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Multi – Robot Exploration Supported by Enhanced Localization with Reduction of Localization Error Using Particle Swarm Optimization

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Abstract

Exploration of an area by a group of robots is an active research field of robotics as multi-robot exploration is applied extensively in several real life scenarios. The major challenges in such exploration are the availability of communication infrastructure as communication plays a key role in the coordination of team of robots for effective coverage of the area under exploration. But in disaster affected scenarios, there will be no existing communication infrastructure available and this makes the exploration ineffective and time consuming. Another challenge is in the localization process each robot is carrying out to update the map as well as for exchange of information with other robots. In this paper, an enhanced Multi-robot exploration strategy is introduced. The base of the exploration strategy is two techniques. The first one being localization of each robot involved in the exploration and this is done with the help of trilateration where three anchors are required which will be setup before the exploration starts. The second part is navigation and avoiding overlapping or missing out sectors while exploring. This is done with help of a navigation policy called frontier cell based approach. Further to this, the exploration strategy is supported with localization error reduction scheme in which the localization error is reduced with the help of Particle Swarm Optimization (PSO). The entire scheme is simulated and exploration time is analyzed for the same environment in different obstacle density and different number of robots to perform exploration. The results show the scheme is better than many existing multi-robot exploration strategies. Precisely, the proposed scheme is able to reduce the localization error to a threshold level of 0.02cm or below which can be considered as novel contribution towards the exploration strategies.

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Keywords: Exploration, Multi-robot Exploration, Localization, Localization Error optimization, Particle Swarm Optimization.

1 Introduction

Exploration of an unknown area is an important research area because of its wide range of applications such as search and rescue, planetary exploration etc. Replacing single robot exploration strategies with multi-robot exploration strategies obviously reduces the time period required to complete the given exploration task. Several multi-robot exploration strategies are suggested by researchers. These can be classified on various aspects such as whether they use exchange of maps or exploration is done independently etc. One way to classify these mechanisms is by looking into the amount of information regarding the search space. Exploration strategies are suggested if information on targets to be reached is known prior to the exploration. But in a search and rescue operation, it may not be practical to expect the robots will have enough information about the search space.

Multi-robot exploration strategies are always advantages over single robot exploration strategies as the total time required to complete the mission will be reduced, fault tolerance will be improved as multiple robots will introduce redundancy. As on the other hand, multi-robot exploration requires good coordination and communication schemes to reduce overlapping.

To search an unknown area by a group of robots, one approach is to make each individual robot to build a local map and exchange those maps each other to avoid overlapping. Also a good communication scheme is essential to avoid collisions. Based on the application, the focus shifts. In planetary exploration map building is the main objective while map building is used to reduce overlapping in a search and rescue application.

In any exploration strategy, localization of each individual robot is the primary step. Localization can be done by the robot itself or by a framework outside the set of robots. In an autonomous system of robots designed for exploration, self-localization is more appropriate as dependence on an external framework for localization will increase the delay the exploration.

Most of the localization schemes face the challenge of localization error and when distributed localization is implemented, these node level errors accumulate to a larger and serious error percentage. Researchers have attempted to overcome this issue by various additional steps such as optimization techniques and genetic algorithms.

This paper addresses the problem of finding an efficient multi-robot exploration and localization scheme. To reduce the localization error and improve the efficiency of the whole process, PSO is incorporated to the localization process. The exploration strategy is done with the help of understanding the search space as a collection of cells and each robot exchange the cell information which it covers to all other robots. Thus the search space is covered efficiently and in a shorter span of time.

2 Related Works

One of the early solution to the multi-robot exploration problems was first designed and proposed (Uslu et al., 2015) where, a map building algorithms was suggested to explore unknown area. It also proposed the idea of frontier cells which are the neighboring unexplored cells in grid which can be the next cell that can be explored by the robot. Dadgar et al., (2016) suggested an extension to Yamauchi’s proposal. He suggested a mechanism to guide the robot to choose right frontier cell so that the exploration time is optimized. Also a communication scheme has been proposed to avoid multiple robots choosing the same frontier cell. The technique used is to assign a cost to each frontier cell with respect to a robot where the cost is the distance between the robot and the frontier cell.

In further improvements to the scheme suggested (Calvo et al., 2011) suggested a multi-robot exploration scheme in which robots exchange mapping and sensing information. In this approach one robot acts as a team leader and collects all the mapping and sensing data and integrates it. This robot will control the other robots' movements.

The aforementioned body of work has two limitations such as i) the method used to find the next frontier cell is quite complex, ii) the amount of information exchanged between robots is huge.

Localization of nodes in Wireless Sensor Networks (WSN) is an essential feature of WSN. Paul & Sato (2017) discusses about the various strategies for localization in WSN. The paper also discusses about centralized and distributed localization schemes. The different distance measuring schemes such as range based and range free techniques are briefed in this paper.

Stanoev et al., (2016) discusses about cooperative localization in WSN. The paper proposes a measurement based statistical model which describes the Time of Angle, Arrival of Angle and Received Signal Strength measurements in WSN. In addition, a variety of localization algorithms and their performance analysis are also discussed in this paper.

Aksu, et al., (2011) proposes a distributive localization algorithm in WSN which is referred as AHLoS (AdHoc Localization System). In this scheme, few nodes are aware about their location and rest of the sensor nodes are estimated their location in a distributed approach using the iterative multi-lateration technique. The proposed system enables all the nodes in the WSN which has at least minimal connectivity to estimate it's location.

Radio Signal Strength (RSS) based approaches are one of the common techniques for localization. But due to the high noise influence, RSS is less preferred over alternative schemes. Balasubramanian, & Kavitha (2012) proposed a RSS based scheme in which it is proven that RSS based scheme can be an alternative strategy to Global Positioning System (GPS) even if the influence of high noise normally reduce the accuracy of RSS based localization schemes. Kumar et al., (2017) proposes a scheme to use PSO in localization. Megalingam et al., (2022) suggest a model to analyze the performance of a search and rescue robot. Maya et al., (2016) discusses a localization and mapping scheme which uses image processing techniques. This scheme assumes the availability of vision devices for localization and mapping.

The authors of Krishna et al., (2016) suggest the use of RFID elements for locating humans trapped in disaster affected sites. Rajesh et al., (2014) suggest distributed map building along with localization. Rajesh et al., (2014) proposes the concept of frontier cells for easier marking of locations while exploring a partially known area using a system of multiple robots. The authors of (Rajesh & Nagaraja 2019) devised an algorithm for multi-robot exploration using communication and coordination among robots of a multi-robot system. Rajesh & Nagaraja (2021) proposes an energy efficient communication and coordination scheme for multi-robot exploration.

3 Exploration Strategy

Many of the exploration strategies which are applied in multi-robot scenario uses the concept of frontier cells. In the proposed scheme, a slight variation of frontier cell concept is used for movement of the robot.

The basic assumption is that the exploration area is divided in to cells of equal size and a method to identify the availability of each cell. This can be implemented by maintaining a table which contains coordinate values of the mid-point of each cell and a unique number corresponding to each cell. This way exchange of details regarding a cell can be easily achieved.

The proposed method involves the following five phases:

- Self-Localization
- Localization Error Optimization with PSO
- Frontier Cell Selection
- Moving to the selected Frontier Cell
- Exchange of information with neighbors

4 Proposed System

The proposed system initially deploys a team of robots. These robots identify their current location using the Self Localization scheme. The errors in localization scheme is addressed with the help of PSO. The obtained location is used to identify the current cell and frontier cell. Once the frontier cell is identified, the robot navigates towards the midpoint of the frontier cell and searches for objects, boundaries and obstacles and localize them. This information is exchanged between the other neighboring robots to complete the exploration.

1) Self-Localization

When the robots are deployed randomly, the first step is to identify its current position. This is self-localization phase. Localization techniques which are developed by researchers are broadly classified into 2 categories Viz., range based and range free techniques. This classification depends on the fact that whether the localization technique uses distance between the nodes to compute the coordinates of the node or not.

- **Range based Localization Methods:** Distance between the nodes is used for calculating the coordinates. Other than using distance value directly, other parameters like Angle of Arrival (AOA), Time of Arrival (TOA), and Time Difference of Arrival (TDOA) are also used for localization. The hardware units required for measuring these values are expensive which makes range based localization techniques less feasible.
- **Range Free Localization Methods:** The coordinates are calculated using parameters other than distance. Mainly two schemes Viz., local information based and hop count based. In local information based techniques, a node collects location information about its neighbors and calculate its current location. In hop count based approach, location is calculated based on the hop count towards the neighbors.

The most commonly used scheme to localize a node that doesn't have location information is referred as trilateration. A node that knows it’s position information is referred as anchor node and three anchor nodes are needed in this scheme. In addition to the position information of anchor nodes, the determination of distance between the node to be localized and anchors is necessary (Lee & Teraoka 2010).

The robot listens to beacons from various anchors and selects the best three anchors. Using RSS measuring technique, robot calculates its’ distance to the anchors and the position of anchors by using trilateration. In this process, errors can occur which reflects the difference between calculated and the actual position. The localization error is critical when the robot decides to move to a new location based on its calculated position, hence optimizing the error is very important.

In trilateration, the first step is to obtain the distance between the node that need to be localized and anchor nodes on a 2D plane. Equation of a circle is shown in (1) where (x_a,y_a) is the centre and d is the radius

$$d^2 = x_a^2 + y_a^2 \qquad (1)$$

If we consider a point (x, y) that is on the circle, the above equation (1) can be redefined as mentioned in (2).

$$d^2 = (x_a - x)^2 + (y_a - y)^2 \qquad (2)$$

We assumed in the beginning that nodes are positioned in the same plane. Anchor nodes are referred as A, B and C. Distance between the node that is to be localized and each anchor node is da, db, and dc respectively. This can be shown in the following figure Fig. 1.

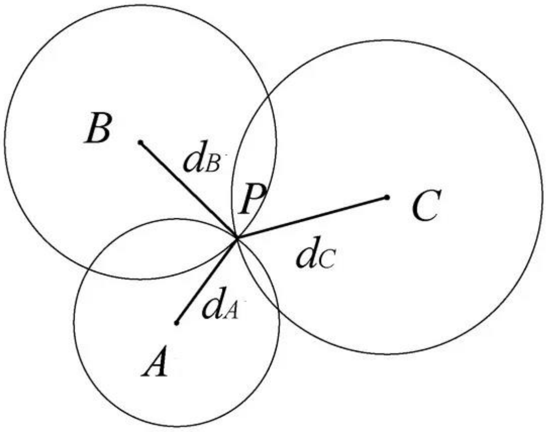


Fig. 1: Intersection of 3 sensing ranges in a plane

Similarly, for the other two circle, the equations are shown in (3) and (4).:

$$\text{Circle with B as center: } d_b^2 = (x_b - x)^2 + (y_b - y)^2 \qquad (3)$$

$$\text{Circle with C as center: } d_c^2 = (x_c - x)^2 + (y_c - y)^2 \qquad (4)$$

The distances are measured using the Received Signal Strength Indicator (RSSI) of the communication signals used. Rearranging the above equations as (5) and (6)

$$v_a = \frac{(d_b^2 - d_c^2) - (x_b^2 - x_c^2) - (y_b^2 - y_c^2)}{2} \qquad (5)$$

$$v_b = \frac{(d_b^2 - d_a^2) - (x_b^2 - x_a^2) - (y_b^2 - y_a^2)}{2} \qquad (6)$$

Then the coordinates of the node are as given in (7) and (8)

$$y = \frac{v_b(x_c - x_b) - v_a(x_a - x_b)}{(y_a - y_b)(x_c - x_b) - (y_c - y_b)(x_a - x_b)} \qquad (7)$$

$$x = \frac{v_a - y(y_c - y_b)}{(x_c - x_b)} \qquad (8)$$

Due to the error in the RSSI values obtained, there will be deviations in the distance calculations. These errors accumulate while calculating the coordinates of the robot. This error in position may lead to wrong decision making while selecting the current cell which in turn affects the decision of choosing the next frontier cell. So localization error optimization is essential. Several methods have been proposed to reduce the localization error [ ].

2) Localization Error Optimization with PSO

When we use RSSI to calculate distance and then to obtain coordinates, most localization techniques will give a possible zone of positions. So Particle Swarm Optimization is adopted to narrow down to most exact position. PSO provides more accurate results for the localization scheme due to the fact that in each iteration, PSO generates the most possible zone where the position of the node can be found is narrowed down to finer values.

The suggested localization technique uses the concept of weighted PSO that consider an initial weight for velocity which renewed in each iteration. The benefit of introducing this inertia weight velocity in the process is to provide faster and accurate results.

The localization process starts by PSO generating a set of random particles in the initial search and through iterative process, achieves accurate position. In each round, particle tries to update its direction based on 2 values P_{best} and G_{best} as shown in Fig. 2. Pbest is the particle's individual best fitness value and Gbest the best fitness value of the group. The update process follows the equations (9) and (10).

$$vi(t+1) = w \,.\, vi(t) + c1 \,.\, rand() \,.\, (Pibest(t) - xi(t)) + c2.\, rand().\, (Pgbest(t) - xi(t)) \qquad (9)$$

$$xi(t+1) = xi(t) + vi(t) \qquad (10)$$

Where,

$vi(t)$ and $xi(t)$ are velocity and position of i^{th} particle in the t^{th} iteration.

$Pibest(t)$ and $Pgbest(t)$ are the personal best and global best position of i^{th} particle in t^{th} iteration.

c1, c2 are acceleration constants.

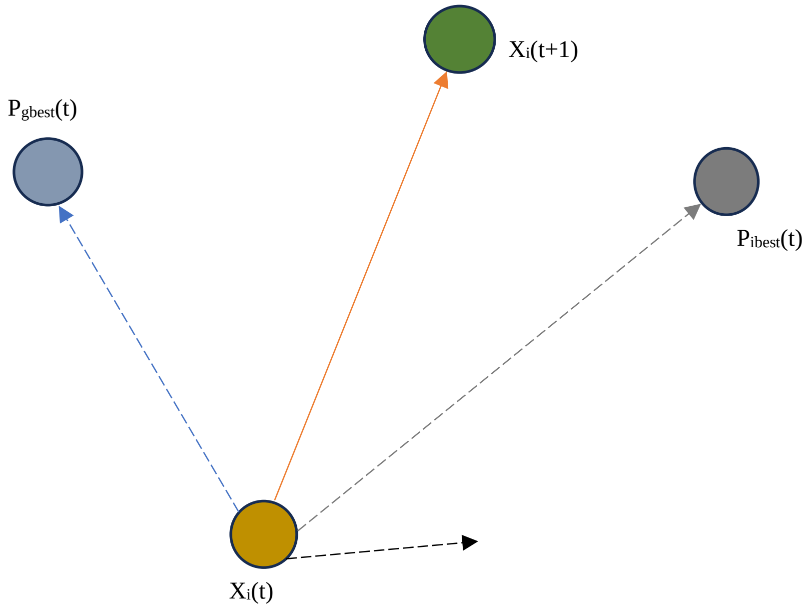


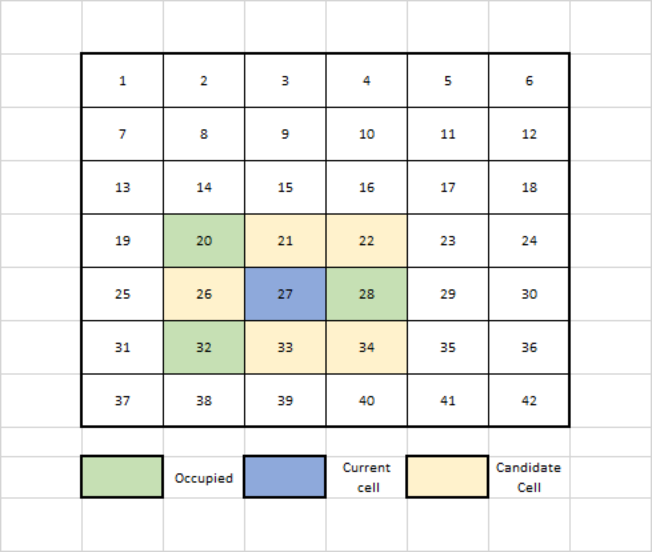
Fig. 2: Particle Swarm Optimization

The Self Localization phase generates the location data (coordinates of the robot whose location is identified). Based on this location data, the PSO algorithm generates randomly locations which are closer to the location data generated by the Self Localization phase. Each of these particles update their position based on the PSO algorithm in each iteration.

From the experiments conducted, it is observed that the localization error is brought down to less than 5cm in 20 iterations.

3) Frontier Cell Selection

After the localization error is reduced, exact coordinates of the robot are identified. The area to be explored is already divided into equal sized cells and the midpoint of each cell is recorded as shown in Fig. 3. The Euclidean distance between calculated coordinate of the robot and midpoints of cells and the cell with least Euclidean distance towards the robot is identified. This is the cell in which the robot is currently present. The next task to be performed by the robot is to navigate to unexplored cell. Along with midpoints of cells, its status (explored / unexplored) is also stored. The robot has to identify the neighbor cells of the current cell in which it is present and identify those neighbor cells which are unexplored. These cells are called the candidate cells. Frontier cell is the one which will be selected as the next cell to which the robot should navigate. Frontier cell is selected from candidate cells.



1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36
37	38	39	40	41	42

🟩 Occupied
🟦 Current cell
🟨 Candidate Cell

Fig. 3: Frontier Cell

The frontier cell selection is based on the following 2 parameters:

1. Status of the cell (explored / unexplored)
2. Occupancy Probability

Status of the cell is stored as binary information. An explored cell has a status value of 1 while an unexplored cell has a status value of 0.

Occupancy probability is the probability of cell that it has been occupied by any robot. If the occupancy probability is higher than the threshold value (threshold value is decided based on previous probability values).

Based on the status value and occupancy probability, the frontier cell is selected from candidate cells.

4) Moving to the Selected Frontier Cell

From the previous phase, the frontier cell is identified. The robot has to move to the frontier cell in order to complete the exploration. For this navigation, the robot first adjusts it orientation towards the destination frontier cell. Once the orientation is adjusted, the robot moves forward and uses the ultrasonic sensors for obstacle avoidance. If an obstacle is detected, the robot takes 90^0 turn and move 5 steps forward and turn 90^0 again keeping the orientation back to its original value. The robot continues moving until it reaches the destination which is the midpoint of the frontier cell.

Once the robot reaches the frontier cell midpoint, it updates the status of the cell to explored. Accordingly, the occupancy probability is also updated.

5) Exchange of Information with Neighbors

Once the robot reaches the frontier cell midpoint, the robot searches for objects, boundaries which can block the navigation of robot. Each object the robot identified is localized using the distance between the object and robot and the change in orientation.

Let's assume the orientation difference is θ and distance towards the object is d, then the coordinates of the object are $(d*\cos\theta, -d*\sin\theta)$. Using this method, all the objects are localized and the information about the objects identified, boundaries identified and obstacles detected is stored into the local repository of the robot. The robot will share this information with its neighboring robots using the customized communication protocol developed for inter-robot communication and coordination. This helps the team of robots to complete the exploration in lesser time which is energy efficient.

5 Implementation

Proposed system is implemented using Player-Stage multi-robot simulator. The simulator has 2 parts. Player and Stage. Player is the robotic control interface part while Stage is the simulator interface where robots, surrounding environment and other actors can be simulated. These units can be controlled using Player interface. Stage is a 2D simulator. In place of Stage, Gazebo is an alternative which is a 3D simulator interface (Lee, H., et al., 2022).

The first phase of the proposed system is that the robots localize themselves. To achieve this, 3 beacon emitting towers – anchor nodes are placed and each robot which is closer to these anchor nodes receive the beacons and identify the location of the anchor node from which it received the beacon. The Received Signal Strength (RSS) value of the beacon is used to calculate the distance between anchor node and the robot. Distance to 3 anchor nodes and their corresponding location information is sued to locate the robot's coordinates using the triangulation method.

The next phase is optimization of localization error using PSO. Around the coordinates calculated using the Self Localization phase, random points are identified as particles and the particles update its position and velocity as per equations 9 and 10.

Following section illustrates the PSO algorithm.

1. **Initialization Step:**
   a. Set t_{max}, p, v_{max}, c1, c2 and w
   b. Randomly generate $x_i(0) \in D$ in Rn, and $0 < v_i(0) < v_{max}$ for i = 1,..., p.
   c. Set t := 1.
2. **Optimization Steps:**
   a. Update the best position $p_{ibest}(t)$ for particle i.
   b. Update the best ever position $p_{gbest}(t)$.

c. Set t := t+1. If $t = t_{max}$, go to 3.
d. Update the velocity v, according to (10).
e. Update the position x, according to (11).
f. Go to 2a.

3. **Termination:** Stop

The above algorithm will reduce the localization error. This final coordinates will be the location of the robot. This information used for identifying the cell in which the robot is currently located.

1. Receive the coordinates of the robot from the Localization Error Reduction phase.
2. Calculate the Euclidean distance to all the midpoints of the cells.
3. Identify the cell where the distance between robot's coordinates and midpoint of the cell is the minimum. This cell will be marked as the current cell of the robot.
4. Identify all those cells where the distance between the midpoints of those cells and midpoint of the current cell is equal to the width of a cell d. These cells will be marked as neighboring cells.
5. Check the status and occupancy probability of all the neighboring cells.
   if status == 0 and Occupancy_Prob < T mark the cell as Candidate Cell.
6. Identify the cell from Candidate Cells, whose Occupancy Probability is lowest. Mark it as Frontier Cell.

The above algorithm explains the selection of frontier cell. Once the frontier cell is identified, the midpoint of the cell is known and using this value, robot adjusts its orientation and move towards the destination which is the midpoint of the frontier cell selected.

Occupancy probability is one of important parameter in deciding the frontier cell. Occupancy probability is a measure of cell describing the likelihood of a robot occupying that cell. If the robot is located exactly at the midpoint of the cell, occupancy probability value will be 1. The value reduces as the location of the robot is moving away from the midpoint and reaches 0 when the robot's location is outside the cell. It is defined as in (11):

$$P_{occupancy} = d_r / \mathrm{r} = d_r / (\mathrm{L}/2) \qquad (11)$$

Once the robot reaches the frontier cell, it has to update the status and occupancy probability of the frontier cell. Also the robot has to gather information about other objects present in the cell and share this information with other robots.

The robot will rotate and whenever it detects any object, the orientation angle is marked. From the orientation angle, coordinates of the object are calculated. These coordinates of objects are also shared among other robots, thus completing the exploration.

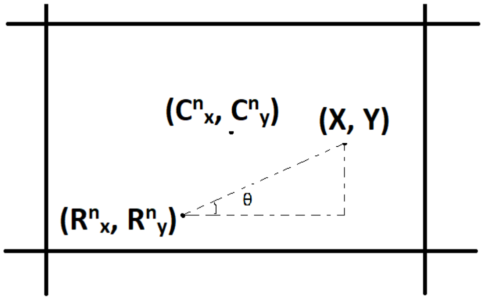


Fig. 4: Object Mapping

The process of mapping the objects in a cell is illustrated in the above figure Fig. 4.

6 Results

The proposed system is simulated using Player-Stage multi-robot simulator. All the different phases are executed and accuracy is ensured.

Initially robots are deployed randomly to the area under consideration. This can be a collapsed building, location under fire or earth quake affected building. Boundaries are marked based on the safety considerations and on the boundaries of the area under consideration, communication infrastructure will be setup. As per the methodology explained, it requires a minimum of 3 anchors which can broadcast its location and by receiving such becons, one robot can calculate its location. Three anchors are setup which will start broadcasting the location in the form of becons. The randomly deployed robots receive these becons. Through the becons, robots get two parameters: location of the anchors and from the received becons' signal strength, distance to anchors. Using this information received from anchors, robots will calculate the location.

The second phase of the system is about reduction in localization error. The previously calculated location may be slightly different from original physical location of the robot due to variation in signal strength. PSO is applied to optimize the error. In the proposed system, 20 iterations of PSO achieves considerable amount of localization error reduction. Based on the current location of the robot and the stored location information of cells center point, robot identifies its current cell and start moving towards unexplored cells. This concept is referred as frontier cell approach which is another contribution.

Following is the image of self - localization where a robot is using trilateration to calculate its coordinates after receiving becons from minimum of 3 anchors.

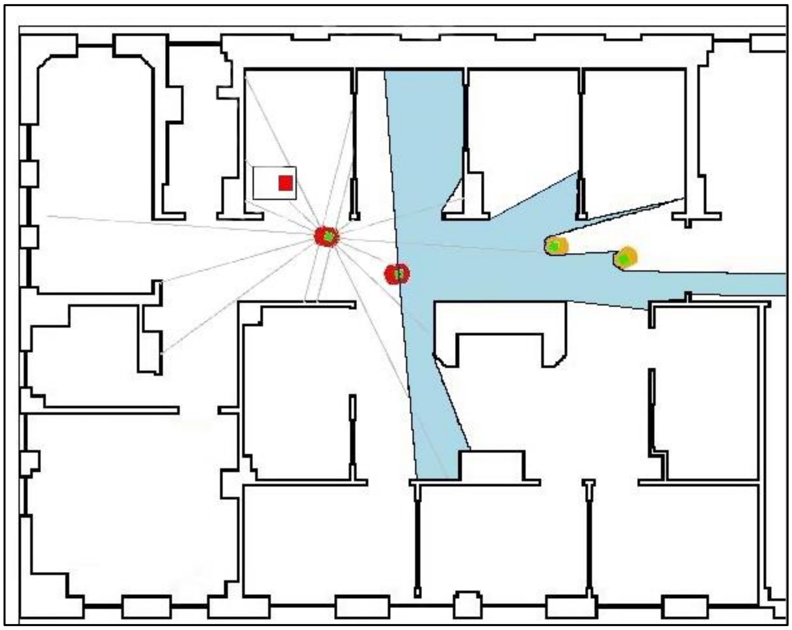


Fig. 5: Self-Localization in Player Stage

The above image Fig. 5 illustrates the test scenario where multiple obstacles are there in the scene and team of robots are navigating through the obstacles, avoiding them and collecting details of other objects and sharing with its neighbours. The navigation and avoidance of obstacles are performed with the help of navigation system of the currently developed system in which robots move based on frontier cell approach and localization is done along with PSO based reduction in localization error.

The below image Fig. 6 indicates the process of object detection. While navigating through the cells, robot collects information about objects identified in each cell. Each of those identified objects' location is mapped and same is communicated to all robots. This helps each robot to update the map it has. Eventually the sharing of information among the robots deployed will lead to the consolidation of location information about the area under consideration. In Fig. 6, an object is identified by the robot and its location is mapped and shared among all the robots.

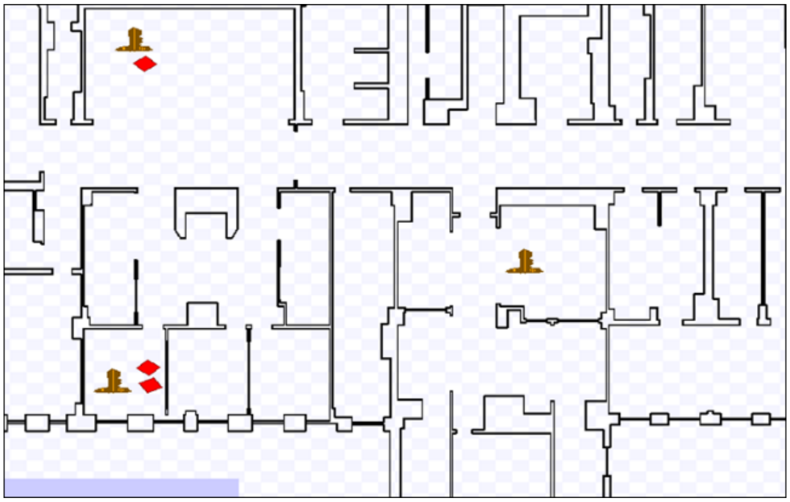


Fig. 6: Object Detection

The proposed system is tested with single robot, 2 robots, 6 robots and 8 robots in the same environment with similar obstacles and objects. Time to explore the area under consideration is tabulated and generated graph to compare the exploration time.

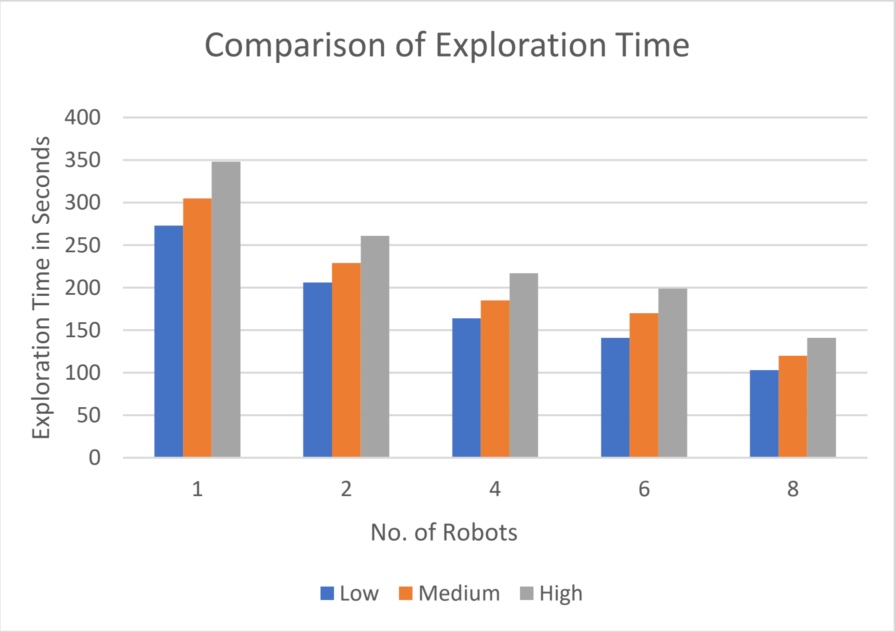


Fig. 7: Comparison of exploration time

Fig. 7 indicates the comparison of exploration time taken by team of single robot, 2 robots, 4 robots, 6 robots and 8 robots under three different obstacle population scenarios: low, medium and high. The results imply that the proposed scheme performs better when team of robots has 8 members.

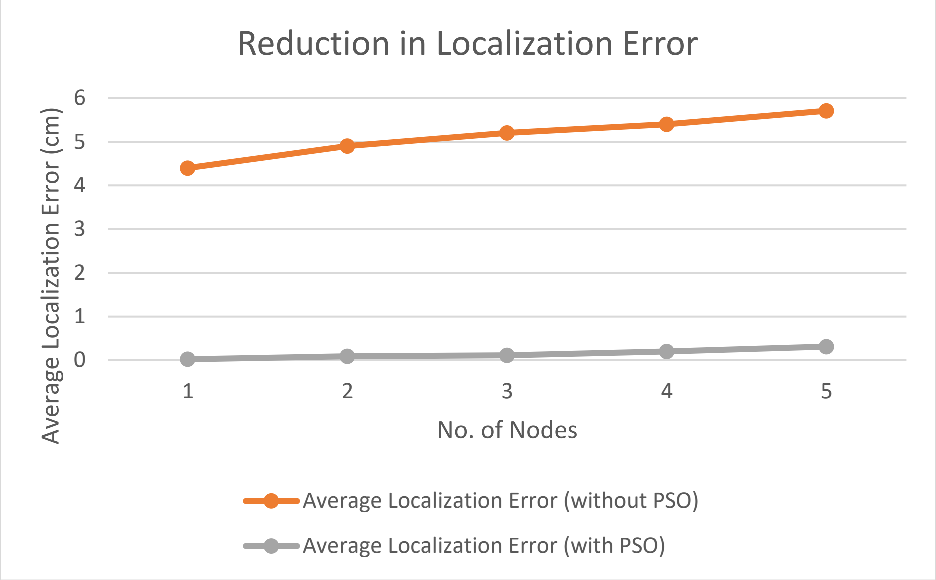


Fig. 8: Reduction in Localization Error

Fig. 8 illustrates the comparison of the magnitude of reduction in localization error with and without PSO. The chart also shows the gradual increase in localization error related to the number of robots deployed.

7 Conclusion

An enhanced Multi-robot exploration strategy is proposed. The base of the exploration strategy is two techniques. The first one being localization of each robot involved in the exploration and this is done with the help of trilateration where three anchors are required which will be setup before the exploration starts. The second part is navigation and avoiding overlapping or missing out sectors while exploring. This is done with help of a navigation policy called frontier cell based approach. Further to this, the exploration strategy is supported with localization error reduction scheme in which the localization error is reduced with the help of Particle Swarm Optimization (PSO). The entire scheme is simulated and exploration time is analyzed for the same environment in different obstacle density and different number of robots to perform exploration. The results show the scheme is better than many existing multi-robot exploration strategies. Precisely, the proposed scheme is able to reduce the localization error to a threshold level of 0.02cm or below which can be considered as novel contribution towards the exploration strategies.

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