Frontier-Based Exploration for Multi-Robot Rendezvous in Communication-Restricted Unknown Environments

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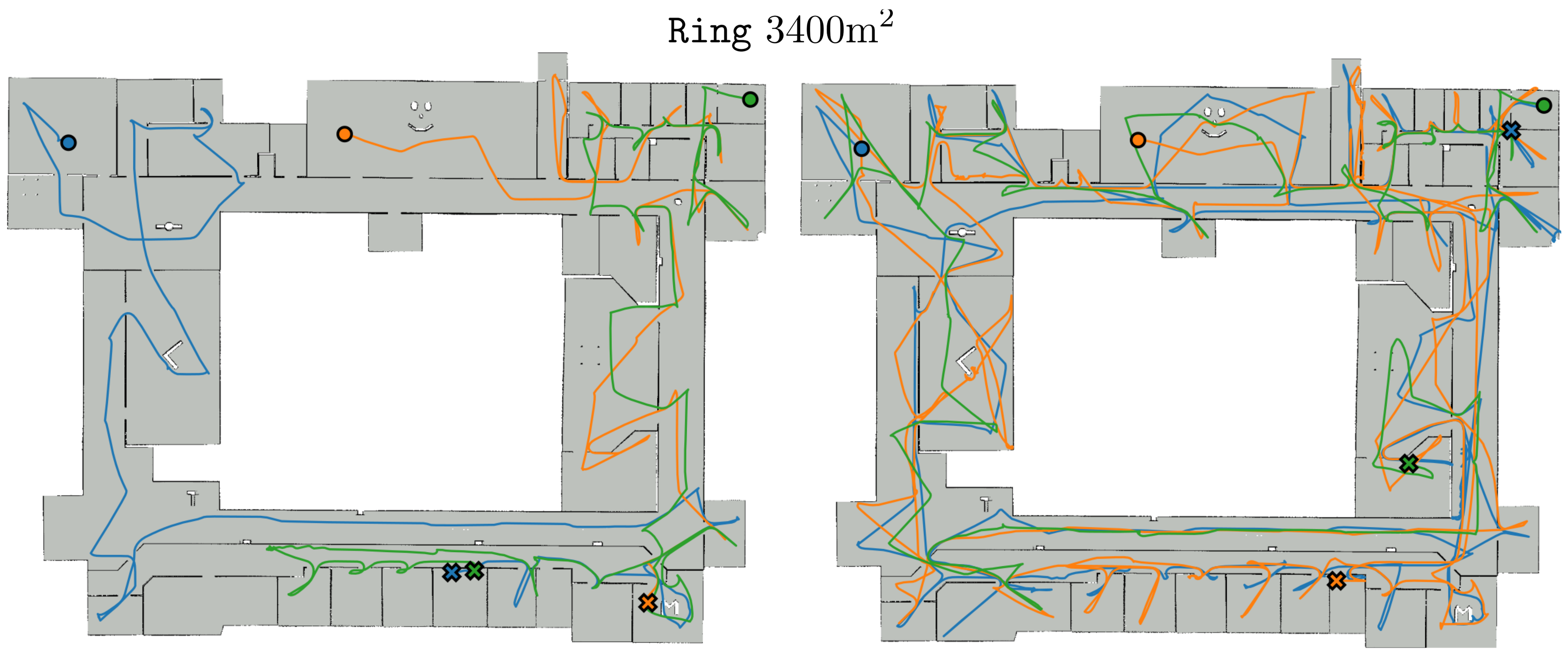
IROS '24 ABU DHABI

Problem Formulation



Rendezvous paths of 3 robots in an initially unknown, communication-restricted environment, using our method (Frontier-Based Rendezvous, FBR, left) and the classical frontier exploration strategy (Frontier-Based Exploration [3], FBE, right) in the map Ring, 3400m². Circles indicate starting positions, while crosses indicate the locations when a robot joins a cluster.

Multi-robot rendezvous [1] involves coordinating a Multi-Robot System (MRS), to efficiently converge at or near a shared location.

A rendezvous strategy is typically evaluated by the total time or distance taken for all robots to reach the meeting point, the smaller the better.

Efficient rendezvous strategies are key components for MRS application domains where robots need to physically meet in order to share collected information or collaborate on some localized task.

In this work, we consider the rendezvous problem for a team of autonomous mobile robots in the challenging setting of a **communication-restricted** [2] and **initially unknown** indoor environment:

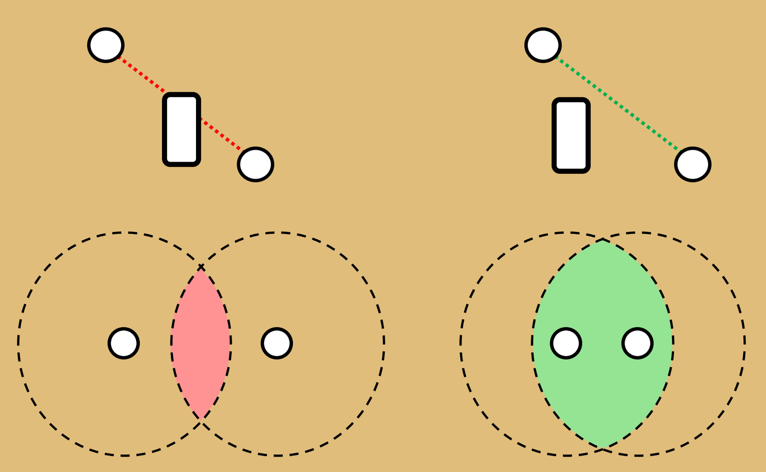
- no map of the environment is available to any robot;
- no pre-determined meeting location or coordination strategy has been agreed upon;
- the communication in the environment is restricted to occur only after a rendezvous.

The MRS is thus tasked to perform a rendezvous while it is exploring the environment [3].

The method we propose is an exploration strategy that is biased towards rendezvous, where the robot is encouraged to backtrack on previously explored areas, often passing through high-connectivity zones as corridors, facilitating episodic (i.e., unplanned) rendezvous.

Communication model

Two robots can communicate only when:



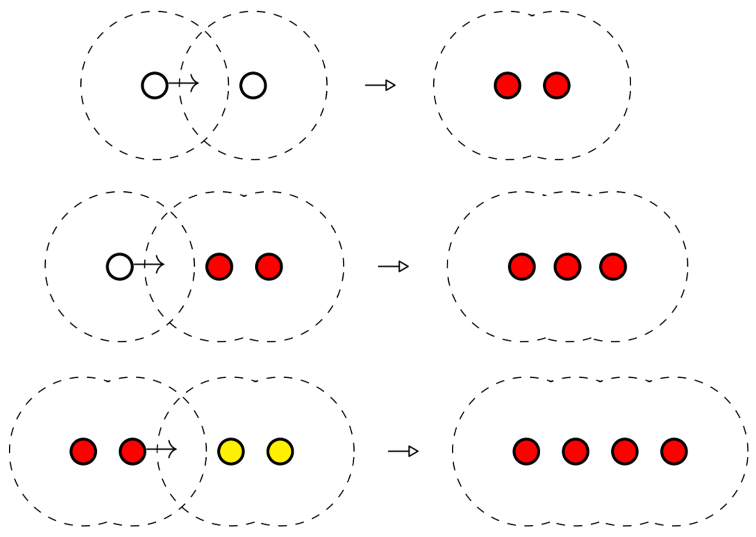
1) are in line of sight

2) each one is within the communication range of the other

When robots communicate, they share their map and their list of frontiers.

Robot clustering

When robots meet, they form a cluster, also sharing information:



1) two robots form a cluster

2) a third one joins

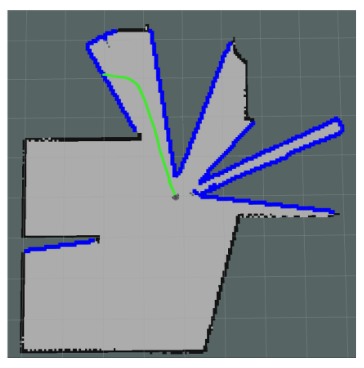
3) two clusters are merged

Each cluster has a leader and one or more followers.

Exploration trace, information decay and hallucinated frontiers

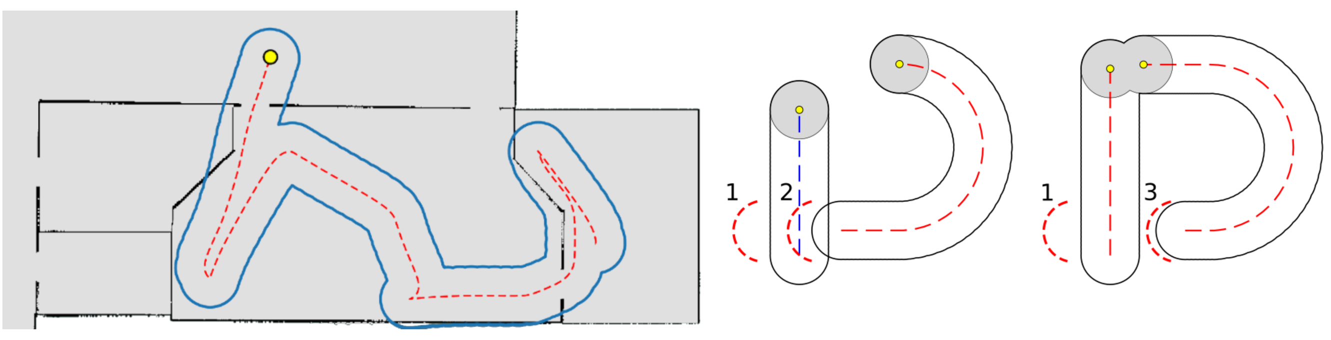
We extend the frontier-based exploration (FBE) approach [3], to incentivize a fast episodic rendezvous.

In FBE, exploration is carried out by iteratively reaching the next most promising *frontier*, integrating the perception in the map.



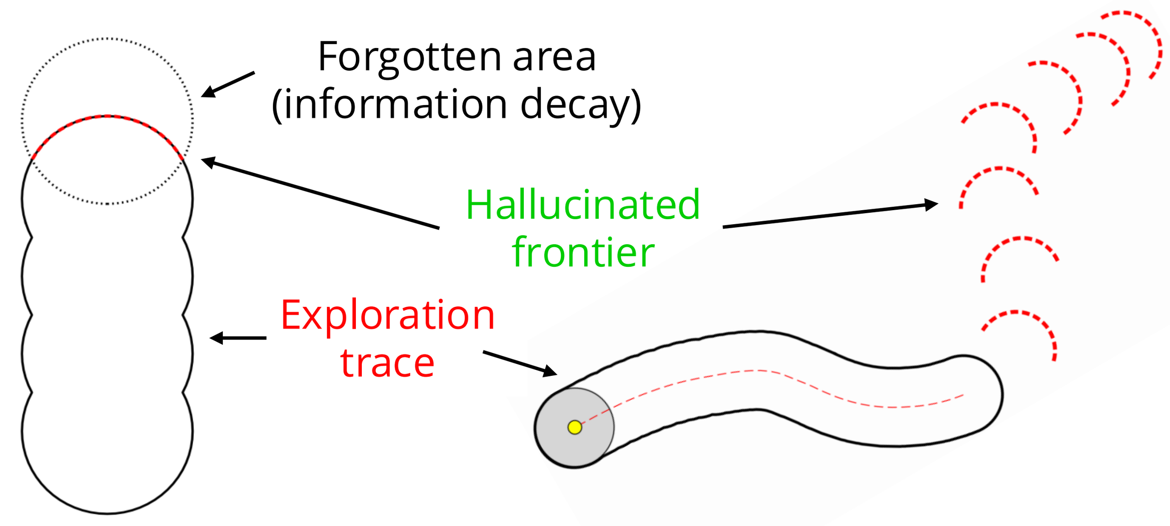
Frontiers are the boundaries between parts of the map that have been explored and those that are still unknown.

We bias exploration by introducing an *information decay* mechanism on the mapping process, so that the robot is also driven to go back on its steps. The backtracking mechanism will promote episodic rendezvous among robots.



We keep track of the *exploration trace* of each robot , defined as an area around the *trajectory* it has followed, with a radius *d* equal to its communication range. When robots meet, they share their *traces*.

When a part of the exploration trace is forgotten, a new hallucinated frontier is created and left behind



Frontiers (real and hallucinated) are ranked according to a linear combination of their distance from the current position of the robot, and their length, as in [1].

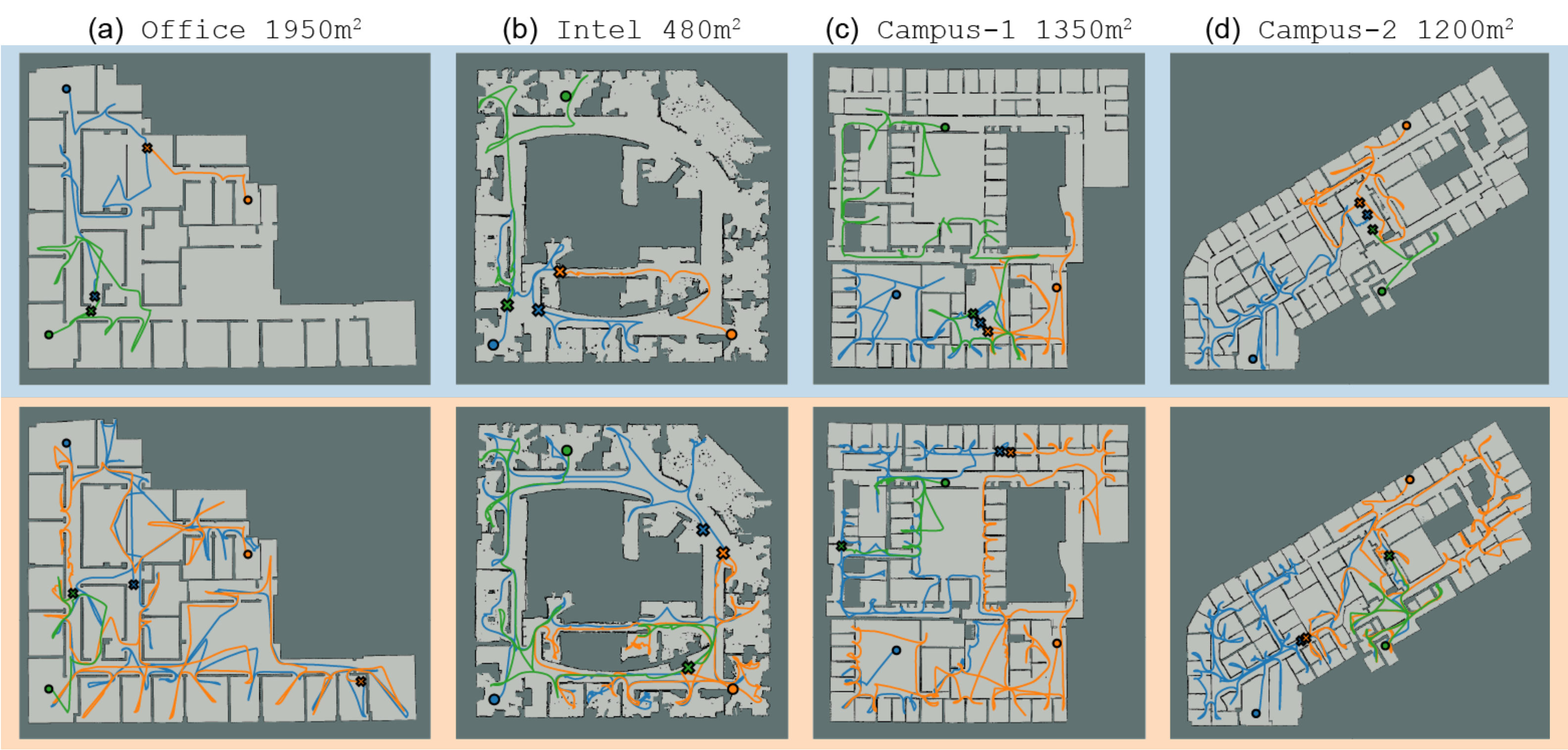
Experimental Results

We evaluate our method Frontier-Based Rendezvous (FBR) in simulation using Gazebo with ROS, comparing with FBE.

We set an information decay of ≈ 5 min and a communication range of d = 2.7 m.

For each method and teams of robots, we performed 10 runs with random initial location in 5 large-scale indoor environments (with ≈ 40 rooms). We tested teams of 3, 5, and 8 robots.

Full results and video



Robots using our method (FBR) travel shorter paths before doing a rendezvous in all environments, when compared with those using a standard frontier-based strategy (FBE).

number of robots

Environment	m	FBR t (s)	FBR σ_t	FBR R	FBE t (s)	FBE σ_t	FBE R	Δ_t
Ring	3	1623.13	978.18	1	2691.64	1557.18	0.6	0.66
	5	2000	936.3	1	2846.06	1246.36	0.7	0.42
	8	1844.08	488.16	1	2003.4	782.05	1	0.09
Office	3	727.46	372.16	1	851.11	791.46	0.9	0.17
	5	1358.55	718.19	1	1478.21	594.59	8.8	0.02
	8	1309.45	437.5	1	1251.54	762.47	1	-0.04
Intel	3	580.13	256.63	1	688.19	553.28	0.9	0.19
Campus-1	3	1070.29	487.82	1	1591.7	1130.81	1	0.49
Campus-2	3	818.09	503.57	1	1370.68	959.97	1	0.68

rendezvous time — rendezvous success rate

We reduce the rendezvous time with a speed-up of ~50% against FBE.

In all runs performed with FBR, the robots performed a rendezvous (R=1)

[1] H. Hourani, E. Hauck, and S. Jeschke, "Serendipity rendezvous as a mitigation of exploration's interruptibility for a team of robots," in Proc ICRA, 2013, pp. 2984–2991

[2] F. Amigoni, J. Banfi, and N. Basilico, "Multirobot exploration of communication-restricted environments: A survey," *IEEE Intell. Syst.*, vol. 32, no. 6, pp. 48–57, 2017.

[3] B. Yamauchi, A. Schultz, W. Adams, and K. Graves, "Integrating map learning, localization and planning in a mobile robot," in *Proc. ISIC*, 1998, pp. 331–336.