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Research Article

Multirobot System to Explore Unknown Environment with Connection Maintenance

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This paper addresses the problem of exploring an unknown environment using multiple robots and maintaining the communication among the team of robots. The existing exploration methods assume that the communication is maintained among the team of robots throughout the exploration process. However, this is not possible when the area to be explored is very large and when there is limited communication range. The presented exploration methods provide communication maintenance among the team of robots and maintain coordination. Three different approaches are presented for exploration. They are centralized approach, leader-follower approach, and ad hoc approach. The concept of centralized approach is developed where the base station is connected to all the robots in the team. The concept of leader-follower approach is developed, where among the team of robots, a leader will be selected. The concept of ad hoc approach is developed in which even though the robots are not within the communication range of one another, communication will occur through ad hoc network. The performance evaluation is done for the above three approaches based on the path length, exploration time, and total number of cycles required to explore the complete area. Systematic approach is used to examine the effect of influence of the exploration parameters like the number of robots, communication range of a robot, and sensor range of a robot on the performance metrics. It is investigated that when there is increase in the exploration parameters, then the exploration time is reduced.

1. Introduction

Exploration is the process of moving a robot in an unknown environment and to build a map that can be used for navigation purpose. Most of the mobile robots are unable to move efficiently in an unknown environment. The map generated during the exploration process should give complete knowledge about the environment. The exploration process can be done efficiently by selecting a frontier. Frontiers are the boundary between the known and the unknown space. When the robot discovers a frontier, the frontier is assigned to the robot so that it can enter the unexplored space and add new information to its map. By moving to successive frontiers, the unexplored space can be reduced by increasing the explored space. Frontier selection process plays a vital role in frontier-based area exploration process. Proper selection of frontier cells helps the robot to reach the goal with minimum number of steps.

In multirobot exploration system, the mobile robots move in an unknown environment in order to collect information about the unknown environment. The collected sensory information is transferred to other robots through ad hoc wireless networks. Here, the coordination among multiple robots is required for efficient functioning. To explore an unknown area using multiple robots, three different approaches are presented in this chapter. The main objective of the three approaches is to gather information about the environment. To build a global map of an unknown environment by autonomous navigation of mobile robot is exploration. The exploration process is carried out step by step. In each step of the exploration process, the next goal position of the robot is determined, and the robot is moved to that goal. These steps are carried out until all the space in the environment is reached by the robots. The exploration time, path length, and number of cycles are the metrics that are to be considered.

Communication is very important for cooperative behavior [1]. Researchers describe three types of communication, such as implicit communication, state communication, and explicit communication. In implicit communication, direct communication is not allowed. The robots communicate only on their own perception of the environment [2]. This type of communication has some disadvantages. The data available at the robots are not always correct, since the sensors are not reliable. The data communicated to the robot via the environment is not sufficient, even though there are many applications employing communication via environment [3–5] and [6] the tasks that can be accomplished are limited. The next type of communication is state communication, in which the robot observes the state of other robots, and the cooperation among the robots is established. The state of the robots can be observed in many ways. One approach is one bit is assigned to represent the state of the robot [7] and this bit is transmitted. The important thing is all the robots should have the prior knowledge about the representation of the states. In another approach, cameras or sensors are used to visually observe the state of the robot [8, 9]. It helps mostly in path planning. The drawback of implicit communication is that limitation in completion of task can be avoided in state communication. The state communication is beneficial for completion of task, and also the time required to complete the task is reduced [10]. The third type of communication is explicit communication. It involves the following steps: status information of the transmitting robot is transmitted. The receiving robot will receive the correct time and data and update its information. The proper data has to be transmitted, and it should be updated by the receiving robot. The transmitting robot should identify the correct receiver. The explicit communication is used in different applications [1, 25]. The taxonomy of multirobot communication using swarm robotics is also described [11].

In most of the research work, it is assumed that the robots always stay connected to each other, and they can communicate with each other. But in many situations when the robots go far away, they cannot maintain communication and the sharing of information is not possible. In that case, the global map cannot be built. So for exploration using multiple robots, the coordination among robots is very important. The multirobot exploration systems can be centralized or decentralized. In centralized multirobot systems, a base station is present, and its function is to store all information about the environment and control the movement of other robots. The other robots collect information about the environment and send it to the base station. In decentralized multirobot system, each robot has its own control. They collect information from other robots and plan the task accordingly.

The communication range is the distance to which the two robots can communicate. The communication topology is the different ways by which the robots can communicate with each other. For example, communication can be through broadcasting, i.e., a robot can send message to specific address or communication through tree structure. The communication bandwidth is the time taken to communicate. If robot A wants to communicate with robot B and if they are within the communication range of each other, they can communicate through direct communication (Figure 1). When two robots want to communicate with each other and if they are not within communication range, then they can communicate with each other via indirect communication (Figure 2). The robots can form a network and then send messages. Mobile Ad hoc NETwork (MANET) is another research area which is used for communication among robots. The various frontier-based exploration approaches are presented in Table 1. An UAV–enabled dynamic multitarget tracking and data collection framework is presented to deal with a dynamic intelligent matching between the UAVs and the targets [12], and an in-depth and stimulating view on the new frontiers in the field of mobile, ad hoc, and wireless computing is provided [13].

2. Methodology

The main objective of the work is to coordinate the multiple robots to explore the unknown environment and to maintain the communication among the team as efficiently as possible. The next objective is to reduce the performance metrics, like exploration time, path length, and total number of cycles. Three approaches are presented for multirobot exploration: centralized approach, leader-follower approach, and ad hoc approach. Extensive simulation experiments are conducted, and the results are compared for the three approaches. The effect of relative increase or decrease in the number of robots, sensor range, and communication range on the performance of the exploration is discussed in detail.

2.1. Frontier Selection. Frontier-based area exploration is the most common technique used for mobile robot area exploration. The main objective of frontier-based area exploration is to identify the frontiers and allocate the robots to every frontier. The process of area exploration terminates when all the frontiers are explored. So, if the frontier selection is done accurately, then the exploration process will be simplified.

2.1.1. Exploration without Frontier Selection. Figure 3 shows the operational flow chart for exploration in an unknown environment. In the proposed approach, only one robot is considered for exploration. Initially, the starting position of the robot is given as input. Then, the robot is moved to the next location after checking the presence of obstacle in that particular location. If the obstacle is present on the left side of the robot, then the robot moves to the right side. Otherwise, the robot moves to the left side in the given environment. If the obstacle is present on the right side of the robot, then the robot moves to the left side. Otherwise, the robot moves to the right side in the given environment. If the obstacle is present on the right side and left side of the robot, then the robot chooses a new target position for exploration. In order to avoid looping, the robot wheel is slightly moved to the right or left direction after every 25 iterations. Then, it is checked whether the total area is explored, and the exploration process is stopped if the total area is explored.

2.1.2. Exploration with Frontier Selection. Figure 4 shows the operational flow chart for exploration in an unknown environment using frontier selection approach. Similar to the above approach, only one robot is considered for exploration, and initially, the starting position of the robot is given as input. The cells that are next to the robot in all the eight directions are considered as frontier. One among the eight cells is considered for further robot movement. Then, the robot is moved to the next location after checking the presence of obstacle in that particular location. If the obstacle is present on the left side of the robot, then the robot moves to the right side. Otherwise, the robot moves to the left side in the given environment. If the obstacle is present on the right side of the robot, then the robot moves to the left side. Otherwise, the robot moves to the right side in the given environment. If the obstacle is present on the right side and left side of the robot, then the robot chooses a new target position for exploration. After a new location is selected for robot motion, then the selected cell is checked whether it is already visited or not. Then, it is checked whether the total area is explored, and the exploration process is stopped if the total area is explored.

Here, two different approaches are proposed for exploration, and their performances are compared based on the time required to explore the total simulation area. In the first approach, exploration is performed without considering the frontiers. Here, the robot will check the presence of obstacle and determine the next location. In the second approach, frontier-based exploration is performed. It prevents the robot from moving to the area which was already visited. That is the main difference between the two approaches.

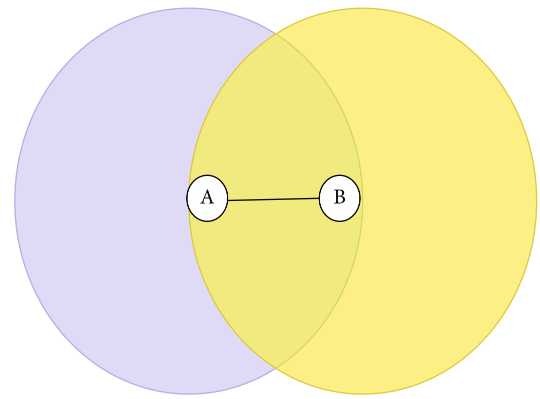


Figure 1: Direct communication.

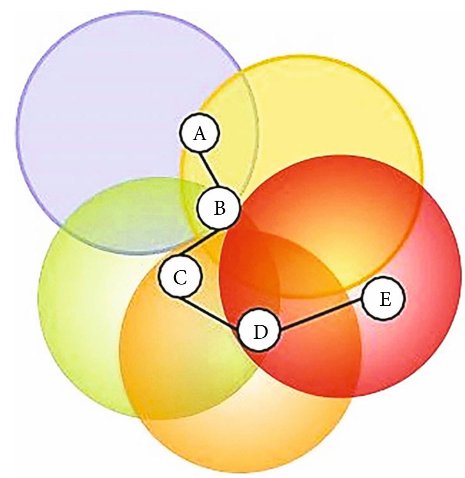


Figure 2: Indirect communication.

3. Simulation Environment for Exploration Using Frontier Selection Approach

The three different environments are used for simulation with different obstacle densities. One of the configuration types is the simulation environment 1 with no obstacles. The other two configurations are building-like obstacle configurations, where the simulation environment 2 contains 25% obstacles, and the obstacle density in the simulation environment 3 is 75%. Figures 5(a)–5(c) show the simulation environment 1, environment 2, and environment 3, respectively. All simulation environments contain the same simulation areas. Table 2 shows the simulation parameters that are used for the two approaches, namely, without frontier selection and with frontier selection.

3.1. System Models

3.1.1. Environmental Model. The environment to be explored is modeled as a 2D occupancy grid. The occupancy grid-based maps maintain information of the environment in a grid, and every cell of the grid corresponds to a specific space in the environment. There are stationary obstacles of different shapes and sizes. The obstacles are distributed in the area to be explored. During the exploration process, each cell of the grid has any one of the following three values. Unknown: if a specific cell is not visited by a robot, then the color of the cell will be gray. Free space: if a specific cell is explored by a robot, then the color of the cell will be yellow. The cell that is next to the unknown cell is frontier. After the robot visits the cell, the state of the cell is changed from unknown to known. Obstacle: the main purpose of the exploration is to explore the area which is occupied by the obstacles and which are free. The color of the cell will be black if the cell contains obstacle. The different state values of the grid cells during exploration are shown in Figure 6.

3.1.2. Robot Model. The shape of the robot is a square and the size of the robot is a cell. Figure 7 shows the robot model. The function of robot is to explore the unknown environment. So, it moves around the environment, senses the obstacles, prepares the local map, and updates the global map. The robot has to maintain communication with each other and with a base station or it has to maintain

Table 1: Comparison of the various frontier-based exploration approaches.

Sl. no.	Approach	Type	Communication/ coordination/complete/base station	Type of environment	No. of robots	Exploration time
1	Yamauchi [14]	Frontier-based	Flexible/decentralized/yes/ no	Office (50×40)	5	1000 seconds (communication range 25-size of the grid cell)
2	Simmons et al. [15]	Frontier-based	Perfect/centralized/no/no	Single corridor ($25\,m \times 20\,m$)	3	200 seconds
				Obstacle free ($20\,m \times 20\,m$)	3	150 seconds
				15% random obstacles ($20\,m \times 20\,m$)	3	250 seconds
3	Vazquez & Malcolm [16]	Frontier-based	Perfect/decentralized/yes/no	Office($10.2\,m^2$)	10	500 seconds (1 m communication range)
				Office ($23.5\,m^2$)	10	1200 seconds
4	Burgard et al. [17]	Frontier-based	Flexible/hybrid/yes/no	Unstructured	5	6 minutes (2.5 communication range/ max. distance in map%)
				Office	5	7 minutes
				Corridor	5	6.5 minutes
5	Sheng et al. [18]	Frontier-based	Perfect/centralized/yes/yes	Square (40×40)	5	6.5 minutes (communication range 24-size of grid cell)
6	Rooker & Brik [19]	Frontier-based	Perfect/centralized/yes/yes	Office (50×40)	5	1000 seconds (communication range 25-size of the grid cell)
7	Pei et al. [20]	Frontier-based	Perfect/centralized/yes/yes	Garden	10	100 seconds
8	Kovács et al. [21]	Frontier-based	Perfect/centralized/no/yes	Obstacle free	7	62 time unit
9	Dai et al.[22]	Market economy-based	Flexible/distributed/yes/no	Obstacle free	2	550 time units
				Geometrics		620 time units
				Line segments		650 time units
10	Lauri & Ritala[23]	POMDP-based and frontier-based	No/no/yes/no	Office environment ($40\,m \times 60\,m$)	1	400 seconds

communication with the leader in the case of absence of a base station. Robot deployment: the robots are deployed in the given unknown environment. Usually, the robots are deployed on the upper left corner of the environment. Sensor region of robot: the robot contains sensors, and the data sensed by the sensors are used to build the map of the environment. Figure 8 shows the sensor region of the robot. Usually, the sensor region is a circle inside the square-shaped cell. The sensor range is denoted as R_{sense}. The robot is located in the specific location of a cell and senses all the neighboring cells. Figure 9 shows that the robot can move from the center of the cell to any one of the 8 different directions. Communication range of a robot: the robot has to move around the unknown environment without colliding with the obstacles and with the other robots. The communication among all the robots and with the base station has to be maintained. It has to be checked periodically. The communication module present inside the robot helps to directly communicate with the other robots within the communication range, and it is denoted as R_{com}, or to a remote robot through ad hoc communication. The robots are capable to communicate only when they are within the communication range of the other robot.

3.1.3. Base Station Model. The base station is the place where the human operator is present in the unknown environment and monitors the environment. Figure 10 shows the base station model. The position of the base station is fixed, and it has the device used for communication through which it can send control information to the robots. The robots in turn will send the details of the explored area to the base station.

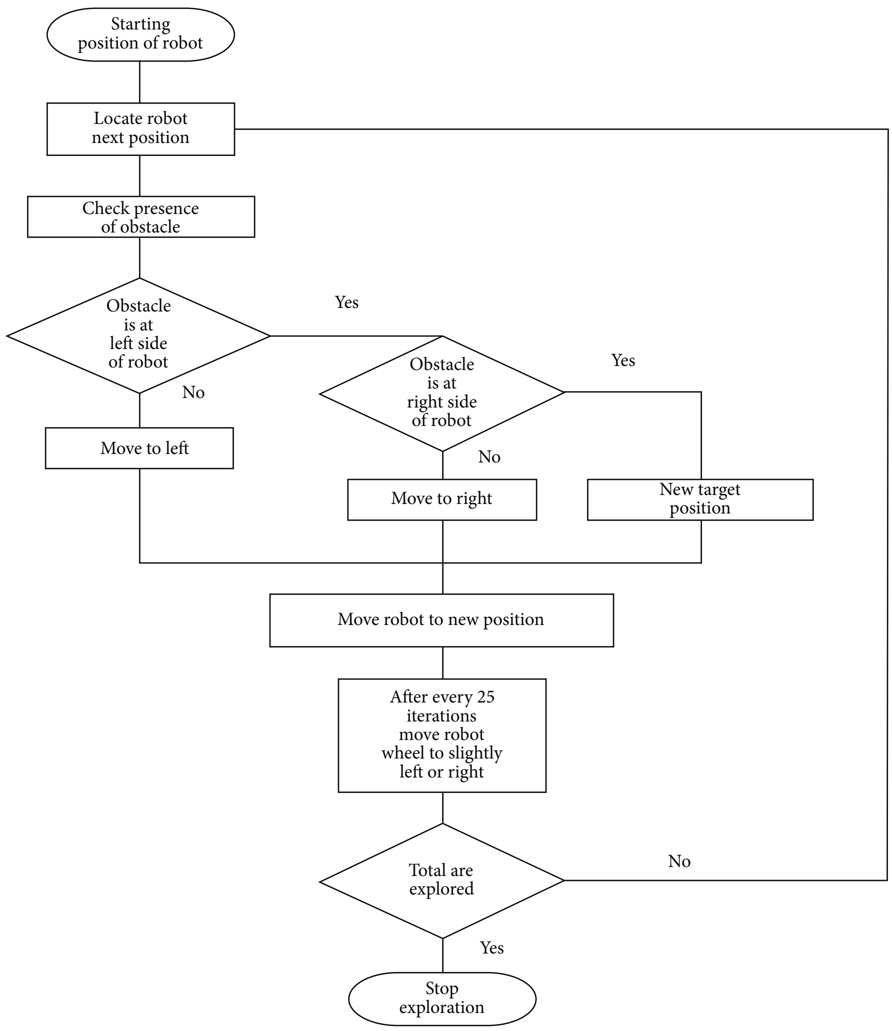


Figure 3: Operational flowchart of exploration without frontier selection.

3.1.4. Operational Model of the System. The operational model of the proposed system is shown in Figure 11. The robot starting location is usually randomly chosen. The sensors sense the state value of the cells. After acquiring information from the sensor, the local map is updated. The local maps received from all the robots are integrated to update the global map. The updated global map is transmitted to all the team members, and then the next location of the robot is determined. Now the robot is moved to the new location from the present location.

In this work, we developed an algorithm that controls the robots to explore the whole area of an unknown communication limited environment with minimum path length and minimum exploration time. The approach should maintain network connectivity among the robots during exploration [3, 5].

The performance of the proposed method is measured in terms of the following parameters:

(i) Total exploration time: the total time required to explore the whole environment

(ii) Path length: the distance travelled by each robot

(iii) Total number of cycles: the total cycles required to explore the whole environment

The assumptions made during the exploration process are as follows: all the robots are able to locate its position and to update its local map. The unknown environment is assumed to be static. The robots are homogenous and equipped with sensors. The robots can sense and communicate even in the presence of obstacles in between them.

3.2. Coordinated Exploration Approach. Assignment of task to the robots is the first step. The robots in the team are assigned any one task: either the robot acts as a base station or an explorer. In the exploration process, simultaneous localization and mapping are important to simultaneously locate the position of the robot and to build the map of the unknown environment by updating it frequently. Different types of sensors are available to find the range measurements like optical- or sonar-based. For

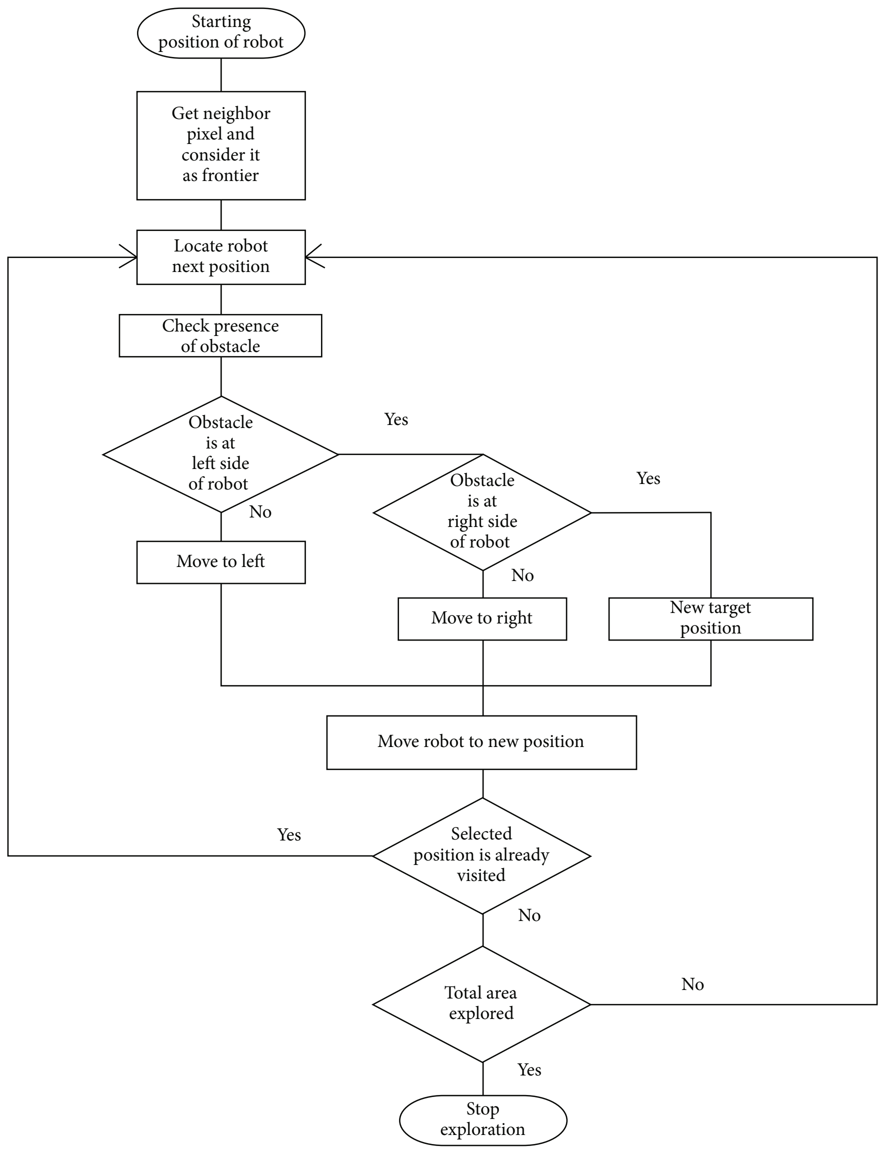


Figure 4: Operational flowchart of exploration with frontier selection.

2-dimensional environment, laser sensors produce most accurate range readings. By knowing the position of the robot and the range finder readings, the map is built for the unknown environment. Building a map from noisy and uncertain readings is really a problem in real-time implementation. Various techniques are used to compute the map: they include particle filters, Kalman filters, or scan matching. For the experiments here, occupancy-grid-based map is used. The occupancy grids contain cells, and each cell stores the information about the environment. The information stored in the cell depicts any one of the three states of the cell (known, unknown, and obstacle). Table 3 shows the information that is stored in each cell of the occupancy grid map. The information is changed after each step of the robot navigation.

If the robot position and sensor readings are known, then the occupancy grid map is updated as explained below. Figure 12 shows the determination of the frontier region. The circle represents the robot. Initially, the scan points (provided by sensors in the robot) are converted to Cartesian coordinates, and the black dots in Figure 12(a) are coordinates. Then, all the points are connected to form a polygon (Figure 12(b)). By using flood-fill algorithm, the polygon which is formed by connecting all the scan points is filled (Figure 12(c)) and considered as known space in the grid cell. The points which are close to each other are considered as obstacle (Figure 12(d)), and they are stored as obstacles in the grid cell. Among the known space in the grid cell, a radius which is half the distance of the sensors' maximum distance range is considered. In Figure 12(e), the grey color area denotes the safe space. The area beyond this safe space is taken as the frontier region. In Figure 12(f), the pink color area denotes the free space. For each frontier region, one can calculate the area of the frontier region and the cost of reaching this region.

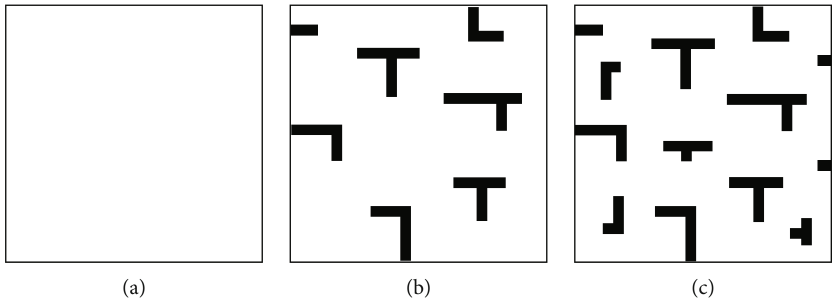


Figure 5: Simulation environment for frontier selection approach.

Table 2: Simulation parameters for the exploration with and without frontier selection approach.

Sl. no.	Parameter	Value
1	Environment	Size: 160 ∗ 160
2	Number of robot	1
3	Sensor range	5
4	Robot initial position	Randomly selected

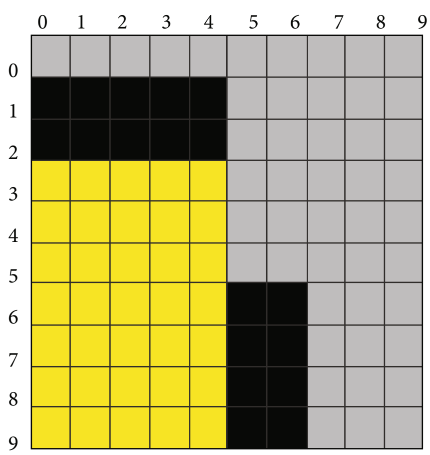


Figure 6: State values of the grid cells during exploration.

The utility value for an exploring robot at a particular position is given by

$$U(R_i, F_j) = \left[\left(\frac{A(F_j)}{(L^m(R_i, F_j))}\right)\right], \quad (1)$$

where

$A(F_j)$ - area of the frontier region

$L^m(R_i, F_j)$ - length of the path to reach the center of that frontier region

$m = 2$ (which determines exploration behavior, if the area is very large then low value is chosen, and if the area is small then high value is chosen).

The assignment of the frontier region to the robot is computed as follows: consider frontier-robot pair (). Calculate the area of the frontier region. To calculate the length of the path from the center of the frontier region to the robot is expensive. So at first, a straight line is connected from the robot to the center of the front region, without considering the obstacles. Then, that distance of the straight line is calculated. The utility value is calculated based on Equation (1). Similarly, the utility values are computed for all the frontier-robot pairs. Then, they are entered in an array in the priority order; that is, the pair having the highest utility value is entered at the top. Then, the utility value is

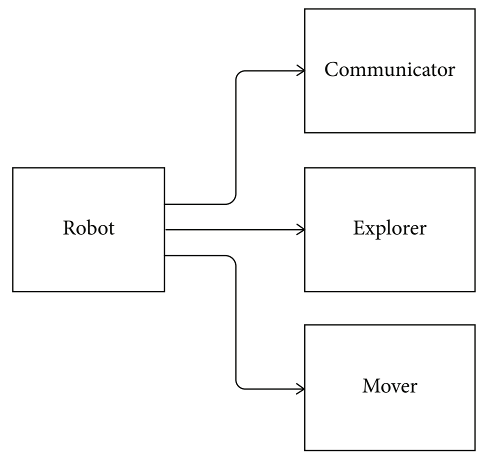


Figure 7: Robot model.

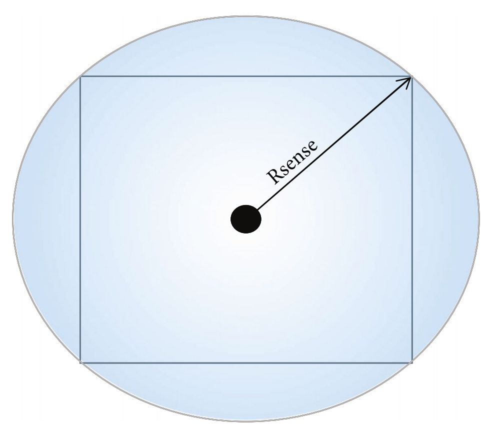


Figure 8: Sensor region of a robot.

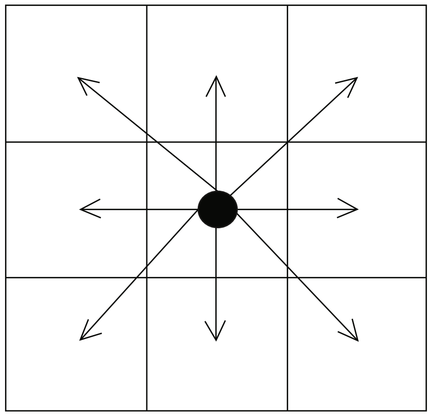


Figure 9: Different directions for the next movement of the robot.

calculated for the first pair using the original path length. If it remains high, then that robot is assigned to that frontier region, and all the pairs having particular robot and frontier are ignored. If the utility value is not high, then the process is repeated for all the pairs in the array. Similarly, all the robots are assigned to the frontier region using the utility values.

4. Experimental Evaluation

4.1. Exploration Parameters. The different parameters that influence the autonomous mobile robot exploration are shown in Table 4. Number of robots: the process of mobile robot exploration is performed by using multiple robots. Therefore, the process is tested for different numbers of robots, and the number of robot is varied from 1 to 10. Then, how the number of robots influence the exploration is tested experimentally. The position of the robot is chosen randomly. Sensor range: the robot contains sensors, and the data sensed by the sensors are used to build the map of the environment. The sensor range is varied from 50 to 250, and the unit for sensor range is the size of the cell. Communication range: by adapting different technologies for communication among robots, the communication range can be varied. If the communication range is large, then the distance between the robots can be increased. The communication range is varied from 50 to 250, and the unit for communication range is the size of the cell.

4.2. Simulator Implementation. To examine the behavior of the proposed mobile robot exploration method, a Java-based self-developed simulator is built. The environment is taken as an image and given as input. The obstacles are represented as black space, and the free areas are represented as gray space. Three different experiments are performed to evaluate the performance of the exploration algorithm.

4.3. Simulation Environment. There are a wide range of possible environments where the robots may be used to explore, and the exploration algorithms may perform better in a particular category of environment while they perform poor in other category of environments. For the experiment, three categories of environments have been chosen: (1) cluttered environment: cluttered environment contains a number of small and fragmented obstacles (Figure 13). (2) Indoor environment: indoor environment contains rooms and corridors (Figure 14). (3) Elongated environment: elongated environment contains long and narrow spaces (Figure 15). The size of the simulation environment is $800 * 600$.

In [6], authors propose reliability measures using various routing protocol along with the calculative measures. In [20], the concept of mobile node optimization was addressed using ANT method by the authors. In [19], the authors address the measures for delay-constrained using control algorithm implemented in both reactive and proactive protocols. In [18], tracking of mobile sensor in multicast mobile environment was addressed using distributed mobility management. In [15], authors show the enhancement of flooding concept in mobile ad hoc network using broadcasting messaging service. In [3], message log was addressed by the author using optimizing techniques with checkpoint mechanism.

4.4. Implementation. The controlling device of the whole system is Arduino. In Bluetooth module, DC motors are interacted to the Arduino. The data received by the Bluetooth module from the Android smartphone is fed as input to the controller. The microcontroller acts accordingly on the DC motors of the robot. The robot can be made to move in all four directions using the Android phone. The direction of the robot is indicated using LED indicators of the robot system. The robot can be developed with ultrasonic sensors. Two sensors are fixed on its right side, and these were responsible for maintaining its distance from the wall and guiding it along the correct path, and one sensor at the front, which was responsible for detecting any obstacles and making left turns. Each sensor controls its distance from the nearest obstacle. The algorithm uses ultrasonic data and controller correction system to navigate autonomously, and the developed logic makes it possible to move to a different location without affecting the function.

Robotic parts for the model consist of robot chassis, the Arduino Uno board, Bluetooth module, electric motors, motor driver module, battery pack, jumper wires, and wheels. The Bluetooth module is connected with the Arduino UNO board for the connection with the user. Through the Bluetooth module, monitoring and controlling the particular motor reaches the board and process accordingly, the output of the Arduino goes to the motor driver IC, and it controls the particular motor. Robot chassis is a load bearing framework for any object. It is also used to assemble all the components that might be used in robot. Arduino Uno board is a microcontroller based on a board on a microchip ATmega328P. ATmega328 has 28 pins in total which has 14 digital total input/output pins, in which 6 pins are providing PWM output and 6 pins are providing analog inputs. The microcontroller operates at 5 V. Arduino Uno needs crystal oscillator for 16 MHz frequency. Bluetooth module (HC-05) acts as a communication bridge between the electronic devices. HC-05 generally connects with small devices like mobile phone for a short range. It is designed for wireless connectivity. HC-05 uses the frequency of 2.45 GHz. It

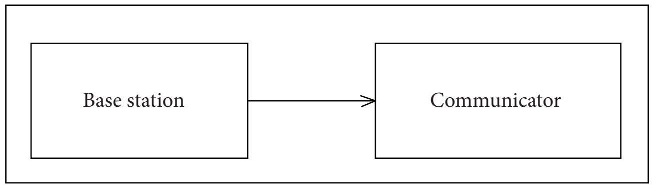


Figure 10: Base station model.

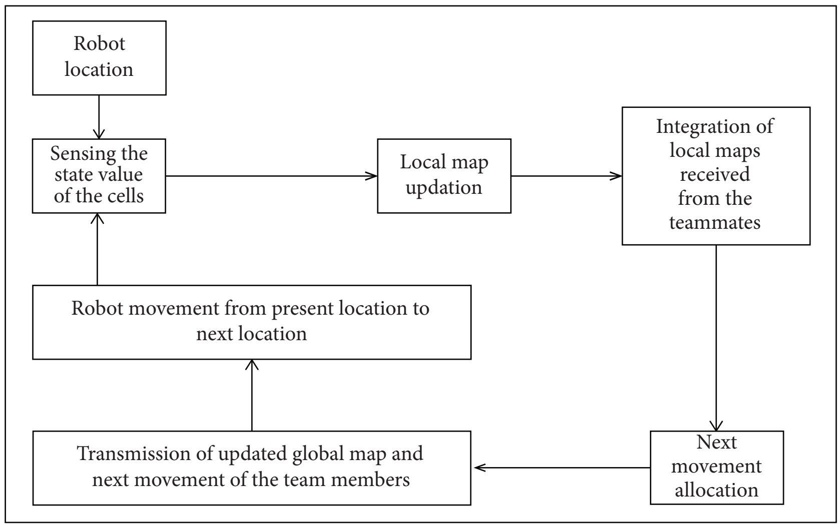


Figure 11: Operational flow chart of the proposed multirobot exploration system.

Table 3: Information stored in each cell.

Bit	Information
0	Unknown
1	Free space
2	Obstacle
3	Frontier

operates at a voltage of 5 V of power supply, and operating current has 30 mA. The range of transferring the data is 10 meters. DC motor and motor driver module (L298N) are operated on direct currents; they also come from small motor to huge ones. To operate the robot, 12 V 1.5A DC motor can be used to operate the robot. In robot L298N, H-bridge motor driver can be implemented, and it is capable to drive two DC motor simultaneously. L298N is a 16 pin IC. A motor driver is connected to Arduino to run the robot. Motor driver's input pins 1, 2, 3, and 4 are connected to Arduino's digital pin number 5, 6, 10, and 11, respectively. Battery is the source of electrical energy in stored form. Lithium-ion battery is a rechargeable battery, with a supply of 14 V. Jumper wires are used for connection in robot, and wheels are providing motion to the robot. Android Bluetooth controlled application should be used to give a command to the robot for the movement in it. The application is first designed in C language. The Bluetooth HC-05 is interfaced with Arduino UNO for connectivity with android mobile to Bluetooth HC-05. Arduino UNO is programmed by using the Arduino Software; it is an integrated development program environment (IDE) which makes it easy to write code and upload it to the board. For Arduino IDE, C/C++ languages are used for programming [24].

If the environment to be explored has a similar structure, then it is believed that the computational results with the proposed approaches will have equivalent results. The complexity is more, when the number of robots is more and when the environment obstacle density is more.

5. Results and Discussion

The two approaches were tested by computer simulation using MATLAB. The simulation area to be explored contains 320 cells. In the case of obstacle configuration type, three different obstacle configurations were considered, and the value of obstacle density was chosen as 0, 0.25, and 0.75. In the case of obstacle density equal to zero, the simulation environment is considered as obstacle-free environment.

5.1. Results of Exploration without Frontier Selection. The exploration is done by considering a single robot. The starting position and initial heading angle of the robot are randomly chosen. In all the obstacle configuration types, the exploration process is performed, and the exploration time required to explore the total area is calculated. Screenshots of the exploration process for the first approach are presented in Figure 16. The explored and the unexplored

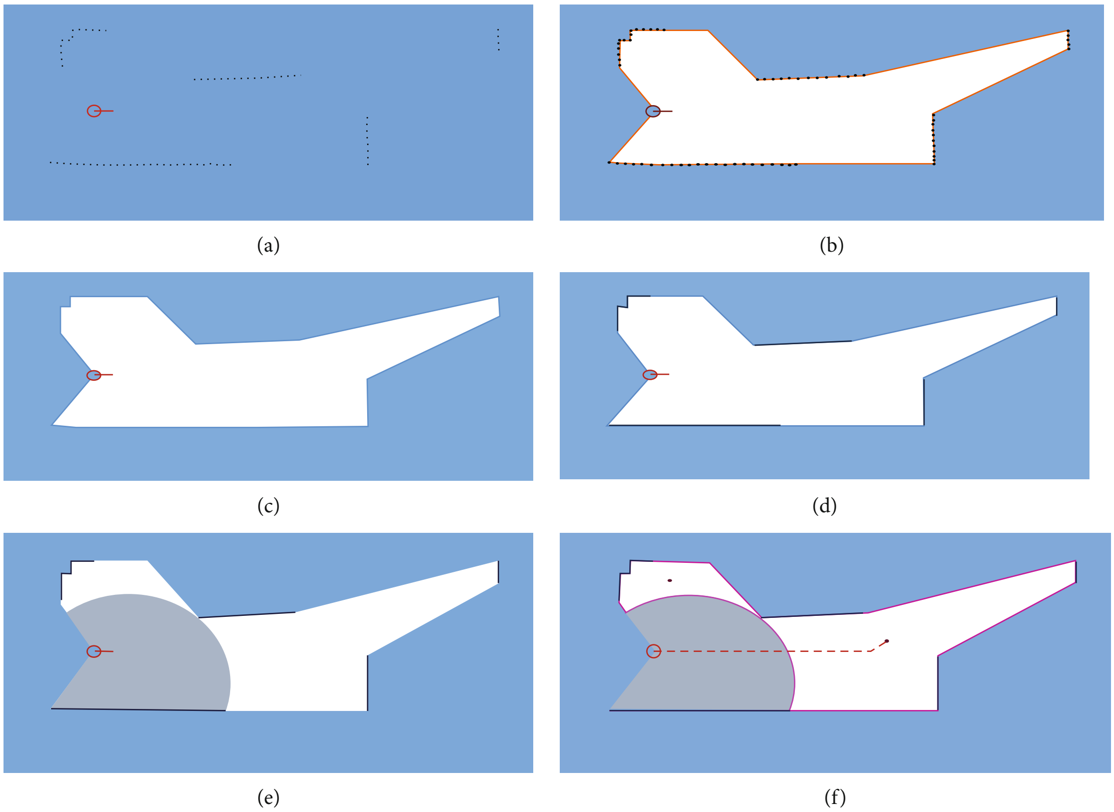


Figure 12: Determination of frontier region.

Input: $R = R_1, R_2 \ldots \ldots ..R_i$ (set of robots that are within the communication range)
$F = F_{(1,)} F_2 \ldots \ldots .F_j$ (set of frontiers)
Output: List of robot–frontier pair (R_i, F_j)
for each $R_i \epsilon R$ do
for each $F_j \epsilon F$ do
$U(R_i, F_j) = [(A(F_j)/l^m(R_i, F_j))]$
$Queue.add\ (\{R_i, F_j\})$
end
end
while not *Queue.is empty* ()do
$\{R_x, F_y\} = Queue.pop\ ()$
$U(R_x, F_y) = [A(F_j)/(L^m(R_i, F_j))]$
if $U(R_x, F_y) > U\ (Queue.peek\ ())$, then
$list.add\ (\{R_x, F_y\})$
for each $\{R_i, F_j\}$ $\epsilon Queue$ where $i{=}{=}x$ *or* $j{=}{=}y$ do
$Queue.remove(\{R_i, F_j\})$
end
else
$Queue.add(\{R_x, F_y\})$
end
end

Algorithm 1:Algorithm for robot to frontier allocation.

Table 4: Simulation parameters for multirobot exploration.

Sl. no.	Parameters	Value
1	Environment	Size: 800 ∗ 600
2	Number of robots	1 to 10
3	Sensor range	50 to 250
4	Communication range	50 to 250
5	Robots initial position	Randomly selected

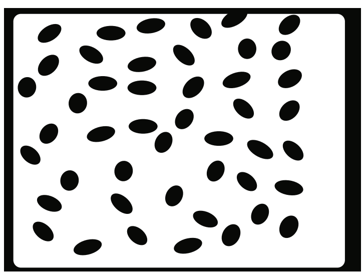


Figure 13: Simulation environment 1 for multirobot exploration.

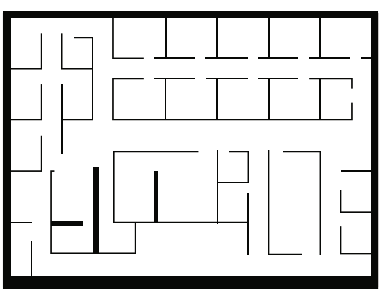


Figure 14: Simulation environment 2 for multirobot exploration.

Figure 15: Simulation environment 3 for multirobot exploration.

areas are marked by yellow and white color, respectively. The obstacles are denoted as black. Table 5 shows the measured exploration time and path length for both the approaches. Figures 17 and 18 show the performance analysis of the exploration time and path length for both the approaches. In the case of obstacle-free environment, the exploration time is 980 seconds, and in the simulation environment with 25% obstacle density, it is 1700 seconds, and for 75% obstacle density, the exploration time is 2300 seconds. Similarly, the path length is also calculated for the three configuration types. The path length is the distance travelled by the robot to complete the exploration. In the case of exploration without frontier selection, the path length is 690; the path lengths for environment 2 and environment 3 were 477 and 384, respectively, in the case of obstacle-free environment.

6. Results of Exploration with Frontier Selection

In the second approach also, the exploration is done by considering a single robot. The starting position and initial heading angle of the robot are randomly chosen. In all the obstacle configuration types, the exploration process is performed, and the exploration time required to explore the total area is calculated. Screenshots of the exploration process for the second approach are presented in Figure 19. The explored and the unexplored areas are marked by yellow and white color, respectively. The obstacles are denoted as black. In the case of obstacle-free environment, the exploration time is 486 seconds; in the simulation environment with 25% obstacle density, it is 840 seconds, and for 75% obstacle density, the exploration time is 1250 seconds. Similarly, the path length is also calculated for the three configuration types. In the case of exploration without frontier selection, the path length is 340 in the case obstacle-free environment, 240 for environment 2, and 180 for the environment 3.

6.1. Centralized Approach. In this approach, the robots always maintain a communication to a fixed base station. The base station is fixed and its position is 140,200. The base station does not perform exploration, and so the sensor range is taken as zero. The base station has to maintain communication among all the robots, so the communication range is taken as 200. The approach is tested with four robots (A, B, C, and D). The initial position of the robot A is 160,220, robot B is 160,180, robot C is 105,220, and robot D is 105,180. The exploration process is carried out by considering sensor range as 200 and communication range as 200 for all the four robots. The exploration progress starts with robots A, B, C, and D. The robots start the exploration progress from the initial start position and explore the environment. Figure 20 shows the screenshot of the progress of centralized approach in the environment 2.

6.2. Comparison of Centralized Approach with Existing Method. The proposed-centralized approach is compared with the existing method [22]. Figure 21 shows the performance analysis of the exploration time for the existing method and the proposed-centralized approach; Figure 22 shows the performance analysis of the total number of cycles for the existing method and the proposed-centralized approach, and Figure 23 shows the performance analysis of the path length for the existing method and the proposed-

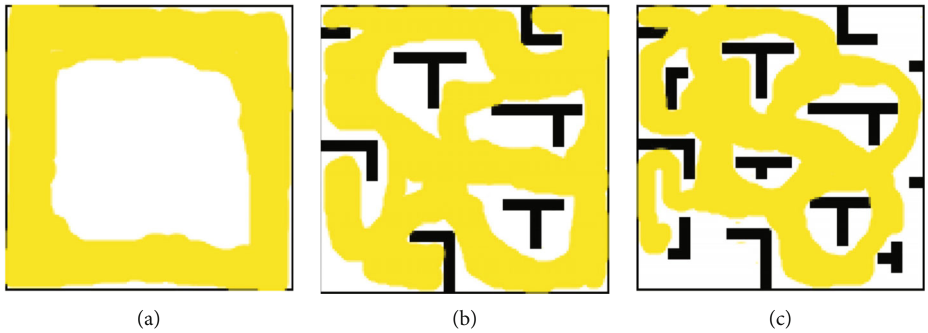


FIGURE 16: Screenshots of the exploration process without frontier selection for the 0% obstacle density (a), 25% obstacle density (b), and 75% obstacle density (c).

TABLE 5: The exploration time and path length for the exploration methods with and without the frontier selection approach on the random obstacle environments.

Obstacle density	Without frontier selection		With frontier selection	
	Path length	Exploration time (seconds)	Path length	Exploration time (seconds)
0%	690	980	340	486
25%	477	1700	240	840
75%	384	2300	180	1250

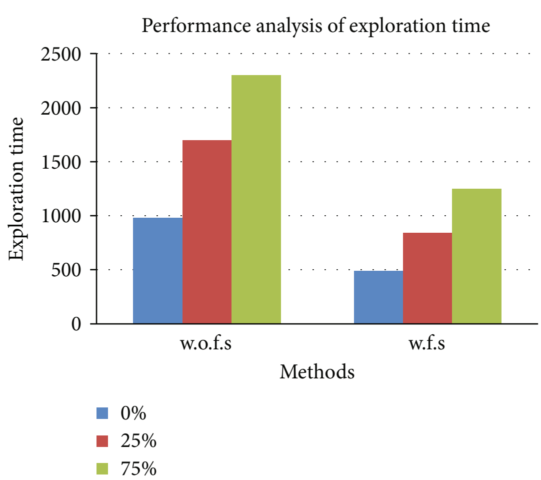


FIGURE 17: Performance analysis of exploration time for the proposed exploration methods with and without the frontier selection approach on the random obstacle environments as a function of the obstacle density for 0%, 50%, and 75%.

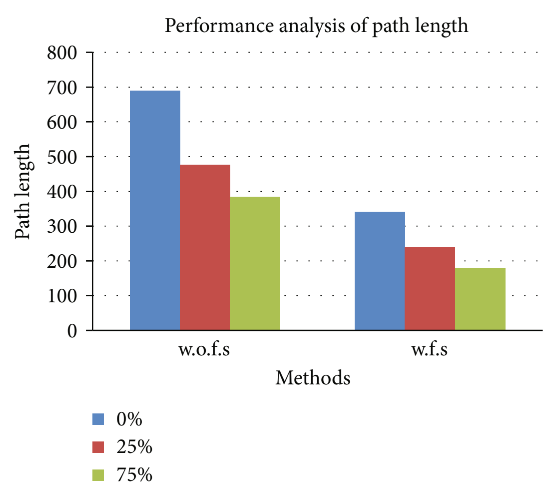
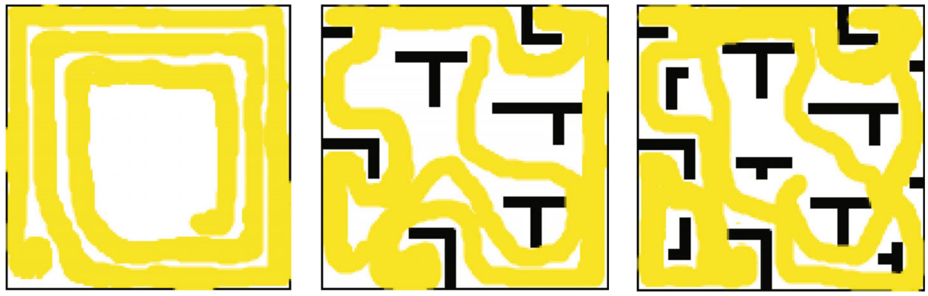


FIGURE 18: Performance analysis of path length for the proposed exploration methods with and without the frontier selection approach on the random obstacle environments as a function of the obstacle density for 0%, 50%, and 75%.

centralized approach. Table 6 shows the comparison of the performance metrics. The analysis shows that the exploration time required for exploring the total area using the centralized approach is less than that of the existing method.

6.3. Leader-Follower Approach. The local map generated by each robot will be sent to both the base station and to the leader robot. In a distributed approach, robots always maintain communication among the teammates either by direct or indirect communication. Full connectivity is maintained among the team members. The roles assigned to the robots may be that of a leader or of a follower. The master robots perform the task of exploration whereas slave robots just pass the information about the environment to the master robots. In this approach, the leader robot always maintains a communication to a fixed base station. The base station need not maintain communication among all the robots. The base station is fixed and its position is 30,180. The base station does not perform exploration, and so the sensor range is taken as zero and the communication range is taken as 200. The approach is tested with three robots (A, B, and C). The initial position of the robot A is 140,200, robot B



(a) (b) (c)

Figure 19: Screenshots of the exploration process with frontier selection for the 0% obstacle density (a), 25% obstacle density (b), and 75% obstacle density (c).

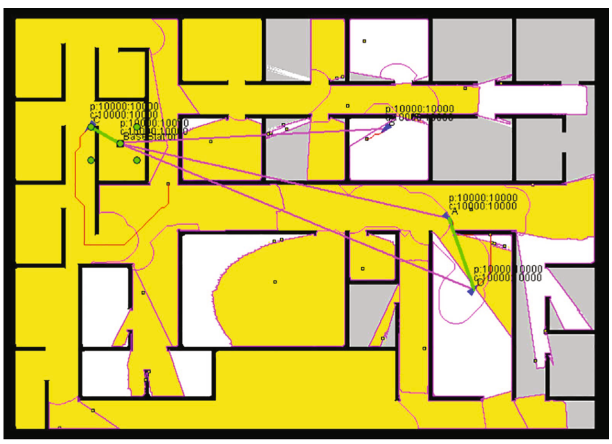


Figure 20: Screenshot of the progress of centralized approach in environment 2 after 68% of the area is explored.

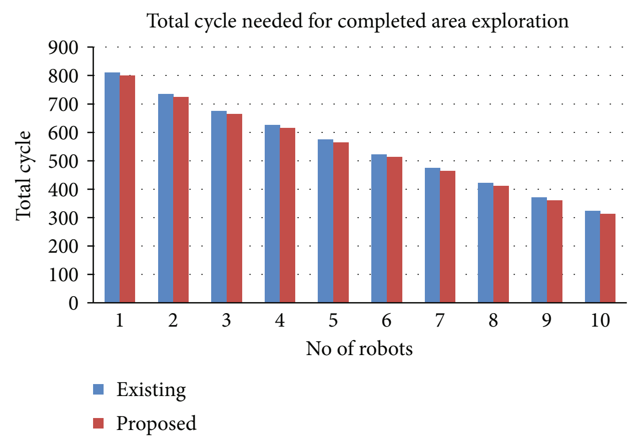


Figure 22: Performance analysis of total number of cycles in environment 2 for the existing method and the proposed-centralized approach.

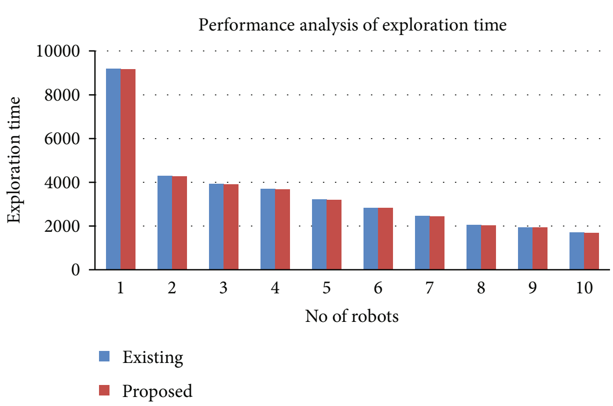


Figure 21: Performance analysis of exploration time in environment 2 for the existing method and the proposed-centralized approach.

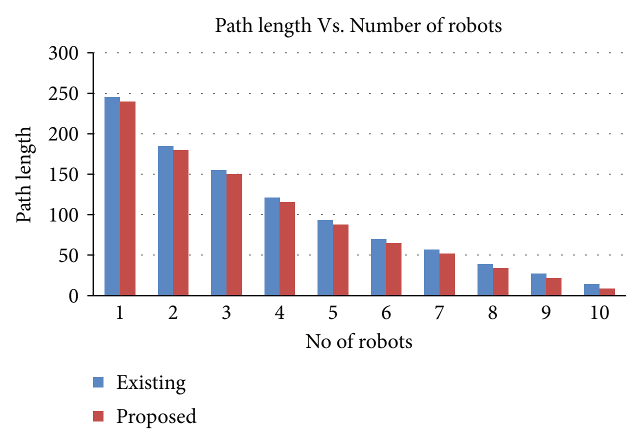


Figure 23: Performance analysis of path length in environment 2 for the existing method and the proposed-centralized approach.

is 90,330, and robot C is 140,530. The robot A is considered as the leader robot and it is connected with the base station and with the follower robot B. The robot B is connected to robot C. The leader robot A can perform multihop communication with all the robots in the team. When the leader robot enters into the communication range of the base station, then all the information are transmitted to the base station. The exploration process is carried out by considering sensor range as 200 and communication range as 200 for all the three robots. The exploration progress starts with robots A, B, and C. The robots start the exploration progress from the initial start position and explore the environment. Figure 24 shows the screenshot of the progress of leader-follower approach in the environment 2.

Table 6: Comparison of multirobot exploration methods.

Sl. No.	Method	Path length (pixels)	Total exploration time (milliseconds)	Total cycles required
1	Dai et al. [22]	245	9181	810
2	Proposed-centralized approach	240	9166	800

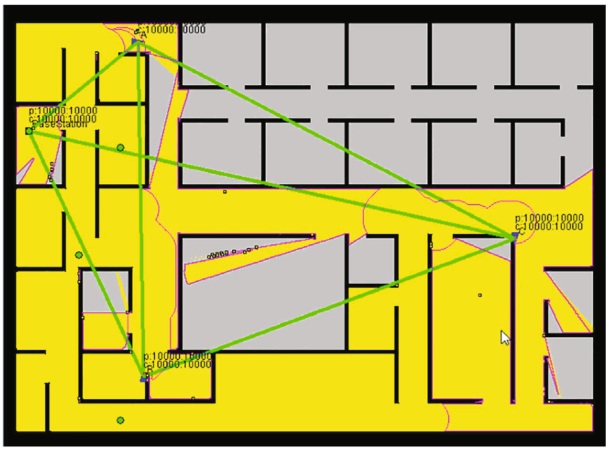


Figure 24: Screenshot of the progress of leader-follower approach in environment 2 after 60% of the area is explored.

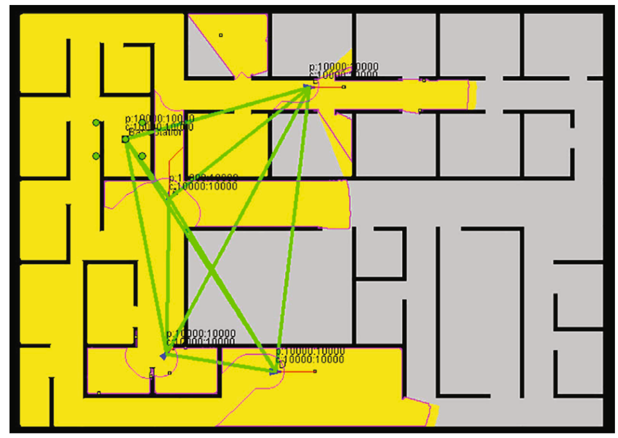


Figure 25: Screenshot of the progress of ad hoc approach in environment 2 after 50% of the area is explored.

6.4. Ad Hoc Approach. In this approach, there is no permanent infrastructure. The robots can connect and communicate whenever they are in the communication range of one another. The base station is fixed and its position is 140,200. The base station does not perform exploration, and so the sensor range is taken as zero. The base station has to maintain communication among all the robots, so the communication range is taken as 200. The approach is tested with four robots (A, B, C, and D). The initial position of the robot A is 160,220, robot B is 160,180, robot C is 105,220, and robot D is 105,180. The exploration process is carried out by considering sensor range as 200 and communication range as 200 for all the four robots. The exploration progress starts with robots A, B, C, and D. The robots start the exploration progress from the initial start position and explore the environment. Figure 25 shows the screenshot of the progress of centralized approach in the environment 2.

6.5. Effect of Parameters on the Exploration Performance

6.5.1. Effect of the Communication Range on the Exploration Performance. This section describes the influence of communication range in the performance of exploration. Different communication ranges of the robots are $R_{com} = \{50, 100, 150, 200, 250\}$. The results of all the three approaches show that the exploration performance is good with increase in the communication range. Larger the communication range, lesser the exploration time, but relative to the three approaches, they are not much affected. Tables 7–9 show the comparison of the proposed exploration approaches with different communication ranges in all the three environments.

6.5.2. Effect of the Sensor Range on the Exploration Performance. This section describes the influence of sensor range in the performance of exploration. Different sensor ranges of the robots are $R_{sense} = \{50, 100, 150, 200, 250\}$. The results of all the three approaches show that the exploration performance is good with increase in sensor range. Larger the sensor range, less the exploration time, but relative to the three approaches, they are not much affected. Tables 10–12 show the comparison of the proposed exploration approaches with different sensor ranges in all the three environments.

6.5.3. Effect of the Number of Robots on the Exploration Performance. This section describes the influence of the number of robots in the performance of exploration. The number of robots is varied from $n = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$. The results of all the three approaches show that the exploration performance is good with increase in team size. The results show that when the number of robots increases, all the performance parameters decrease. The following observations are viewed during the experiment: usually, single hop communication is performed when the team size is small and the communication range is large. But when the team size is large and the communication range is short, then the communication is mostly multihop. Hence, small number of robots with large communication range and large number of robots with short communication range perform better. The results show that the leader-follower approach performs faster than the other two approaches, namely, centralized approach and ad hoc approach. The path length, that is, the distance travelled by each robot, is reduced in ad hoc approach unlike in the other two approaches, namely, centralized approach and ad hoc approach.

Table 7: Comparison of the proposed exploration approaches with different communication ranges for environment 1.

No. of robots	Communication range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
1	50	304	366	300	10466	10571	10366	860	840	845
	100	280	342	276	10216	10321	10116	785	765	770
	150	260	322	256	9716	9821	9616	735	715	720
	200	240	302	236	9166	9271	9066	675	655	660
	250	228	290	224	8576	8681	8476	595	575	580
2	50	244	306	240	5571	5676	5471	785	765	770
	100	220	282	216	5321	5426	5221	710	690	695
	150	200	262	196	4821	4926	4721	660	640	645
	200	180	242	176	4271	4376	4171	600	580	585
	250	168	230	164	3681	3786	3581	520	500	505
3	50	214	276	210	5200	5305	5100	725	705	710
	100	190	252	186	4950	5055	4850	650	630	635
	150	170	232	166	4450	4555	4350	600	580	585
	200	150	212	146	3900	4005	3800	540	520	525
	250	138	200	134	3310	3415	3210	460	440	445
4	50	180	242	176	4979	5084	4879	675	655	660
	100	156	218	152	4729	4834	4629	600	580	585
	150	136	198	132	4229	4334	4129	550	530	535
	200	116	178	112	3679	3784	3579	490	470	475
	250	104	166	100	3089	3194	2989	410	390	395
5	50	152	214	148	4503	4608	4403	625	605	610
	100	128	190	124	4253	4358	4153	550	530	535
	150	108	170	104	3753	3858	3653	500	480	485
	200	88	150	84	3203	3308	3103	440	420	425
	250	76	138	72	2613	2718	2513	360	340	345
6	50	129	191	125	4117	4222	4017	573	553	558
	100	105	167	101	3867	3972	3767	498	478	483
	150	85	147	81	3367	3472	3267	448	428	433
	200	65	127	61	2817	2922	2717	388	368	373
	250	53	115	49	2227	2332	2127	308	288	293
7	50	116	178	112	3745	3850	3645	524	504	509
	100	92	154	88	3495	3600	3395	449	429	434
	150	72	134	68	2995	3100	2895	399	379	384

Table 7: Continued.

No. of robots	Communication range	Path length Centralized	Path length Leader-follower	Path length Ad hoc	Exploration Centralized	Exploration Leader-follower	Exploration Ad hoc	Total no. of cycles Centralized	Total no. of cycles Leader-follower	Total no. of cycles Ad hoc
	200	52	114	48	2445	2550	2345	339	319	324
	250	40	102	36	1855	1960	1755	259	239	244
	50	98	160	94	3334	3439	3234	472	452	457
	100	74	136	70	3084	3189	2984	397	377	382
8	150	54	116	50	2584	2689	2484	347	327	332
	200	34	96	30	2034	2139	1934	287	267	272
	250	22	84	18	1444	1549	1344	207	187	192
	50	86	148	82	3226	3331	3126	421	401	406
	100	62	124	58	2976	3081	2876	346	326	331
9	150	42	104	38	2476	2581	2376	296	276	281
	200	22	84	18	1926	2031	1826	236	216	221
	250	10	72	6	1336	1441	1236	156	136	141
	50	73	135	69	2989	3094	2889	373	353	358
	100	49	111	45	2739	2844	2639	298	278	283
10	150	29	91	25	2239	2344	2139	248	228	233
	200	19	71	5	1689	1794	1589	188	168	173
	250	7	69	3	1099	1204	999	108	88	93

Table 8: Comparison of the proposed exploration approaches with different communication ranges for environment 2.

No. of robots	Communication range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
1	50	301	363	302	10266	10581	10351	840	842	848
	100	277	339	278	10016	10331	10101	765	767	773
	150	257	319	258	9516	9831	9601	715	717	723
	200	237	299	238	8966	9281	9051	655	657	663
	250	225	287	226	8376	8691	8461	575	577	583
2	50	241	303	242	5371	5686	5456	765	767	773
	100	217	279	218	5121	5436	5206	690	692	698
	150	197	259	198	4621	4936	4706	640	642	648
	200	177	239	178	4071	4386	4156	580	582	588
	250	165	227	166	3481	3796	3566	500	502	508
3	50	211	273	212	5000	5315	5085	705	707	713
	100	187	249	188	4750	5065	4835	630	632	638
	150	167	229	168	4250	4565	4335	580	582	588
	200	147	209	148	3700	4015	3785	520	522	528
	250	135	197	136	3110	3425	3195	440	442	448
4	50	177	239	178	4779	5094	4864	655	657	663
	100	153	215	154	4529	4844	4614	580	582	588
	150	133	195	134	4029	4344	4114	530	532	538
	200	113	175	114	3479	3794	3564	470	472	478
	250	101	163	102	2889	3204	2974	390	392	398
5	50	149	211	150	4303	4618	4388	605	607	613
	100	125	187	126	4053	4368	4138	530	532	538
	150	105	167	106	3553	3868	3638	480	482	488
	200	85	147	86	3003	3318	3088	420	422	428
	250	73	135	74	2413	2728	2498	340	342	348
6	50	126	188	127	3917	4232	4002	553	555	561
	100	102	164	103	3667	3982	3752	478	480	486
	150	82	144	83	3167	3482	3252	428	430	436
	200	62	124	63	2617	2932	2702	368	370	376
	250	50	112	51	2027	2342	2112	288	290	296
7	50	113	175	114	3545	3860	3630	504	506	512
	100	89	151	90	3295	3610	3380	429	431	437
	150	69	131	70	2795	3110	2880	379	381	387

Table 8: Continued.

No. of robots	Communication range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
	200	49	111	50	2245	2560	2330	319	321	327
	250	37	99	38	1655	1970	1740	239	241	247
	50	95	157	96	3134	3449	3219	452	454	460
	100	71	133	72	2884	3199	2969	377	379	385
8	150	51	113	52	2384	2699	2469	327	329	335
	200	31	93	32	1834	2149	1919	267	269	275
	250	19	81	20	1244	1559	1329	187	189	195
	50	83	145	84	3026	3341	3111	401	403	409
	100	59	121	60	2776	3091	2861	326	328	334
9	150	39	101	40	2276	2591	2361	276	278	284
	200	19	81	20	1726	2041	1811	216	218	224
	250	7	69	8	1136	1451	1221	136	138	144
	50	70	132	71	2789	3104	2874	353	355	361
	100	46	108	47	2539	2854	2624	278	280	286
10	150	26	88	27	2039	2354	2124	228	230	236
	200	6	68	7	1489	1804	1574	168	170	176
	250	4	66	5	899	1214	984	88	90	96

Table 9: Comparison of the proposed exploration approaches with different communication ranges for environment 3.

No. of robots	Communication range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
1	50	305	360	305	10274	10591	10366	830	844	850
	100	281	336	281	10024	10341	10116	755	769	775
	150	261	316	261	9524	9841	9616	705	719	725
	200	241	296	241	8974	9291	9066	645	659	665
	250	229	284	229	8384	8701	8476	565	579	585
2	50	245	300	245	5379	5696	5471	755	769	775
	100	221	276	221	5129	5446	5221	680	694	700
	150	201	256	201	4629	4946	4721	630	644	650
	200	181	236	181	4079	4396	4171	570	584	590
	250	169	224	169	3489	3806	3581	490	504	510
3	50	215	270	215	5008	5325	5100	695	709	715
	100	191	246	191	4758	5075	4850	620	634	640
	150	171	226	171	4258	4575	4350	570	584	590
	200	151	206	151	3708	4025	3800	510	524	530
	250	139	194	139	3118	3435	3210	430	444	450
4	50	181	236	181	4787	5104	4879	645	659	665
	100	157	212	157	4537	4854	4629	570	584	590
	150	137	192	137	4037	4354	4129	520	534	540
	200	117	172	117	3487	3804	3579	460	474	480
	250	105	160	105	2897	3214	2989	380	394	400
5	50	153	208	153	4311	4628	4403	595	609	615
	100	129	184	129	4061	4378	4153	520	534	540
	150	109	164	109	3561	3878	3653	470	484	490
	200	89	144	89	3011	3328	3103	410	424	430
	250	77	132	77	2421	2738	2513	330	344	350
6	50	130	185	130	3925	4242	4017	543	557	563
	100	106	161	106	3675	3992	3767	468	482	488
	150	86	141	86	3175	3492	3267	418	432	438
	200	66	121	66	2625	2942	2717	358	372	378
	250	54	109	54	2035	2352	2127	278	292	298
7	50	117	172	117	3553	3870	3645	494	508	514
	100	93	148	93	3303	3620	3395	419	433	439
	150	73	128	73	2803	3120	2895	369	383	389

Table 9: Continued.

No. of robots	Communication range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
	200	53	108	53	2253	2570	2345	309	323	329
	250	41	96	41	1663	1980	1755	229	243	249
8	50	99	154	99	3142	3459	3234	442	456	462
	100	75	130	75	2892	3209	2984	367	381	387
	150	55	110	55	2392	2709	2484	317	331	337
	200	35	90	35	1842	2159	1934	257	271	277
	250	23	78	23	1252	1569	1344	177	191	197
9	50	87	142	87	3034	3351	3126	391	405	411
	100	63	118	63	2784	3101	2876	316	330	336
	150	43	98	43	2284	2601	2376	266	280	286
	200	23	78	23	1734	2051	1826	206	220	226
	250	11	66	11	1144	1461	1236	126	140	146
10	50	74	129	74	2797	3114	2889	343	357	363
	100	50	105	50	2547	2864	2639	268	282	288
	150	30	85	30	2047	2364	2139	218	232	238
	200	10	65	10	1497	1814	1589	158	172	178
	250	8	63	8	907	1224	999	78	92	98

Table 10: Comparison of the proposed exploration approaches with different sensor ranges for environment 1.

No. of robots	Sensor range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
	50	307	362	302	10276	10606	10372	845	847	848
	100	283	338	278	10026	10356	10122	770	772	773
1	150	263	318	258	9526	9856	9622	720	722	723
	200	243	298	238	8976	9306	9072	660	662	663
	250	231	286	226	8386	8716	8482	580	582	583
	50	247	302	242	5381	5711	5477	770	772	773
	100	223	278	218	5131	5461	5227	695	697	698
2	150	203	258	198	4631	4961	4727	645	647	648
	200	183	238	178	4081	4411	4177	585	587	588
	250	171	226	166	3491	3821	3587	505	507	508
	50	217	272	212	5010	5340	5106	710	712	713
	100	193	248	188	4760	5090	4856	635	637	638
3	150	173	228	168	4260	4590	4356	585	587	588
	200	153	208	148	3710	4040	3806	525	527	528
	250	141	196	136	3120	3450	3216	445	447	448
	50	183	238	178	4789	5119	4885	660	662	663
	100	159	214	154	4539	4869	4635	585	587	588
4	150	139	194	134	4039	4369	4135	535	537	538
	200	119	174	114	3489	3819	3585	475	477	478
	250	107	162	102	2899	3229	2995	395	397	398
	50	155	210	150	4313	4643	4409	610	612	613
	100	131	186	126	4063	4393	4159	535	537	538
5	150	111	166	106	3563	3893	3659	485	487	488
	200	91	146	86	3013	3343	3109	425	427	428
	250	79	134	74	2423	2753	2519	345	347	348
	50	132	187	127	3927	4257	4023	558	560	561
	100	108	163	103	3677	4007	3773	483	485	486
6	150	88	143	83	3177	3507	3273	433	435	436
	200	68	123	63	2627	2957	2723	373	375	376
	250	56	111	51	2037	2367	2133	293	295	296
	50	119	174	114	3555	3885	3651	509	511	512
7	100	95	150	90	3305	3635	3401	434	436	437
	150	75	130	70	2805	3135	2901	384	386	387

Table 10: Continued.

No. of robots	Sensor range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
	200	55	110	50	2255	2585	2351	324	326	327
	250	43	98	38	1665	1995	1761	244	246	247
8	50	101	156	96	3144	3474	3240	457	459	460
	100	77	132	72	2894	3224	2990	382	384	385
	150	57	112	52	2394	2724	2490	332	334	335
	200	37	92	32	1844	2174	1940	272	274	275
	250	25	80	20	1254	1584	1350	192	194	195
9	50	89	144	84	3036	3366	3132	406	408	409
	100	65	120	60	2786	3116	2882	331	333	334
	150	45	100	40	2286	2616	2382	281	283	284
	200	25	80	20	1736	2066	1832	221	223	224
	250	13	68	8	1146	1476	1242	141	143	144
10	50	76	131	71	2799	3129	2895	358	360	361
	100	52	107	47	2549	2879	2645	283	285	286
	150	32	87	27	2049	2379	2145	233	235	236
	200	12	67	7	1499	1829	1595	173	175	176
	250	10	65	5	909	1239	1005	93	95	96

Table 11: Comparison of the proposed exploration approaches with different sensor ranges for environment 2.

No. of robots	Sensor range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
1	50	309	364	304	10476	10611	10376	870	848	851
	100	285	340	280	10226	10361	10126	795	773	776
	150	265	320	260	9726	9861	9626	745	723	726
	200	245	300	240	9176	9311	9076	685	663	666
	250	233	288	228	8586	8721	8486	605	583	586
2	50	249	304	244	5581	5716	5481	795	773	776
	100	225	280	220	5331	5466	5231	720	698	701
	150	205	260	200	4831	4966	4731	670	648	651
	200	185	240	180	4281	4416	4181	610	588	591
	250	173	228	168	3691	3826	3591	530	508	511
3	50	219	274	214	5210	5345	5110	735	713	716
	100	195	250	190	4960	5095	4860	660	638	641
	150	175	230	170	4460	4595	4360	610	588	591
	200	155	210	150	3910	4045	3810	550	528	531
	250	143	198	138	3320	3455	3220	470	448	451
4	50	185	240	180	4989	5124	4889	685	663	666
	100	161	216	156	4739	4874	4639	610	588	591
	150	141	196	136	4239	4374	4139	560	538	541
	200	121	176	116	3689	3824	3589	500	478	481
	250	109	164	104	3099	3234	2999	420	398	401
5	50	157	212	152	4513	4648	4413	635	613	616
	100	133	188	128	4263	4398	4163	560	538	541
	150	113	168	108	3763	3898	3663	510	488	491
	200	93	148	88	3213	3348	3113	450	428	431
	250	81	136	76	2623	2758	2523	370	348	351
6	50	134	189	129	4127	4262	4027	583	561	564
	100	110	165	105	3877	4012	3777	508	486	489
	150	90	145	85	3377	3512	3277	458	436	439
	200	70	125	65	2827	2962	2727	398	376	379
	250	58	113	53	2237	2372	2137	318	296	299
7	50	121	176	116	3755	3890	3655	534	512	515
	100	97	152	92	3505	3640	3405	459	437	440
	150	77	132	72	3005	3140	2905	409	387	390

Table 11: Continued.

No. of robots	Sensor range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
	200	57	112	52	2455	2590	2355	349	327	330
	250	45	100	40	1865	2000	1765	269	247	250
8	50	103	158	98	3344	3479	3244	482	460	463
	100	79	134	74	3094	3229	2994	407	385	388
	150	59	114	54	2594	2729	2494	357	335	338
	200	39	94	34	2044	2179	1944	297	275	278
	250	27	82	22	1454	1589	1354	217	195	198
9	50	91	146	86	3236	3371	3136	431	409	412
	100	67	122	62	2986	3121	2886	356	334	337
	150	47	102	42	2486	2621	2386	306	284	287
	200	27	82	22	1936	2071	1836	246	224	227
	250	15	70	10	1346	1481	1246	166	144	147
10	50	78	133	73	2999	3134	2899	383	361	364
	100	54	109	49	2749	2884	2649	308	286	289
	150	34	89	29	2249	2384	2149	258	236	239
	200	14	69	9	1699	1834	1599	198	176	179
	250	12	67	7	1109	1244	1009	118	96	99

Table 12: Comparison of the proposed exploration approaches with different sensor ranges for environment 3.

No. of robots	Sensor range	Path length			Exploration			Total no. of cycles		
		Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc	Centralized	Leader-follower	Ad hoc
1	50	312	368	306	10479	10619	10379	875	852	853
	100	288	344	282	10229	10369	10129	800	777	778
	150	268	324	262	9729	9869	9629	750	727	728
	200	248	304	242	9179	9319	9079	690	667	668
	250	236	292	230	8589	8729	8489	610	587	588
2	50	252	308	246	5584	5724	5484	800	777	778
	100	228	284	222	5334	5474	5234	725	702	703
	150	208	264	202	4834	4974	4734	675	652	653
	200	188	244	182	4284	4424	4184	615	592	593
	250	176	232	170	3694	3834	3594	535	512	513
3	50	222	278	216	5213	5353	5113	740	717	718
	100	198	254	192	4963	5103	4863	665	642	643
	150	178	234	172	4463	4603	4363	615	592	593
	200	158	214	152	3913	4053	3813	555	532	533
	250	146	202	140	3323	3463	3223	475	452	453
4	50	188	244	182	4992	5132	4892	690	667	668
	100	164	220	158	4742	4882	4642	615	592	593
	150	144	200	138	4242	4382	4142	565	542	543
	200	124	180	118	3692	3832	3592	505	482	483
	250	112	168	106	3102	3242	3002	425	402	403
5	50	160	216	154	4516	4656	4416	640	617	618
	100	136	192	130	4266	4406	4166	565	542	543
	150	116	172	110	3766	3906	3666	515	492	493
	200	96	152	90	3216	3356	3116	455	432	433
	250	84	140	78	2626	2766	2526	375	352	353
6	50	137	193	131	4130	4270	4030	588	565	566
	100	113	169	107	3880	4020	3780	513	490	491
	150	93	149	87	3380	3520	3280	463	440	441
	200	73	129	67	2830	2970	2730	403	380	381
	250	61	117	55	2240	2380	2140	323	300	301
7	50	124	180	118	3758	3898	3658	539	516	517
	100	100	156	94	3508	3648	3408	464	441	442
	150	80	136	74	3008	3148	2908	414	391	392

Table 12: Continued.

No. of robots	Sensor range	Path length Centralized	Path length Leader-follower	Path length Ad hoc	Exploration Centralized	Exploration Leader-follower	Exploration Ad hoc	Total no. of cycles Centralized	Total no. of cycles Leader-follower	Total no. of cycles Ad hoc
	200	60	116	54	2458	2598	2358	354	331	332
	250	48	104	42	1868	2008	1768	274	251	252
8	50	106	162	100	3347	3487	3247	487	464	465
	100	82	138	76	3097	3237	2997	412	389	390
	150	62	118	56	2597	2737	2497	362	339	340
	200	42	98	36	2047	2187	1947	302	279	280
	250	30	86	24	1457	1597	1357	222	199	200
9	50	94	150	88	3239	3379	3139	436	413	414
	100	70	126	64	2989	3129	2889	361	338	339
	150	50	106	44	2489	2629	2389	311	288	289
	200	30	86	24	1939	2079	1839	251	228	229
	250	18	74	12	1349	1489	1249	171	148	149
10	50	81	137	75	3002	3142	2902	388	365	366
	100	57	113	51	2752	2892	2652	313	290	291
	150	37	93	31	2252	2392	2152	263	240	241
	200	17	73	11	1702	1842	1602	203	180	181
	250	15	71	9	1112	1252	1012	123	100	101

7. Conclusion

Based on the results obtained from the computer simulation, the following conclusions can be drawn. With the help of simple experiments it was found that the exploration process which is performed by considering frontiers performs well when compared to the approach without frontier selection. The exploration time and path length is reduced to almost 50%. Here, a single robot is considered for exploration of an environment. In the next chapter, the exploration using multiple robots is demonstrated. When the number of robots increases, the exploration time and path length will be reduced further. A coordinated communicative exploration has been introduced to accomplish the process of autonomous multiple robot exploration. The main idea of the strategy is to maintain a full communication among the multiple robots throughout the process of exploration. In this work, three different approaches are presented, and they are compared by considering the influence of communication range and sensor range on the performance parameters. The process of exploration enables the robot to move in an unknown environment. In this work, frontier-based exploration approach is used for exploration process. The space between the explored space and the unexplored space is the frontiers. When the robot reaches the frontier, it can explore the unknown area. The performance analysis for the exploration method using the frontier selection approach is done, and the results are compared with the exploration method without frontier selection approach. It was verified that the frontier selection approach produce better results. This work also investigates multirobot exploration in an unknown environment. The number of robot engaged for exploration can be a single robot or multiple robots. When multiple robots are used for exploration, then the process is faster than using a single robot. The future work to improve the proposed methods may include the analysis of the effect of moving target on the robot and hence provide mobile robot navigation in dynamic environment. Quasistatic environment is considered in this study, and in the future it may be extended to a dynamic environment where obstacles and targets are moving. The obstacle avoidance algorithm can be extended to multirobot in the future. The presented work considers only robot as a point. By integrating the proposed algorithm with other methods, the obstacle avoidance algorithm can be extended to the whole robot. In the future, 3D and concave objects can also be taken into account instead of 2D and convex obstacles. There are many ways by which coordinated multirobot exploration can be extended for future enhancement. In the proposed method, the structure of the hierarchy is fixed, and in the future, dynamic hierarchy structure can be introduced. In the presented work, the robots considered for exploration are homogeneous in nature, and in the future, it can be considered as heterogeneous, that is, with different types of robots with different capabilities. Finally, this work can be extended to 3D environment.

Data Availability

We recognize that it is not always possible to share research data publicly, for instance, when individual privacy could be compromised, and in such instances data availability should still be available in the manuscript.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

All the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.

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