2017 Conference on Information and Communication Technology (CICT'17)

Comparative Study Of Frontier Based Exploration Methods

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***Abstract*—Exploration of an unknown area is a challenging topic in the field of robotics. It has gained concern of many researchers due to its pertinence to various applications. In this paper we present the survey of frontier based exploration techniques for single and multi robot. Main challenge in frontier based exploration techniques is to allocate the most promising frontier cell to each robot. Variety of approaches have been implemented for both single and multi robot in practical and simulated experiment. The objective of this paper is to provide an understanding of frontier based exploration methods. We also provide taxonomy of frontier based techniques and compared them based on their characteristic features.**

Keywords*—*Robotics, Area exploration, Frontier based exploration.

I. Introduction

Exploration is a vital task for mobile robot and is an important field of research. Initially single robot exploration was well studied and novel methods were proposed [1], [2], [3]. Later interest shifted towards multi robot exploration. Many potential applications, search operations inside buildings, caves, tunnels and mines are sometimes extremely dangerous activities. The use of autonomous robots to perform such tasks in complex environment reduces the risk of these missions for human beings.

Exploration is the process of effectively covering an environment by a single or a team of robots in order to gain as much information about the world as possible in a reasonable amount of time. Various exploration approaches: leader follower, graph theoretic approaches, behavior based approaches, exploration with environmental tagging, frontier based approaches have been proposed by researchers in the literature. A landmark paper is given by Yamachui [2] in 1998 which serves as the foundation for frontier based exploration. Frontiers are defined as the boundaries between the explored and unexplored region. In frontier based algorithms robots detect the frontiers and then they navigate towards the most promising frontier to complete the exploration. This process continues until there is no frontier cell left.

In this paper we focus on multi robot and single robot frontier based exploration methods. Frontier based approaches are based on the concept of frontiers which forms the boundary between unknown and known region. There are several frontier based exploration techniques which mainly varies in their approach of handling communication, providing coordination among robots, reducing computational overhead, minimizing energy consumption and reducing redundant coverage. This paper provides taxonomy of frontier based exploration methods and also gives a detailed survey of the same with a comparison chart highlighting the features of various frontier based techniques.

II. TAXONOMY OF FRONTIER BASED EXPLORATION

Frontier based techniques are broadly classified in single and multi robot frontier based techniques as shown in Fig. 1. The single robot frontier based methods are broadly divided based on their goals such as reducing computational overhead, reducing energy consumption and minimizing redundant coverage. Multi robot frontier based techniques are also divided based on their goals such as handling communication, reducing energy consumption and minimizing redundant coverage.

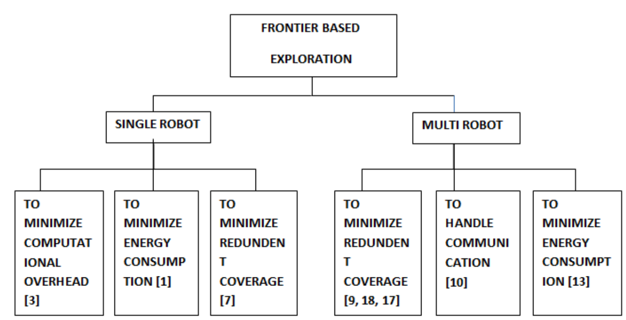

Fig. 1. Taxonomy Of Frontier Based Techniques

A. *Single robot frontier based exploration method.*

Single robots are constrained by the amount of on board processing power and the amount of energy consumed during exploration process frontier based technique by yamachui [2] has been modified to later to these goals.

1) Energy efficient mobile robot exploration: Mei et al. [1] proposed an approach for energy efficient robot exploration. Grid cell map is used to represent the area. Robot is allowed to move from one cell to its one of eight neighboring cells. At each step robot is represented by its location and direction.

Exploration is divided in two major steps one is target selection and other is motion planning. Direction based target selection method is used in which a robot select the target on its left side first then in clockwise order front and right side targets are selected. For target selection frontier cells within the sensing range are identified. Then these cells are listed according to the clockwise order starting from robots left direction. Dijkastras is used to generate minimum energy path. For this purpose grid map is transformed into a graph, in which vertices represent robots state including both direction and location. Each cell is transformed into 8 vertices, represents 8 possible states of robot at this cell. These are the states when robot leaving the cell. Labeling of cells is done by their directions. The neighbors of the cell are also labeled in the same manner. These neighbors show 8 possible leaving states at that cell. Edges are directed and connect two states. Weight is assigned to the edges, correspond to the energy required to move from one state to another. Path represents the trajectory of robot and sum of the weights assigned to the edges represents the energy consumption of that trajectory. Simulation results show that proposed method requires less energy and shorten exploration path.

2) A frontier based approach for autonomous exploration: Yamachui [2] proposed a new approach for exploration by introducing the concept of frontier, the boundary between open and unexplored space. A technique is also defined to minimize the specular reflections in evidence grid. Central idea in frontier based exploration is to move towards the frontier in order to gain new information about the world. Evidence grid is used for environment representation. A prior probability is assigned to each cell in the grid. Each time when a sensor reading is obtained grid is updated by using the corresponding sensor model. To reduce the effect of specular reflections caused by sonar sensors, laser-limited sonar is used. In which a laser rangefinder is used in combination with sonar sensors and each sensor reading is assumed to be free from other sensors. Each cell in the grid is classified as open, unknown or free cell by comparing its occupancy probability to its prior probability. Adjacent frontier cells are group together to form the frontier region. After the detection of frontier cell, robot moves towards the nearest unvisited accessible frontier cell by using the depth first search on evidence grid. Reactive obstacle avoidance behavior is used to prevent collision with obstacle. After reaching at the destination, robot performs a 360 degree sweep and adds new information to the evidence grid. Location of the destination is added to previously visited frontiers list. Robot detect frontier in updated grid and navigate towards the nearest accessible frontier. If a robot is not able to reach to a particular destination in a certain amount of time that destination is added to the list of inaccessible frontier. Robot performs the sweep update the grid and move towards a new frontier until there is no frontier cell left in the environment. Approach is tested with real robot in two real world office environments. Results show the ability of the approach to explore both narrow cluttered space and large open space

3) Robot exploration with fast frontier detction: Theory and experiment: Keidar and Kaminka [3] proposed two novel approaches for frontier detection algorithms (1) Wavefront Frontier Detection, which is an iterative method, based on the graph search techniques. (2) Fast frontier detection which requires processing of the new laser readings. WFD uses the breadth first search to find the points on the map those contained frontier. A queue data structure is used to store the points that contain frontier in occupancy grid then BFS is performed to extract the frontier only from the area that has not been scanned yet and represents the open space. It assures, algorithm will not scan the entire map data. To avoid rescanning of the same frontier points, map points are marked by indications: (a) Map-Open-List (b) Map-close-List (c) Frontier-Open-List (d) Frontier-Close-List. FFD algorithm performs four steps: (i) Sorting: Performed on the sensor reading based on their angles. These readings are assumed to be the set of Cartesian coordinated points. To speed up the sorting, cross product method is used to sort the points on the basis of their polar angle. (ii) Contour: sorted laser readings are used to build the contour. The line to join adjacent points is computed using the Bresenhams line algorithm [4]. Then all the lines are merged into contour. (iii) Detecting new frontiers: Three situations occur for each two adjacent points in the contour (a) These points are not a frontier cell so they did not contribute any new information and get ignored. (b) Previously detected and newly detected frontier cells both belong to same frontier and new points are added to last detected frontier. (c) Newly detected points are frontier and previously detected points are not, newly detected frontier points are added. (iv) Maintaining previously detected frontiers: Previously detected frontier points, are joined together with newly detected frontier points. And the frontiers points those are no longer remain frontier, are eliminated. Data structure i.e. an extension to occupancy grid is used to maintain previously detected frontiers. In this each cell have occupancy information along with the frontier index, which points to a frontier to which grid cell belongs. To avoid redetection of same frontier: frontier points are redefine as a point which is in unknown region, have at least one open space neighbor and never been scanned before. Algorithms are integrated in single robot exploration system to evaluate the performance. Testing is performed on the data get collected from Robotics Data Set Repository. Results show that WFD is Faster than SOTA algorithm and FFD is faster than WFD.

4) Histogram based frontier exploration: Mobarhani et al. [5] proposed an approach for frontier based exploration. Histogram based approach is used to cluster the frontier cells. A novel idea is given for selecting sub goals. Philosophy behind the idea is to consider both the closeness and cardinality of the sub goal. A mobile robot with laser range finder is placed in the priori unknown indoor environment. Occupancy gird is used for map exploration. After the construction of grid map all the frontiers are extracted from it and a global frontier map is created. To choose the sub goal histogram based method is used. First all the points in the map are transformed into the robots coordinate frame then polar histogram is calculated. Height of each bin is equivalent to the number of frontiers available in that bins area. To avoid parameter tuning and unnecessary calculation normalization and smoothing techniques are applied to the histogram. After that, sets having height greater than a predefined threshold are determined. For each set number of frontier cells and its relative distance from robot is calculated and stored in two different sets. These sets are normalized and score of each set is given by,

$$Si = \Omega * 1/Di + \Theta * Ci \qquad (1)$$

Where S_i is the score of set i, D_i is the normalized distance and C_i is the cardinality of the set. Ω and Θ are tuning parameters. The set with the best score is chosen and its centroid is selected as next sub goal. For path planning A* search algorithm with image distance transform is used. After applying the distance transform to the digital image, each pixel is labeled according to the distance from obstacle. Trajectory generated by A* cannot be fed directly to the robot because it contains sharp turns which can put the stability of robot motion in danger. To deal with this a reference trajectory is generated by using B-spline approximation. Method is implemented in real world scenario. Results shows that proposed method outperforms the original frontier based method.

B. Multi robot frontier based exploration method.

Multi robot area exploration provides several advantages such as robustness, accuracy, speed and fault tolerance. On the other hand, with multiple robots there are several issues like collision avoidance, coordination, cooperation, communication etc. various methods have been provided by researchers to handle these issues.

1) Frontier based exploration using multiple robots: Yamachui [6] proposed the concept of frontier based exploration for multiple robots. First the evidence grid is constructed on the basis of probability, whether a cell is free or occupied. After that each cell is categorized as open, unknown or occupied cell based on its occupancy probability. Open cells, those are adjacent to unknown cells are the frontier cells. Adjacent frontier cells are group together to form the frontier region. After the detection of frontier cell, robot moves towards the nearest unvisited accessible frontier cell by using the depth first search on evidence grid. Robot shares information about environment and each robot have their own global map. Whenever a robot finds a new frontier it moves to the frontier and performs a 360 degree sweep then add new information to its local grid which represent its surroundings. Then this information is added to the global grid and broadcasted to all other robots and each robot updates their global map. In this way robots share the information and cooperate with each other to guide the exploration. The approach has been implemented on real robots. Results show they can explore and map, the office environments as a team.

2) Collaborative multi robot exploration: Burgard et al. [7] proposed an approach for frontier based multi robot exploration so that they can choose appropriate target points to explore the different regions of the environment. To assign the target point, cost and utility of these target points is calculated. Cost is calculated by computing the optimal path from robots to all frontier cells. A heuristic, i.e. a robot which has a big open terrain can cover large area as compare to the robot which has a small open terrain, is designed for utility. For the target point selection both cost and utility is considered. Whenever a robot assigned a target point, the utility of area visible from that target point is reduced for others. In this way they can coordinate and explore different regions of unexplored area. Results show time to explore the environment is reduced with coordinated approach.

3) Autonomous multi robot exploration in communication limited environment: De hoog et al. [8] proposed a new idea to use role based exploration for multiple robots in order to allow the communication among team members beyond the communication range. Problem is defined as consolidation of the information from all robots at a single place. Each robot is assumed to be equipped with a SLAM module. Each robot can have one of two roles either Explorer or Relay. Explorers are responsible to explore the environment and relays are responsible to transfer information between explorer and base station. This is achieved by meeting periodically at previously agreed rendezvous points. Team is represented as a tree, every node in the tree is a robot, where base station is considered as tree's root and leaves of the tree are explorer. Chain of relay exists between root and explorer. Communication among team member is performed by multi hop communication if they are within the communication range. When unexplored area is beyond the communication range, then explorer robots explore the far reaches in the environment and relay transfers the information between explorer and base station. For exploration simple frontier based exploration technique is used and frontier utility is calculated by

$$U(f) = A(f)/C^n(f) \tag{2}$$

Where A(f) is the area of frontier f, C(f) is the cost for reaching from robot to that frontier, and exponent n represents the exploration behavior. To assign the frontiers a simple agent frontier assignment algorithm [9] is used. To improve the efficiency rendezvous points are calculated by the explorer when relays are within the communication range. Hilditch's algorithm [10] is used for this purpose. Rendezvous points those lies inside the frontier and having a good communication range was chosen. To further improve the efficiency dynamic role swapping is allowed in the team. For evaluation java based simulator is used. Experiments are conducted in different environment by varying the team size. Approach is compared with greedy frontier based and static role based exploration, results show that this approach leads to faster exploration and has a better team responsiveness and inter robot awareness.

4) Multi Robot Exploration Using a Modified A Algorithm:* Pal et al. [11] provides an approach to produce an efficient path and to complete the exploration as early as possible. Environment is represented as 2D occupancy grid. Path planning is done by using EA* algorithm. Exploration task is divided in three modules. First, environment partitioning: done using K-Mean [12] in which number of subareas is equal to the number of robots. Second, robot region assignment: done using Hungarian method [13]. Third, robot frontier assignment: frontier cell which leads to minimum cost are assigned as destination frontier cell. Cost of frontier cell is calculated using the path planning algorithm and cost function is defined in which Δ is used to penalize the frontier cells those do not belong to the region to which robot is assigned. To avoid the overlap, penalty is given to the frontier cells those lies within the sensor range of robot's target location. To reduce the computational overhead frontier pruning [14] is done. An admissible heuristic is used for cost estimation, given by

$$D_{ij} = |f_j - R_i| \tag{3}$$

R_i is the robots current location, || is the Euclidean distance of two points. By using this heuristic they did not needed to compute the cost of all frontier cells, some of the cells those are less favorable (cells those are far away from robot) did not computed. Exploration finishes when there is no unknown cells left in the environment. The proposed approach is tested using java based simulator in different environment. Results shows that time and energy consumption required to explore the environment both are reduced.

5) An automation exploration strategy for cooperative mobile robots: Khawaldah et al. [15] proposed a frontier based technique to minimize the exploration time by the team of cooperating mobile robots. Robots work in a coordinated manner to reduce the overlap. To achieve this, new bidding function which considers cost, utility and the distance of the other robot from the cell is introduced. All the distance calculation is done according to the flood fill algorithm. Each robot calculates the bidding value B_i for each frontier cell on the basis of bidding function, given by

$$B_i = W_n N_u + W_p D_p - W_c D_r \tag{4}$$

Where, B_i is the bidding value for target cell i, D_r is the distance between robot and target cell, D_p is the distance between closest robot and target cell, N_u number of unknown neighbors correspond to the target cell. W_p, W_n, and W_c are the weight factors for D_p, N_u, and D_r, respectively. To enhance the algorithm bidding function is adjusted. Rather than calculating the distance of closest robot, distance of the closest target cell that has been assigned by any other robot is calculated. The proposed approach is tested with different number of robots in various environments. They also compared results with A* algorithm. Results show that proposed approach requires less energy and computation time.

6) Minpos: frontier based area exploration algorithm: Bautin et al. [16] proposed a decentralized method for frontier allocation which is based on the relative ranking of robots. Wavefront propogation [17] method is used to evaluate the criteria for ranking. Robots are allocated to the frontier according to the lowest rank. The occupancy grid [18] is used as map representation of the environment. Each robot performs four steps. (i) Frontier identification and clustering: robots maintain list of frontier cells and cluster the contiguous frontier cells according to the size of sensing area, so that robots will not be assigned to the cells those are in the same perception. (ii) Computation of distances to frontiers: a cost matrix is used which evaluates the position of robots by building artificial potential field using Wavefront Propogation Algorithm. (iii) Assignment to a frontier: it is done in a decentralized manner. Robots are assigned to the frontier for which they are in the first position. (iv) Navigation towards the assigned frontiers for a fixed time period: Wavefront propagation is stopped when propagating wavefront finds a robot which computing its allocation. Corresponding frontier cell is then assigned to that robot. If all wavefront stops on the robots those are not calculating their assignment then they restarts sequentially from lower to higher potential value. Robots achieve coordination by building the map in a cooperative manner and by sharing information about their locations. Proposed approach is compared with existing approaches and results show validity and efficiency of algorithm.

III. COMPARATIVE STUDY

Comparison among various frontier based methods is done for both single and multi robot exploration and listed in table I and table II respectively. We compare these methods on the basis of their relevant features. We have discussed about (1) objective of the paper which includes handling communication, reducing computational overhead, reducing energy consumption and minimizing redundant coverage. (2) Software hardware used for the implementation purpose, some researchers has been simulated their approaches and some have implemented on real robots. (3) Strength and weaknesses of the approach. (4) Target allocation strategy for which various factors like cost, utility and closeness of frontier cell from other robots are considered. Relative ranking based approach is also provided for target allocation.

IV. CONCLUSION

In Multi robot area exploration, based on frontier allocation main problem is to choose appropriate frontier cells for each individual robot, so that they can move to different areas of unexplored region. Complexity of choosing the target points increases with the number of robots. In this paper various methodologies has been studied for frontier based allocation focusing on coordination, energy consumption, dispersion, workload sharing and communication. The main focus in both single and multi robot exploration is to allocate the target in such a way so that redundant coverage can be minimized.

Future work involves to study the various techniques of exploration and compare these techniques on the basis of their relevant features.

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TABLE I. COMPARATIVE STUDY OF SINGLE ROBOT FRONTIER BASED EXPLORATION METHODS

Paper	Objective	Software,/ Hardware used	Target allocation strategy	Strength	Weakness
[1]	To propose an approach for energy efficient exploration	Simulation	Direction based target selection	Energy efficient motion planning Minimize redundant coverage	Grid cell map needs to transform in graph
[2]	To provide a new technique for exploration	Nomad 200 mobile Robot Sensors, laser, range finder	Nearest unvisited accessible frontier	Novel method of exploration is given	Redundant coverage
[3]	To Speed up the frontier detection.	Exploration system based on GMapping, grid SLAM processor, fast desktop system with intel core 2 duo T6600 CPU,clock speed 2.20GHz, RAM 4 GB, slow desktop with intel Pentium III, clock speed 800 MHz, RAM 1 GB	Not specified	Both of the algorithm do not need to process entire map data Able to detect the frontier faster than other SOTA methods	Maintaining previously detected frontiers requires tight integration with mapping component
[5]	To propose a method which has the least dependency on parameter tuning	Melon, the mobile robot, UHG-OSLX Hokuyo LRF	Scoring function which considers both closeness and cardinality of set	Applicability in real world scenario where surface may not be flat Flexibility of use simplicity	Adjustment of algorithm coefficients

TABLE II. COMPARATIVE STUDY OF MULTI ROBOT FRONTIER BASED EXPLORATION METHODS

Paper	Objective	Software/Hardware	Target Allocation strategy	Strength	Weakness
[6]	To extend frontier based exploration for multi robots team	Two Nomad 200 mobile robot, Sensors, laser, range finder	Nearest unvisited frontier cell	Robust to the loss of individual robot No explicit coordination or synchronization is required	Not optimally efficient Robots may waste their time to move to the same frontier One robot may block another.
[7]	Reducing redundant coverage	RWI B21 robot Pioneer I robot laser range-finders	Consider both cost and utility	Prevent Robots from selecting the same target location	Risk of redundant work Reliability on the central base station
[8]	Exploration beyond communication range	Java based simulator	Considers both cost and utility	No need for exact communication model Better connectivity and teammate awareness Adaptability to the size of environment and available communication range	Heavily reliant on SLAM Information regarding robots failure may not be reached to the base station
[11]	Reducing energy consumption and computational overhead	Java based simulator	Considers both cost and utility	Does not require explicit coordination or synchronization among robots Energy efficient Less computational overhead	To apply K Mean prior knowledge of environment is needed
[15]	Reducing redundant coverage	Netlogo	Consider cost, utility and other robot distance from frontier cell	Overlap among robots gets reduced Robots can explore simultaneously and work parallel	Weight adjustment is required to get optimal results
[16]	Reducing redundant coverage	MiniRex robot, Hokuyo utm-30lx laser range sensor, ultrasound range sensors	Relative ranking based approach	Good coordination with less complexity Well balanced spatial distributionof robots Navigation of grouped robots in different directions	In some situations performance is lower than greedy approaches

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