Comparison of exploration strategies for multi-robot search

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Content

- Problem definition (exploration × 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:
  \[ T_f = \mathbb{E}(T|R) = \int_{0}^{\infty} tp(t) \, dt, \]

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

$$\mathcal{R}^{opt} = \arg \min_{\mathcal{R}} \mathbb{E}(T | \mathcal{R}) = \arg \min_{\mathcal{R}} \sum_{t=0}^{\infty} t A_t^{\mathcal{R}}$$
Objectives of exploration and search are not the same
Objectives of exploration and search are not the same

**Exploration**

\[ T = 2 + 3 + 7 = 12 \]
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ACBD is better

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<table>
<thead>
<tr>
<th>Exploration</th>
<th>Search</th>
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<tbody>
<tr>
<td><img src="#" alt="Diagram of Exploration" /></td>
<td><img src="#" alt="Diagram of Search" /></td>
</tr>
<tr>
<td>$T = 2 + 3 + 7 = 12$</td>
<td>$T = 3 + 3 + 5 = 11$</td>
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</table>

ACBD is better
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\[ T = 2 + 3 + 7 = 12 \]

\[ B = 2 \]
\[ C = 2 + 3 = 5 \]
\[ D = 2 + 3 + 7 = 12 \]
\[ E(T) = \frac{2 + 5 + 12}{3} = 6.33 \]

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\[ T = 3 + 3 + 5 = 11 \]

**Search**

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

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**ABCD is better**
Goal Assignment Strategies for Exploration

1. **Greedy Assignment**
   - Randomized greedy selection of the closest goal candidate

2. **Broadcast of Local Eligibility**
   ```
   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 → 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

\[ T_f = \mathbb{E}(T|R) = \sum_{t=0}^{\infty} t \frac{A_t^R}{A_{total}} \approx \sum_{t=0}^{\infty} tA_t^R \]
Results

Empty map $50 \times 50$ m
Results
Hospital-section map $138 \times 110.75 \text{ m}$
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!

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