Efficient Frontier Management for Collaborative Active SLAM

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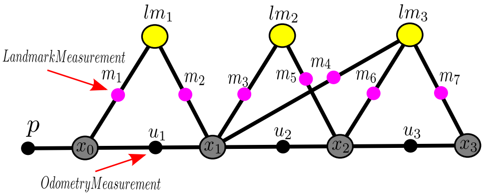
Outline

Simultaneous Localization And Mapping (SLAM)

1. Robot localizes itself and simultaneously maps the environment while navigating through it.
2. Localization is a problem of estimating the pose of the robot with respect to the map, while mapping makes up the reconstruction of the environment.
3. Modern SLAM approaches adopt a graphical approach. Where each node represents the robot or landmark pose and each edge represents a pose to pose or pose to landmark measurement measurement.
4. The objective of the SLAM problem is to find the optimal state vector x^* which minimizes the measurement error



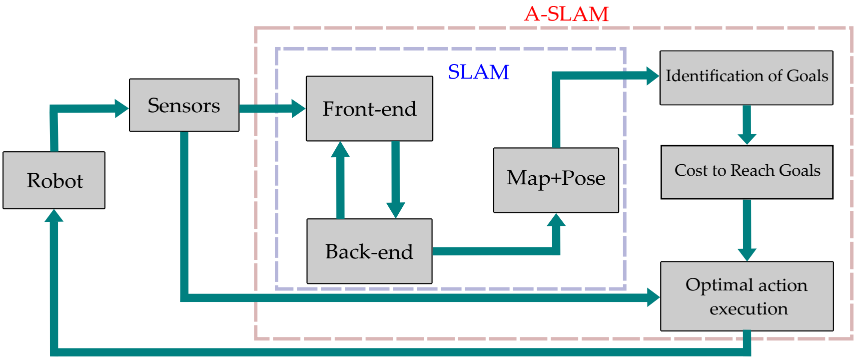
$$\mathbf{x}_i = \begin{pmatrix} x_i \\ y_i \\ \theta_i \end{pmatrix} \quad \mathbf{x}_l = \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

$$\mathbf{e}_i(\mathbf{x}) = \mathbf{Z}_i - f_i(\mathbf{x})$$
$$e_i(\mathbf{x}) = \mathbf{e}_i^T(\mathbf{x})\Omega_i\mathbf{e}_i(\mathbf{x})$$

$$\begin{aligned} \mathbf{x}^* &= \arg\min_x \textstyle\sum_i e_i(\mathbf{x}) \\ &= \arg\min_x \textstyle\sum_i \mathbf{e}_i^T(\mathbf{x})\Omega_i\mathbf{e}_i\mathbf{x} \end{aligned}$$

What is the Active SLAM (A-SLAM) problem?

1. A-SLAM deals with designing robot trajectories towards the goal locations subject to minimizing the uncertainty in its map localization.
2. The aim is to perform autonomous navigation and exploration of the environment without an external controller or human effort.



Proposed approach

- Motivated by AGS[1]

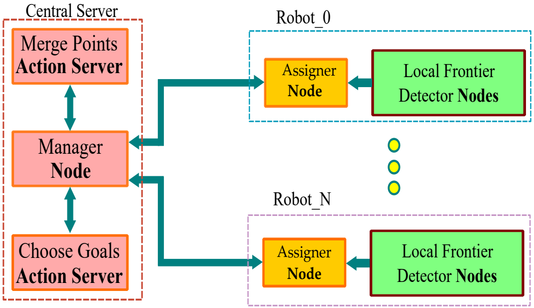
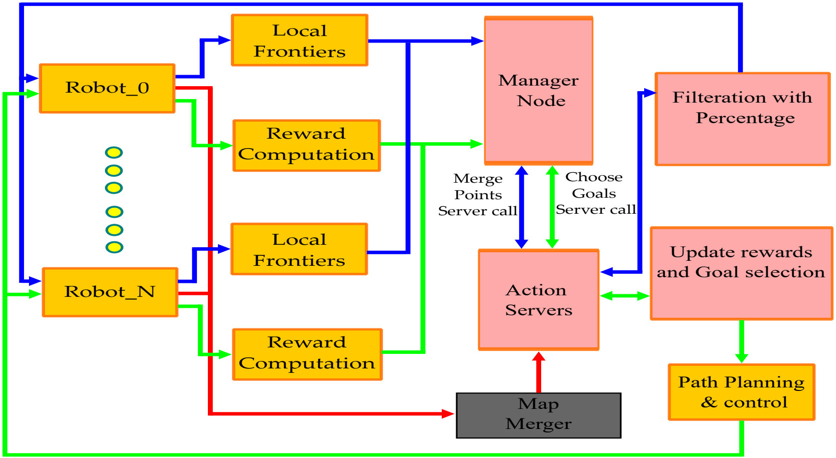


Figure 1: Central server, and local nodes communication.

[1] Placed, J.A. et al"Fast Autonomous Robotic Exploration Using the Underlying Graph Structure", IROS, 2021

Proposed approach

Figure 2: Architecture of the proposed method.

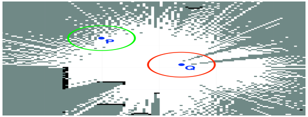


Proposed approach

1. For a set of frontiers $F = \{f_0, f_1, \ldots, f_N\} \subset \mathbb{R}^2$, where $\forall i \in 0, 1, \ldots, N$, $f_i = (x_i, y_i)$, each robot computes a matrix of rewards $R = \{r_0, r_1, \ldots . r_N\} \in \mathbb{R}$

$$R = \begin{bmatrix} \text{Reward} & \text{X} & \text{Y} \\ \hline r_0 & x_0 & y_0 \\ \vdots & \vdots & \vdots \\ r_N & x_N & y_N \end{bmatrix} \tag{1}$$

2. *Frontiers Management:*



3. *Spread Policy:*

$$K = \frac{\texttt{max reward}}{\texttt{number of targets assigned}} \tag{2}$$

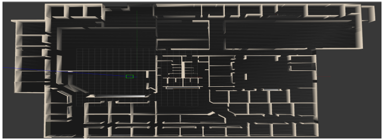
$$k = \frac{K}{d^2} \tag{3}$$

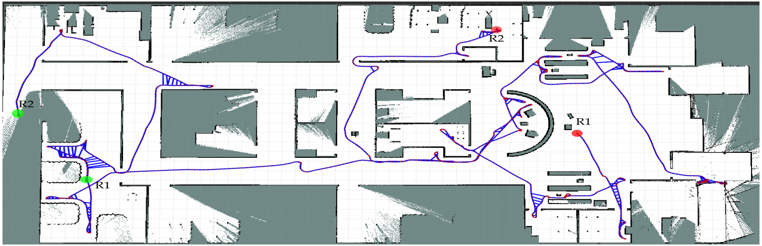
$$R_{new} = R_{old} - k \tag{4}$$

4. *Synchronous and Asynchronous coordination:*

Simulation Environment

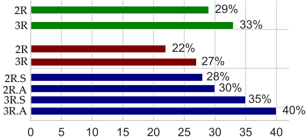
- ROS Noetic, Gazebo, and Ubuntu 20.04 on Intel Xeon® W-2235 CPU 3.80GHz x 12, with 64Gb RAM and Nvidia Quadro RTX 4000 GPU.

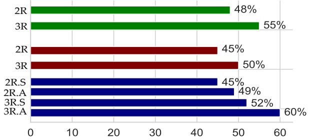


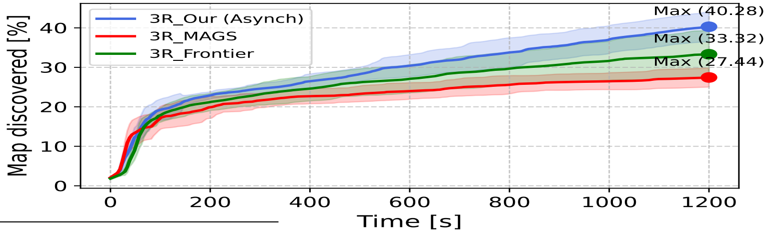


Simulation Results

- 15 simulations of 20 minutes each for both W.G. and HOS using Frontier[2] (green), MAGS (red), and Our (blue) methods rendering a total simulation time of 15 hours.
- PER_UNK, RAD, MIN_PTS and MAX_PTS were initialized to 60 %, $1m$, 0 and 10 respectively.

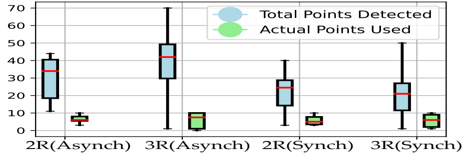


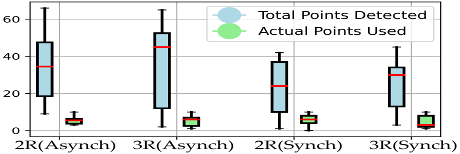




[2] Yamauchi, B."A frontier-based approach for autonomous exploration", IEEE CIRA'97, 1997

Simulation Results



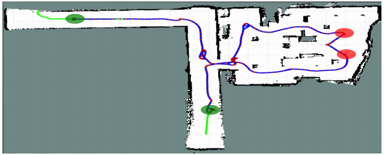


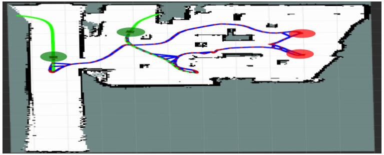
Env.	PER_UNK	**Used**
W.G	60 %	34.5 %
	50 %	1.4 %
	$\leq$ 40 %	**64.0 %**
HOS	60 %	**67.3 %**
	50 %	4.3 %
	$\leq$ 40 %	28.2 %

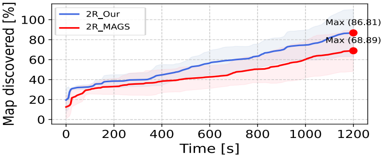
Env	RAD	**Used**
W.G	1.00	**87.0 %**
	1.25	1.8%
	$\geq$ 1.50	9.7%
HOS	1.00	**76.2 %**
	1.25	5.1 %
	$\geq$ 1.50	8.5 %

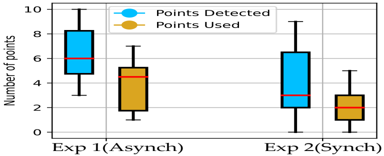
Env	**Method**	**SSIM**	**RMSE**	**AE**
W.G	Our (Asynch)	0.74	5.43	25.68
W.G	MAGS	**0.86**	6.34	28.39
W.G	Frontier	*0.20*	**10.04**	**40.89**
HOS	Our (Asynch)	**0.74**	4.89	25.39
HOS	MAGS	0.72	6.39	29.98
HOS	Frontier	0.35	**12.67**	**42.89**

Experimental Results









Conclusion

1. We proposed a method for the coordination of multiple robots in a collaborative exploration domain performing AC-SLAM.
2. We proposed a strategy to efficiently manage the global frontiers to reduce the computational cost and to spread the robots into the environment.
3. Two different coordinating approaches were presented for efficient exploration of the environment.
4. We presented extensive simulation analysis on publicly available datasets and compared our approach to similar methods using ROS and performed experiments to validate the efficiency and usefulness of our approach in the real-world scenario.