Energy Efficient Multi-Robot Exploration and Rendezvous

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1. Introduction

- **Motivation**: When two or more robots work together, they may need to meet or *rendezvous* first.
- **Goal**: We consider the case where multiple robots have been deployed in an unknown bounded environment at unknown locations and are unable to communicate unless they are co-located. In such a scenario, the robots must find one another to speed-up the exploration task.

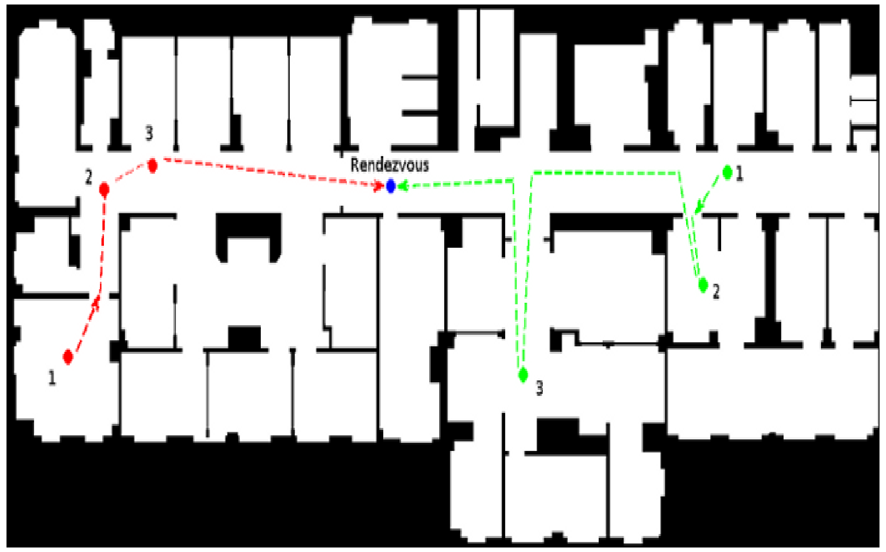

Fig.1: A rendezvous simulation of two robots

2. Proposed Approach

- An energy efficient combination of exploration and rendezvous is proposed and its overview is presented in Fig. 2.
- The robots initially discover potential rendezvous locations while exploring the unknown environment.
- These locations are ordered using different *ranking criteria* and visited during the rendezvous phase using the following strategies:
  - **asymmetric**: (a.k.a) "wait for mommy" [1], where one robot waits while the others search
  - **symmetric**: All robots search and have symmetric behaviors
  - **exponential**: The robots visit ranked locations based on exponential probability.

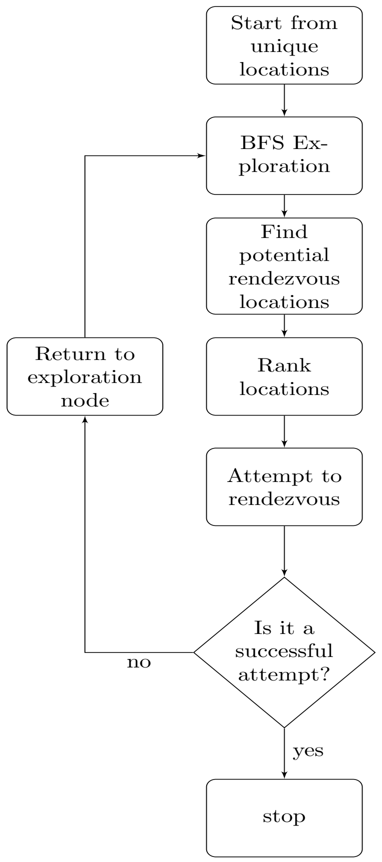

Fig.2: Combining exploration and rendezvous [3]

3. Ranking Criteria

- Our ranking criteria are based on a *cost-reward* model which considers the distinctiveness $\mathbf{D(p_k)}$ of a potential rendezvous location $\mathbf{p_k}$ as measured by robot $\mathbf{k}$, to find other robots, along with its distance $\mathbf{d(c_k, p_k)}$ from its current location $\mathbf{c_k}$.
- This model helps to reduce the total travel time in case of unsuccessful rendezvous attempts and also increases the area explored.
- The following are two variants of the model:
  - **linear distance-based ranking**:

$$L(p_k) = \frac{D(p_k)}{d(c_k, p_k)} \tag{1}$$

  - **sigmoid distance-based ranking**:

$$S(p_k) = \frac{D(p_k)}{\text{sigmoid}(d(c_k, p_k))} \tag{2}$$

4. Simulation Results

- The performance of the ranking criteria and rendezvous strategies for three robots in an abstract environment were compared with respect to the time taken to rendezvous.
- These results are shown in Fig. 3 which illustrate that the asymmetric rendezvous strategy and sigmoid-distance based ranking criterion performed the best.

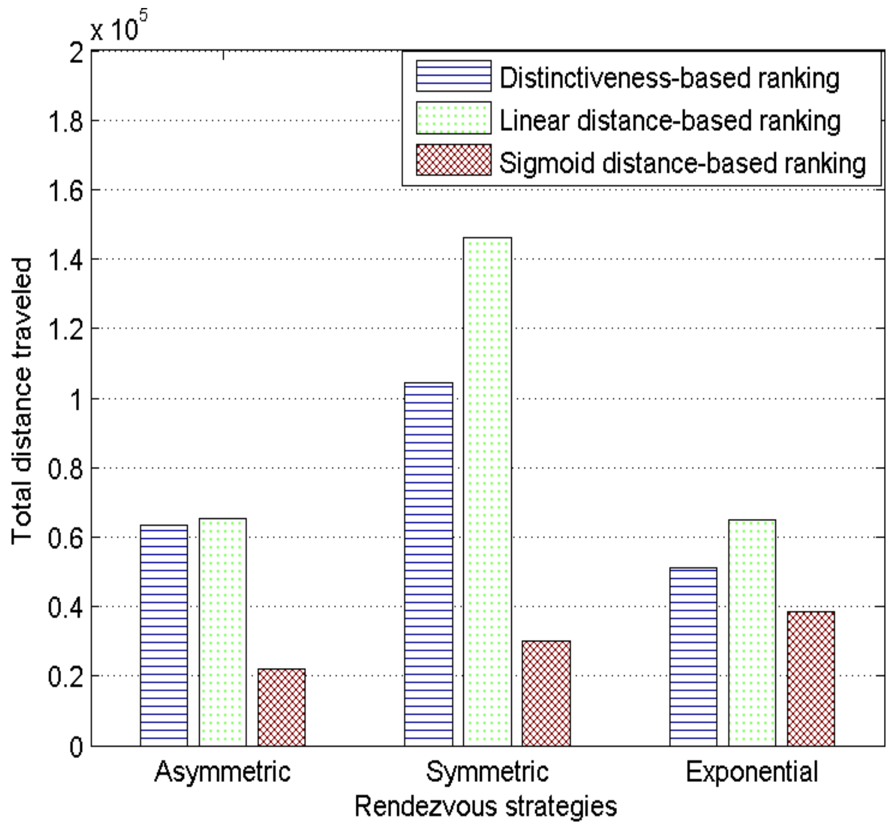

Fig.3: Total distance traveled for different rendezvous strategies and ranking criteria

5. Hybrid Ranking

- The cost-reward model (sigmoid-based ranking) is most effective when there is less overlap and the distinctiveness measure is useful with more overlap.
- Thus, we propose a combination of the two ranking criteria based on the area explored using the following hybrid ranking $\mathbf{D'(p_k)}$:

$$D'(p_k) = (1-\alpha)D(p_k) + \alpha\frac{D(p_k)}{d(c_k, p_k)} \tag{3}$$

- α in the above equation is a weighting function which is inversely proportional to the area explored. These results are presented in Fig. 4.

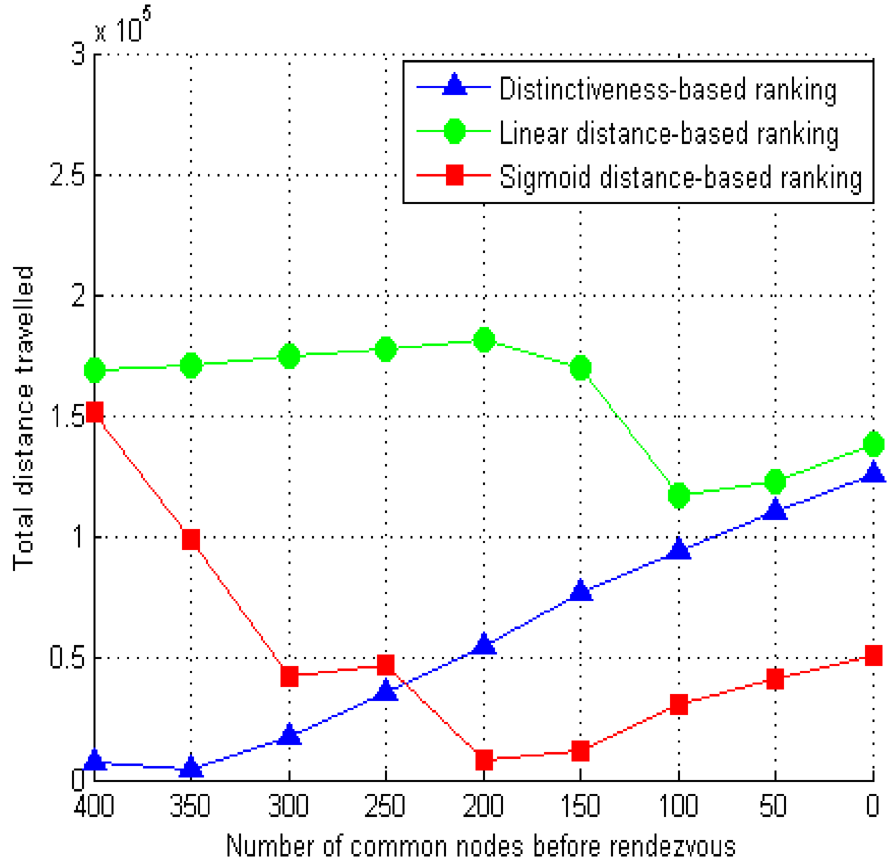

Fig.4: Hybrid ranking criterion

6. Conclusion

- Efficient combination of multi-robot exploration and rendezvous tasks.
- Cost-reward model was shown to be a better ranking criterion than pure distinctiveness-based ranking.
- Hybrid-ranking criterion was proposed to capture the best aspects of distinctiveness and cost-reward model based ranking.

7. References

[1]. S. Alpern and S. Gal. *The theory of search games and rendezvous*. Springer, 2003.

[2]. N.Roy and G.Dudek. *Collaborative exploration and rendezvous: algorithms, performance bounds and observations*. Autonomous Robots 2001.

[3]. M.Meghjani and G. Dudek. *Combining Multi-robot exploration and rendezvous*. Canadian Conference on Computer and Robot Vision 2011.

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