Multi-Robot Exploration in the Polygonal Domain

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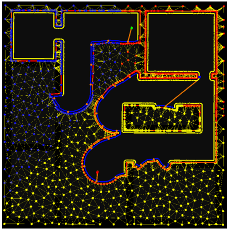
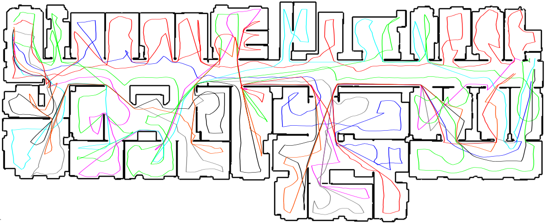
Outline

- Problem definition
- Exploration framework
- Polygonal domain
- Exploration strategies
- Experimental results
- Conclusion





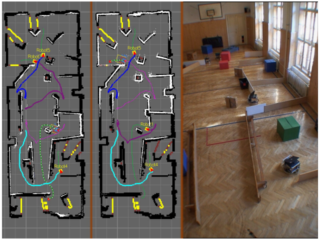
Mobile Robot Exploration

- Create a map of the environment
- Frontier-based approach

  Yamauchi (1997)
- Occupancy grid

  Moravec and Elfes (1985)
- Laser scanner sensor
- Next-best-view approach

  Select the next robot goal



Performance metric:

Time to create the map of the whole environment

search and rescue mission

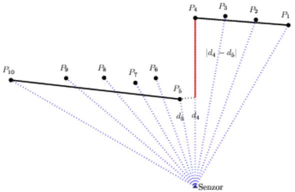
The Algorithm

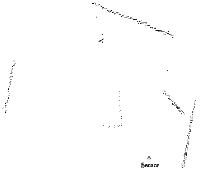
Exploration is an iterative procedure:

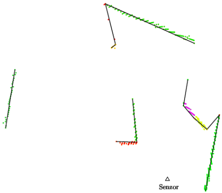
while *unexplored areas exist* **do**
    read current sensor information;
    update map with the obtained data;
    determine new goal candidates;
    assign the goals to the robots;
    plan paths for the robots;
    move the robots towards the goals;
end

Polygonal Domain

- The environment represented as a polygon with holes
- Sensor measurement represented as a polygon:
  - Successive Edge Following
  - Ramer-Douglas-Peucler algorithm
  - Least Squares Fit
- Map is incrementally built as a union of measurements



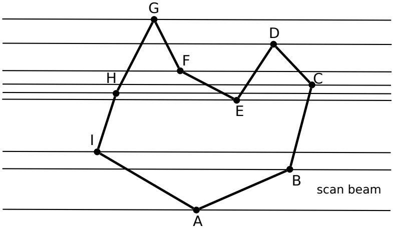


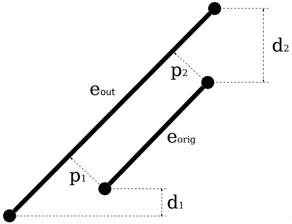


Map Building

- Vatti clipping algorithm
- Clipper library
- Problem: storing information about edges
- Operations: clipping, offsetting (Minkowski sum): output edges post-processing:

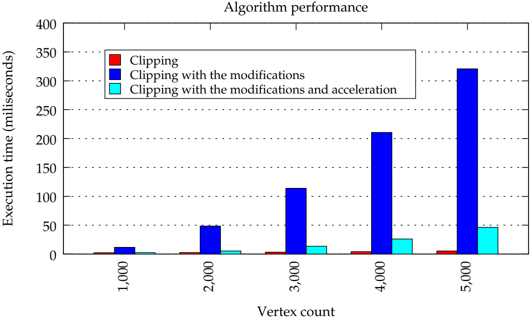
$$P = p_1 + p_2 + |d_1| + |d_2|$$





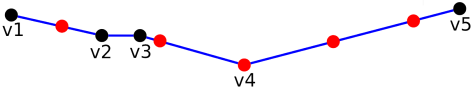
Comparison Optimization

- Rules applied:
  - The bounds with *y*-coordinate of its local minimum higher than *y*-coordinate of the top vertex of the output edge can be completely skipped.
  - If *y*-coordinate of the bottom vertex of the edge from the bound is higher than the top vertex of the output edge then the rest of the bound can be skipped.
  - If the penalty value is zero then skip further comparison of the output edge.



Map Management

- All-in-one map is not robust due to uncertainty of sensors
- Separate maps of the free space and obstacles
- Maps are merge before planning
- The number of vertices grows fast $\rightsquigarrow$ Ramer-Douglas-Peucker algorithms for reduction
- The map is used for:
  - Determination of goal candidates
  - Evaluation of goal candidates: Visibility graph + several runs of Dijkstra *We use distance cost only.*
  - Planning



Multi-Robot Exploration Strategy

- A set of m robots at positions $\boldsymbol{R} = \{r_1, r_2, \ldots, r_m\}$
- A set of n goal candidates $\boldsymbol{G} = \{g_1, g_2, \ldots, g_n\}$
- The exploration strategy (at each planning step):

  Select a goal $g \in \boldsymbol{G}$ for each robot $r \in \boldsymbol{R}$ that will minimize the required time to explore the environment

The problem is formulated as the task-allocation problem

$$(\langle r_1, g_{r_1} \rangle, \ldots, \langle r_m, g_{r_m} \rangle) = \text{assign}(\boldsymbol{R}, \boldsymbol{G}, \mathcal{M}),$$

where $\mathcal{M}$ is the map

Comparison - Goal Assignment Strategies

1. **Greedy Assignment**

   Yamauchi B, Robotics and Autonomous Systems 29, 1999

   - Randomized greedy selection of the closest goal candidate

2. **Iterative Assignment**

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

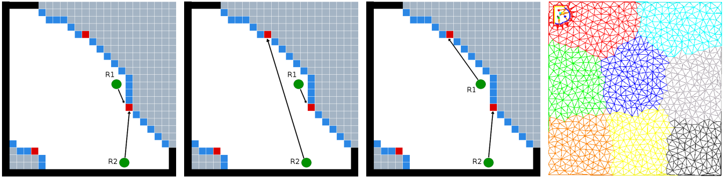
   - Centralized variant of the broadcast of local eligibility algorithm (BLE)

3. **Hungarian Assignment**

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

4. **K-means Clustering**

   - $\langle$cluster–first, route–second$\rangle$ *Solanas A, Garcia M. A. IROS, 2004.*



Evaluation Methodology

Experimental setup

- 4,6,8,10 robots, 4 goal-assignment strategies, 4 environments, 30 runs
- sensor range: 5 m, FOV: 270°, SND driver
- Planning period: 1 sec
- CPU 4x3.3GHz, 8GB RAM, x86_64 GNU/Linux kubuntu 3.0.0-20, ROS electric
- total number of runs: 1440 (speeded up 3x: 240 hours)

Performance metrics

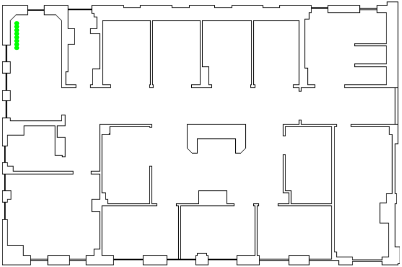
- t_{exp} - total required exploration time
- d_{max} - maximal distance:

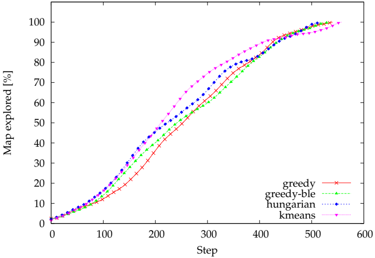
$$L = \max\{l_1, l_2, \ldots l_m\},$$

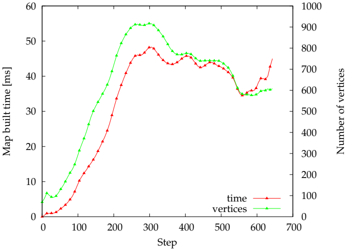
where m is the number of robots and l_i the traveled distance.

Experiments

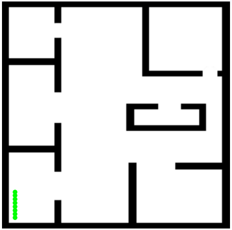
- a portion of hospital map
- map size: 138x110 m
- 8 robots, sensor range: 10 m

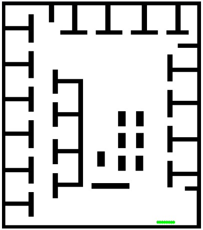


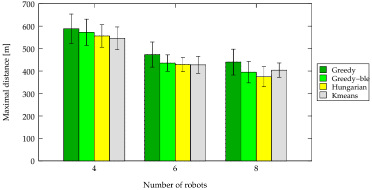


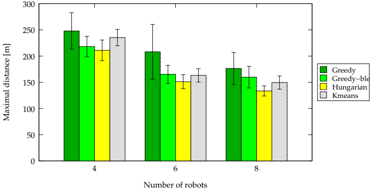


Comparison






700
600
500
400
300
200
100
0
Maximal distance [m]
4
6
8
Number of robots
Greedy
Greedy–ble
Hungarian
Kmeans


300
250
200
150
100
50
0
Maximal distance [m]
4
6
8
Number of robots
Greedy
Greedy–ble
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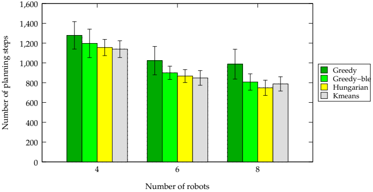
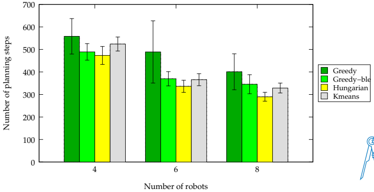

1,600
1,400
1,200
1,000
800
600
400
200
0
Number of planning steps
4
6
8
Number of robots
Greedy
Greedy–ble
Hungarian
Kmeans


700
600
500
400
300
200
100
0
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8
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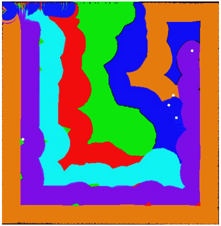
Kmeans

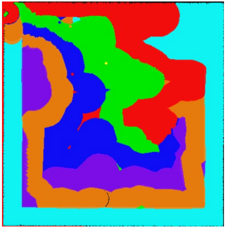
Hospital-section Map

- map size: 271x110 m
- 10 robots, Hungarian strategy, sensor range 10 m
- the final map contains 1226 vertices

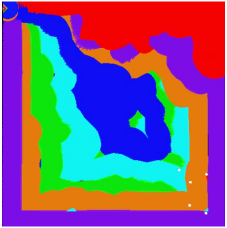
Graphical Comparison



(a) Greedy



(b) BLE



(c) Hungarian

(d) Kmeans

Comparision of a Polygonal and Grid-based Representation

- Hospital-section map, 1 robot
- size 271x110 m

Polygonal

- 1226 vertices

Occupancy Grid

- 1 cell: 5 cm ⇒ 12 076 800

	Polygonal		Grid	
$S\ [m^2]$	$t_{plan}\ [ms]$	$t_{total}\ [ms]$	$t_{plan}\ [ms]$	$t_{total}\ [ms]$
1000	10	35	274	471
3000	22	50	985	1224
5000	14	70	2141	2410
10000	45	116	3369	3854
13000	36	132	4902	5611

Conclusion

- Multi-robot exploration framework for the polygonal domain implemented in ROS
- Extension of Clipper with user-defined information
- Implementation of several goal-assignment strategies
- Experimental evaluation

Future work

- Code cleaning $\rightsquigarrow$ code publication
- Statistical evaluation of strategies on real robots
- Implement more strategies

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Thank You!

Technology Agency
of the Czech Republic

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