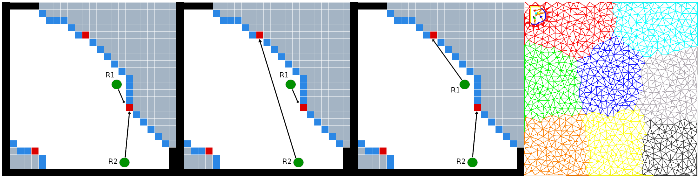
   while *any robot remains unassigned* **do**
   find the robot-goal pair (i, j) with the highest utility
   assign the goal j to the robot i and remove them from the consideration

3. **Hungarian Assignment** *Kuhn, 1955*

   - Optimal solution of the task-allocation problem for assignment of n goals and m robots in $O(n^3)$

4. **K-means Clustering** *Solanas A, Garcia M. A. IROS, 2004*

   - Cluster an unknown space



Evaluation Methodology

Experimental setup

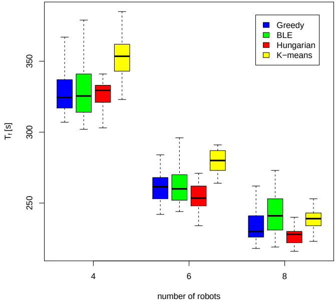
- 4,6,8 robots, 4 goal-assignment strategies, 4 environments, 10-30 runs
- sensor range: 5 m, FOV: 270°, SND driver
- planning period: 1 sec (speeded up simulation $\rightsquigarrow$ 3 sec)
- CPU 4x3.3GHz, 8GB RAM, x86_64 GNU/Linux kubuntu 3.0.0-20, ROS electric, polygon-based mapping
- total number of runs: 700

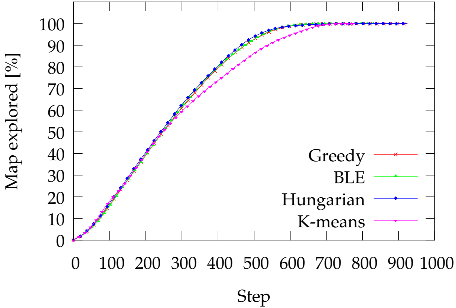
Performance metrics

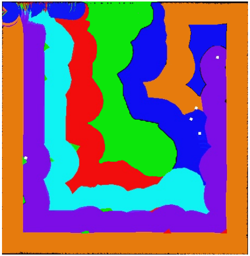
$$T_f = \mathbb{E}(T|\mathcal{R}) = \sum_{t=0}^{\infty} t \frac{A_t^{\mathcal{R}}}{A_{total}} \approx \sum_{t=0}^{\infty} t A^{\mathcal{R}_t}$$

Results

Empty map 50 × 50 m

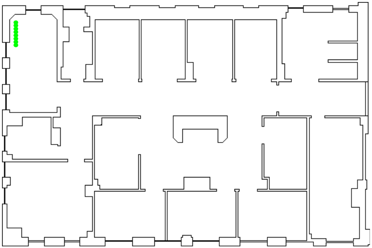


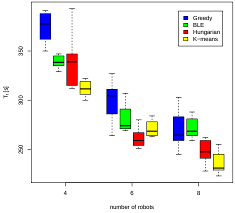


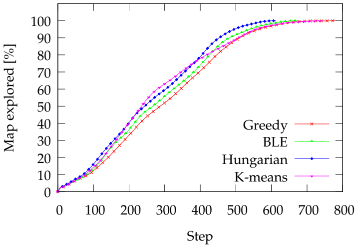


Results

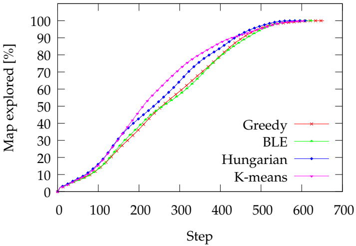
Hospital-section map 138 × 110.75 m







6 robots



8 robots

Conclusion

- The problem of multi robot search in an unknown space formulated.
- Several distance-cost-only strategies presented and statistically evaluated.
- Sophisticated methods outperformed the simple ones.
- Hungarian approach seems to be best (statistical significance not evaluated).
- Incorporating gain of visiting a goal will be interesting.
- Do we need a methods designed especially for multi-robot search?

Thank You your attention!

Technology Agency
of the Czech Republic

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