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# Comparative study of multi-robot area exploration algorithms

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***Abstract— In this paper, different Multirobot exploration algorithms and their comparison has been presented. These algorithms, which have been taken into consideration, are dependent on different parameters. Collectively there are five parameters Minimum distance, Minimum time, Cooperation for avoiding collision, Low cost communication and Optimization of the path for effective mapping and localization. It is worth mentioning here that each parameter itself opens new doors of exploration field. Therefore comparison of performance of multirobot area exploration algorithms has been done on the basis of minimum distance and minimum time only. The paper also provides the detailed description regarding use of a particular multi-robot algorithm in a specific circumstance.***

***Keywords— Multi-Robot, Mapping, Localization, path-planning, Spanning Tree Coverage, Particle Swarm Optimization, Simultaneously Localizations and Mapping.***

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## I. INTRODUCTION

Search operation in and around buildings, cave, tunnels and mines are inherently dangerous activity. The use of autonomous, untethered robots to perform search mission in these difficult environments has the potential to reduce the risk to operators and to improve search performance by infiltrating small spaces inaccessible to human searchers. Structural damage to mines and buildings can generate complex maze like environments that may be more effectively searched by multiple cooperating robots.

If we see in the regard of usage, distance is an important constraint related to these multi- robot path planning. Generally speaking by reducing the distance we bridle the energy consumption (except in some cases like unmanned aerial vehicle where the energy consumption is linked more to the time of flight than to distance) and travel time.

Another important constraint is reduction of time which is the motivation behind the multi-robot system and this is achieved by making many robots to work parallel in same time frame. It is further kept in mind that there must not be any collision between these robots. By using map transferring among robots, cooperation among them is done for multi-robot exploration.

Energy consumption should be minimized because mobile robots are usually powered by batteries with limited capacity and as a result power requirement is large if mobile robots are exploring large area. Methods which these robots use, also play a vital role in the power that is required for exploring an area. It is obvious that the method which includes tedious and long communication will require more energy as in the case of centralized CPU while in the case of decentralized CPU, the robots maintain a strong algorithm to transfer from one cluster to other.

Optimization is another important constraint, during multi-robot exploration, Robots divide whole area in sub areas and only after exploration of one subarea, Robots may enter to another subarea. This emphasizes that no robot should enter in an area which has already been explored and the robots should strictly follow the optimal path going from one subarea to other during exploration.

## II. RELATED WORK

This sector of multi-robot area exploration algorithm is so vast that till now enormous numbers of papers have been published based on focussing different parameters. Cabrera-mora and Xiao[1] have discussed about benefits of multirobot by comparing time which reduces. Gong and tully [2] discussed about the problem of rendezvous situation which is solved by using breath first search based technique, but the concept requires a large number of robots, in spite of leaving a token (RFID). This problem was solved by sheng and yangn[12] with bidding algorithm. Yamauchi[5] developed a distributed asynchronous multi robot exploration algorithm which introduced the concept of frontier cell or border area between known and unknown environment. The basic idea is to let each robot move to the closet frontier cell independently. Senthilkumar and Bharadwaj[10] proposed a multi-robot coverage algorithm based on Spanning tree coverage(STC). Here the area which is needed to be explored is divided into small blocks of cell, and the robots traverse in a specific order during exploration. The performance of algorithm degrades as the number of obstacles increase in the terrain .Kapanoglu and M. Ozkan [8] solved this problem by reducing turn in an environment and thus traverse time was considerably reduced using Pattern based Genetic algorithms.

## III. REQUIREMENT

During the recent years of developments in this field, it has been proven that even if there is a room for error in the localization of a robot for its exact position, it can be eliminated by using simultaneous localisation and mapping (SLAM)[5].The presumptions that are needed to be assumed based on the recent developments in the field of mobile robotics can be summarised as under :

1. Robots are equipped with a module commonly known as SLAM in which the robots are given RFID tag for marking a path, they may include LiDAR , Range Finder or a odometer.
2. Based on these sensing, LiDAR, SONAR, and LASER acting as a range finder maps the areas for exploration. These modules are of tremendous importance on ground level due to their exact result in present scenario.
3. ODOMETER is used for measuring the displacement that a robot exactly make during its movement and based on its coordinate displacement, itself relocate its current position.

## IV. MULTI-ROBOT AREA EXPLORATION ALGORITHMS

### A. *A Flooding Algorithm for Multirobot Exploration*

This algorithm is basically an outline which covers the concept of sending multiple robots for exploration instead of sending one robot to explore the whole area [1]. These multi robots communicate with each other through suitable medium during the traversing of path. The discrete position and time is a measure which is kept in consideration during the traverse. A remarkable efficiency in time is obtained during this implementation. The elaboration of this concept can be understood by taking in account an example.

If the exploration is being performed by a single robot it will take 20 steps to explore the whole tree as shown above in fig.1. In this flooding algorithm author has used depth first search method in which when a robot reaches at any vertices confirms the information about its arrival at edge to centralized CPU and consequently the CPU sends another robot as per requirement. While if the prior robot reaches at leaf then this robot deploy a token which contain information about vertices and this RFID token informs other robots that this edge has been traversed. Total time take by robots to explore the whole environment is given by the expression-

$$2e/k \le T_c \le 2e$$

Where e= Total no. Of edges in this graph
K= Total no. Of robots used in this exploration
$T_c$= total time required for the exploration

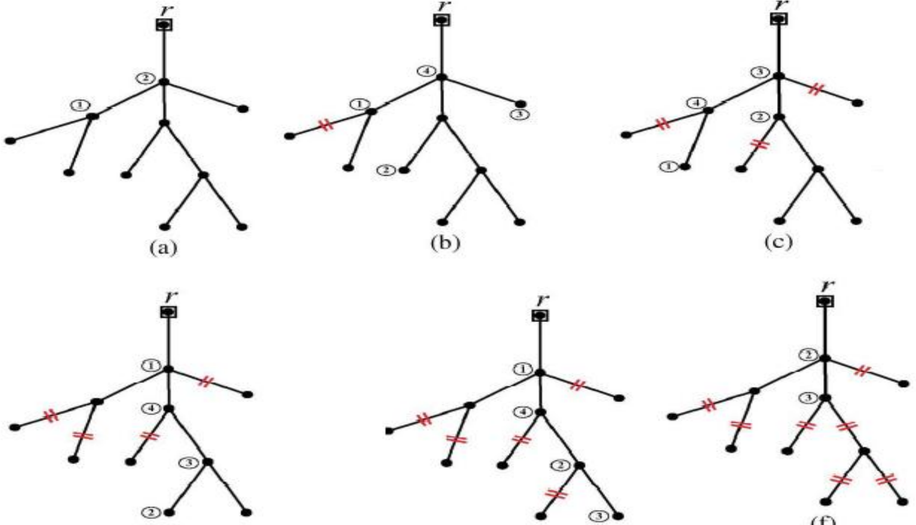


Fig.1. Four Robot exploring the environment using the flooding algorithm. Snapshots of the position of the robots after (a) two steps (b) four steps (c) five steps (d) seven steps (e) eight steps (f) ten steps. Crossed lines marks show that an edge has been finished. Exploration is complete after 12 steps

Moving further if we examine on larger scale there is a serious drawback of this technique. It can only be beneficial for tree type environment which is fully acyclic in nature. It loses its grip on the environments which follow a cyclic behaviour in their edges. It is further assumed in this technique that the distance between the two consecutive vertices is always kept equal which may or may not be possible. In practical scenario the arrival of a node or vertex is not certain, it may depends on type of environment, or Area to be explored or any other parameter which is not defined due to uncertainty in the structure to be explored. Due to these limitations the flooding algorithm can't be viewed as a sure and shot method of exploration.

### B. *Multirobot Tree and Graph Exploration.*

The concept of multirobot for finding exact location in an unknown environment has been ascended one step further in this technique. We assume a cyclic path as shown in fig2. which two robots starting from same vertex explores an area and their position after 5, 8, 11 and 15 steps.

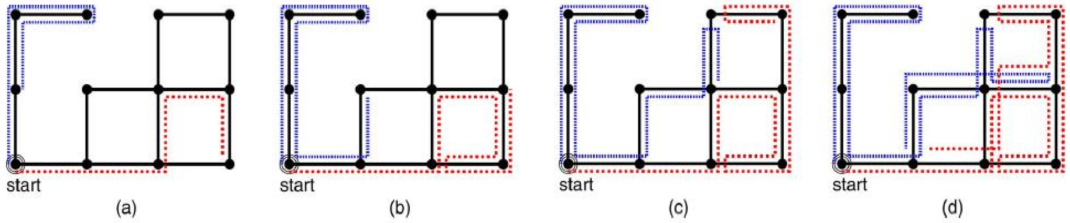


Fig.2. Path of two robots after (a) five steps (b) eight steps (c) eleven steps (d) fifteen steps.

The technique states that if during an exploration, robot reaches at a vertex where it has already been traversed then it compares the two paths which it had follow the outgoing edge and the incoming edge. The comparison is based on the data received from the RFID kept at the middle of edge containing information about the path that has been travelled. If the two paths are same that means, this particular area has been explored. While if the two edges are different, it only corresponds to an unexplored area left behind and the robot will immediately start along that edge again. In case if the robot meets another tree then they will divide the outgoing edges for exploration by choosing an unexplored edge by each one of them. In case of several robots jointly exploring an area and a returning robot, finds no unexplored edge any more it will simply join another consecutive partner in the branch. The only situation in which all the robots will enter to their original entrance edge is if each edge has been followed by a robot in both directions.

The author has proposed a way to describe his opinion in this contrast that if we assume a tree type environment in which the length of edges are not same. So as a factor to explore the area, the author has made virtual nodes at equal distances and divided the whole area where two robots are exploring the path as shown in fig 3.

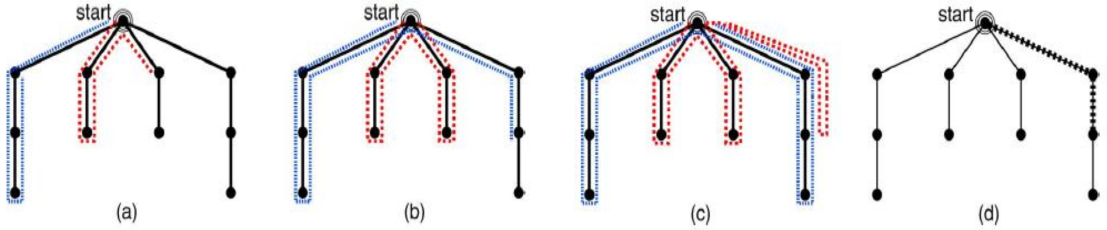


Fig.3. Path of two robots after (a) five steps (b) eight steps and (c) twelve steps on a tree of degree four. (d) Edges traversed by both robots.

After the completion of the exploration, an area (although small) has been covered by both the robots which depend on complexity of the path. The time that MR-DFS algorithm takes to explore a tree with e edges by k robots is given by

$$T_c = 1/k[\ 2e+2\sum\mu(e_i)]$$

Where $\mu(e_i)$= excess multiplicity.

$T_c$ = total time

This algorithm explores a tree with e edges and radius r using k robots in time is at most

$$\min(2e,\ 2e/k + 2/k\ ({}^{k+r}{}_{k-1})\ ) < 2e/k + (1+k/r)^{k-1}\ 2/k!\ r^{k-1}$$

another important aspect that can be visualised from this algorithm is, the robots whenever explores a tree having radius r and containing e edges takes an at most time of e+r which in other sense at most 3/2 of the optimum exploration time and this is further worth mentioning that no any other algorithm for two robots guarantee a factor less than 3/2. Using above mentioned algorithm the average reduction in exploration time is up to 50% for wide trees and 30% for long trees. But this algorithm suffers from a serious drawback that is the robots are almost completely unaware of the action of the other robots because this algorithm is based on local communication model, where communication happens only between a robot and a bookkeeping device left at that node, or between robots standing simultaneously at the same node. The another side of coin can be viewed as there is no any communication between the bookkeeping devices and the algorithm will succeed even if some robots are lost or destroyed.

### *C. Frontier Based Multi Robot Map Exploration Using Particle Swarm Optimisation(PSO)*

During exploration of any unknown area the overall view of the area or mapping plays a key role which include two important constraint that are to know the area as much as possible, and in minimum possible time. According to Brian Yamauchi[5] one way to know most about surrounding area is to move the boundary between open space and uncharted territory which is frontier based exploration. Actually Frontiers are the regions on boundaries between open space and unexplored space, and by moving to the successive frontiers, the robot can constantly increase its knowledge of the world. It has been mentioned by the author that use of evidence grid can be a way of spatial representation. Evidence grid is a Cartesian grid having cells and each cell stores the probability that the corresponding region space is occupied. A new technique of using SONAR in combination with a planer laser rangefinder has been introduced which reduces specular reflection and thus helps in exact mapping of a region. At the time of exploration each robot has its own global evidence grid and at the frontier the robot sweeps its sensor and constructs a local evidence grid which is integrated with the robot's global grid and further through suitable communication medium broadcasted to other robots.

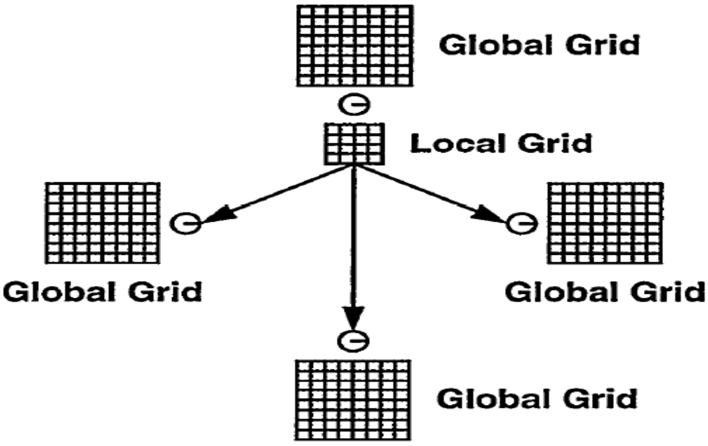


Fig. 4: Local and Global grid of a robot.

The log odd probability is used to sum up the each pair of corresponding cell and the same is stored in the corresponding cell of new grid as can be shown in fig.4. This approach has the advantage of being both cooperative and decentralized. Any robot goes through two states during exploration- one is exploration state in which the robot explores the area from a particular frontier, and the other in which the robots move to another consecutive frontier for further exploration often termed as walking state. The particle swarm optimisation (PSO) basically targets on how to reduce the time consumed during walking state so that total exploration time can be optimised. The optimisation refers to the finding of a minimum value or a maximum value. Minimization task is defined as

Given $f: R^n \rightarrow R$
Then find $R^n$ such that $f(z^\wedge) \leq f(z)$ for all $zR^n$

And similarly a maximization task is defined as

Given $f: R^n \rightarrow R$
Then find $\hat{z} \epsilon R^n$ such that $f(\hat{z}) \geq f(z)$ for all $z \epsilon R^n$

Here $R^n$ is called candidate solution.
$\hat{z}$ is optimal solution and n denotes number of dimension of search space.
Following three steps are repeated in PSO according to author until stopping condition is met:

1. Fitness of each particle is evaluated.
2. Individual as well as global best fitness and position is updated.
3. Further updating of velocity and position of each particle is done.

The velocity and position updating is basically key constraint of optimization ability of PSO, and to update the velocity according to situation available in following equation is used:

$$v_i(t+1)= wv_i(t)+c_1r_1[\hat{z}_i(t)-z_i(t)]+ c_2r_2[g(t)-z_i(t)]$$

Where,
I= index of particle & $v_i(t)$ is velocity of particle i at time t
$z_i(t)$ = speed of particle i at time t, and the parameters w, $c_1$, and $c_2$ are user supplied coefficients & the random value regenerated for each velocity update id denoted by $r_1$ and $r_2$.
Further there are three components in this equation
1st: $wv_i(t)$ called inertia component which is responsible for movement of particle in same direction in which it was moving.
2nd: $c_1r_1[\hat{z}_i(t)-z_i(t)]$ referred to as cognitive component and acts as particle memory.
3rd: $c_2r_2[g(t)-z_i(t)]$ is termed as social component causing the particle to move to the best region the swarm has found so far.
After the calculation of velocity , the position of particle is calculated by applying new velocity to the particle's previous position:

$$z_i(t+1)=z_i(t)+v_i(t+1)$$

Where $z_i(t+1)$ as show new position after updating by velocity $v_i(t+1)$.Robots update their position after each iteration with time.

### *D. Multi-Robot Area Exploration With Limited Range Communications*

This algorithm describes, how the different robots decide which robot is best suited for exploring the same area. The answer to this question will indirectly reduce our exploration time and hence the ambiguity in any exploration related to task operation of each robot will be substantially reduced. A special technique called as bidding algorithm[12], is used which uses the concept of bidding based on different parameters and based on the result, it is decided that which robot among all available robots will transverse the area. Here the authors have considered a special case in which the range of communication for each robot is limited. This model basically focuses on how to accommodate the limited range communication to complete the mission without any substantial performance downgrade. The author further takes into consideration, previous works where an adaptation of central agent or group leader for selection of the robot that actually traverses an area having multiple options. But by doing so the negotiation protocol become complicated and the load on different robots is unbalanced. During the exploration each cell of the grid has either occupied (cell is occupied by obstacles), or free (no obstacle exists) or unknown (cell has not been detected by any robot's range sensor) state. It has been considered that when the robot is travelling, it will not carry out sensing and mapping. A measurement parameter termed as nearness parameter (how near a robot is from that point) has been defined by Author to characterize its communication capability.

$$\lambda_i = e^{-d1/rc} + \alpha\, e^{-d2/rc} + \ldots\ldots\ldots\ldots\ldots + \alpha^{nk-2}\, e^{dnk-1/rc}$$

Here,

$\lambda_i$= Nearness measure of $i^{th}$ robot

d1, d2,....dn= Distance between the $i^{th}$ robot to other robots.

$r_c$= communication range.

$\alpha$= positive fading factor, which is always smaller then 1

$r_a$= sensing range

As can be illustrated from the diagram (fig 5), the robot no. 6 has least nearness measure because its distance to other robots are more than the communication range $r_c$. It is further worth mentioning over here is that, in order to calculate the nearness measure $\lambda_i$ of the robot at each frontier cell i, the travel distance from that cell to each other robot's current or target position is calculated.

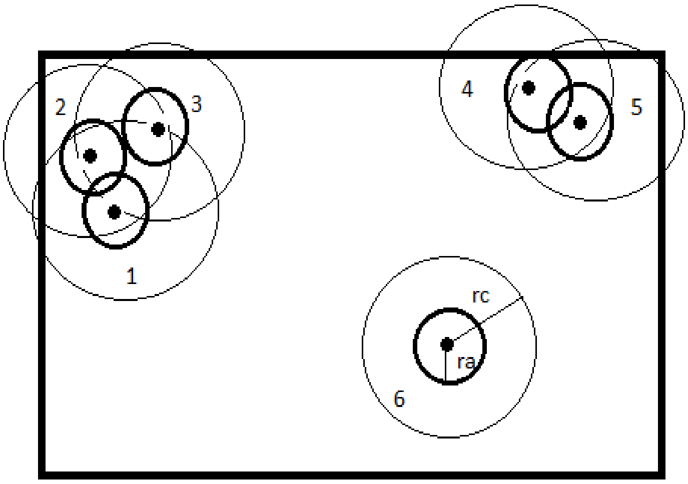


Fig. 5. Robot 6 has least nearness measure.

The second parameter discussed is Information gain($I_i$). The information gain $I_i$ for the specific frontier cell i is the number of unknown cells within the sensor range of one specific robot and not any other robot. The third parameter is shortest distance. The robot calculates shortest distance $D_i$ to each frontier cell i. Due to existence of obstacles and unknown areas, the shortest distance may not be straight line distance. Based on these three parameters, the net gain $g_i$ for frontier cell i is the weight combination of three measure given by:

$$g_i = w_1 I_i - w_2 D_i + w_3 \lambda_i$$

Where $w_1$, $w_2$, $w_3$ are the positive weights. By changing the specific weights, the importance of each component can be varied. The bid B of a biding robot is the maximum net gain of all the frontier cells i.e.

$$B = \max g_i$$

After the calculation of bid value B, it is broadcasted to other robots within the same subnetwork and the robot waits for a constant bidding time $t_{bid}$ to hear the response of others. This robot will win the bidding only when no other robot either participate or not provide better bid in current bidding session. While in second situation if one or more robots after completion of their mapping and sensing send new map, the robot will recalculate the bid value B and apply the procedure again to identify the winner.

### *E. Multi-Robot Topological Exploration Using Olfactory Cues*

This paper discusses how to generate an efficient method or a strategic approach for finding a point of location of odour source. An example may also include the case of fire in a building. The autonomous robots are used, as in such cases, visibility is reduced and noise from fire may create problem in communication. It has been proposed that the robots are equipped with sensors for measuring the odour intensity and air flow direction with the help of these sensors, all the odour sources are localized and the whole area is explored to generate a topological map. The paper basically concentrates on two important constraints among which one is correcting the uncertainty in localization of each robot while the second is merging of maps explored by individual robot with each other [9].

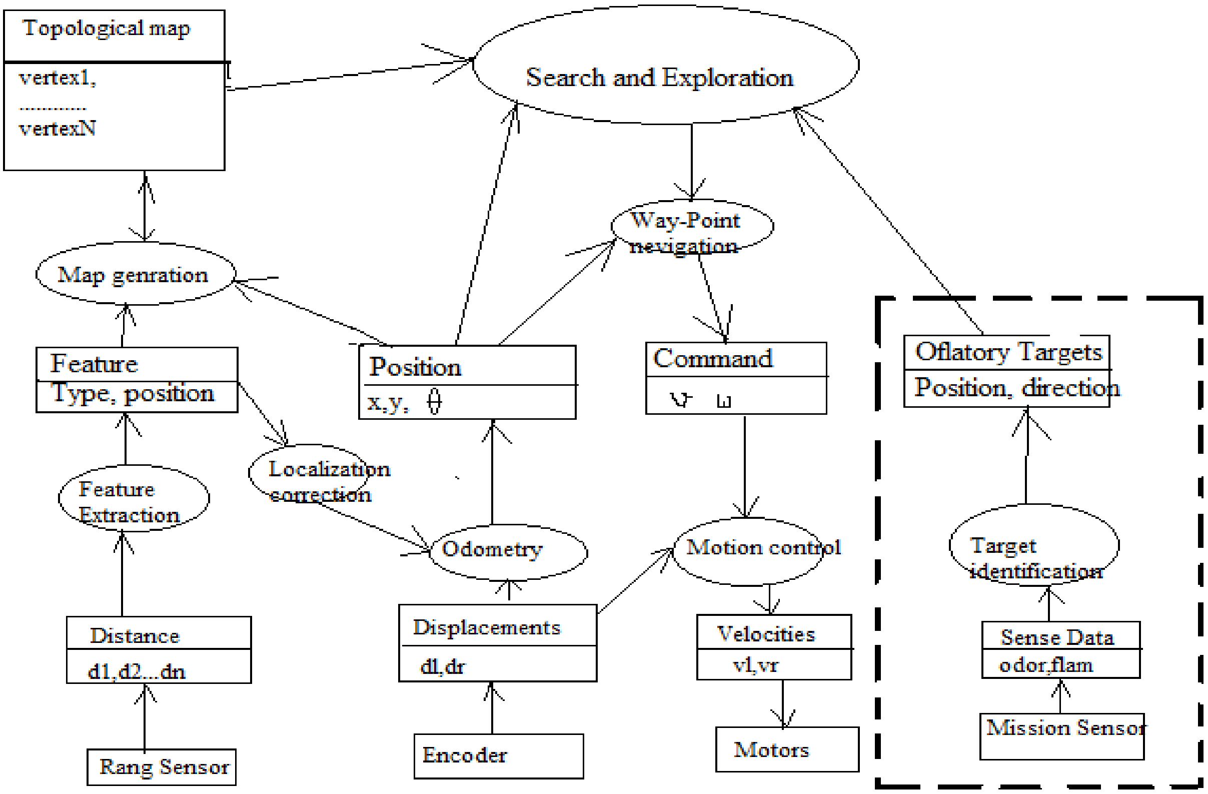


Fig.6 Architecture of odour intensity based exploration

As shown in fig.6. The last dotted block is an addition in exploration of a task using an odour sensor. Each robot will generate its own topological map and transmit it to others, after which it will measure the odour concentration at that place. If the odour concentration is more than a certain concentration threshold, it will indicate that the robot is in the zone of odour source and it should go to the direction of wind to localize that. In case of the travelling in explored area for frontier selection two parameters are kept in consideration- the cost of reaching there and utility it can provide to exploration. Cost is (as told by author) proportional to the distance that the robot has to pass to reach at frontier and given by:

$$\text{Cost}=\text{dist}(A^*_{i=0,n}[(X_R,Y_R),(X_{fi},Y_{fi})])$$

Where $(X_R,Y_R)$ is "position of robot"
$(X_{fi},Y_{fi})$ is "position of the frontier i"
N is "number of frontiers"

While the utility depends on level of odour concentration'

$$\text{Utility (i)=Odour\_concentration(i)} \quad \forall i \in \{1..n\}.$$

The use of this procedure will make the robots disperse and explore the environment in an efficient way. The other constraint is map merging which will give an overall view of unknown terrain and the area explored by each robot can be efficiently used.

During critical conditions, as explained earlier in case of fire, this method can be helpful in finding which area should be explored first to minimise the damage. It is a fruitful approach in practical scenario of this level.

### *F. Genetic algorithm for task completion time minimisation for multi-robot sensor based coverage.*

Genetic algorithm utilizes the Darwinian and Mendelian principles of genetic evolution which basically focuses on how to combine two chromosomes (patterns of exploration) to find out a more enhanced way of doing exploration. Coverage algorithms results in sharp turns and for which robots slow down turn and then accelerate. So the actual travel time of a mobile robot depends on travelled distance and number of turns both. Here the method of reducing these turns (sharp in some cases) has been introduced. The author emphasizes on Back Tracking Spiral Algorithm (BSA) and proposed the utilization of the rectilinear moves represented by eight neighbour disk prioritization patterns. He illustrated following major steps which comprises the algorithm:

1. Generate initial population.
2. Evaluation and selection.
3. Crossover operator.
4. Mutation operator

The author proposed that the whole area should be divided into small circles having radius equal to the radius of sensing range of robot and the movement of the robot will be based on the priority of each cell which is decided by different prioritization patterns(PP), some of the patterns are shown in fig.7.

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 13 | | | |
| | | 24 | 5 | 14 | | |
| | 23 | 12 | 1 | 6 | 15 | |
| 22 | 11 | 4 | P1 | 2 | 7 | 16 |
| | 21 | 10 | 3 | 8 | 17 | |
| | | 20 | 9 | 18 | | |
| | | | 19 | | | |

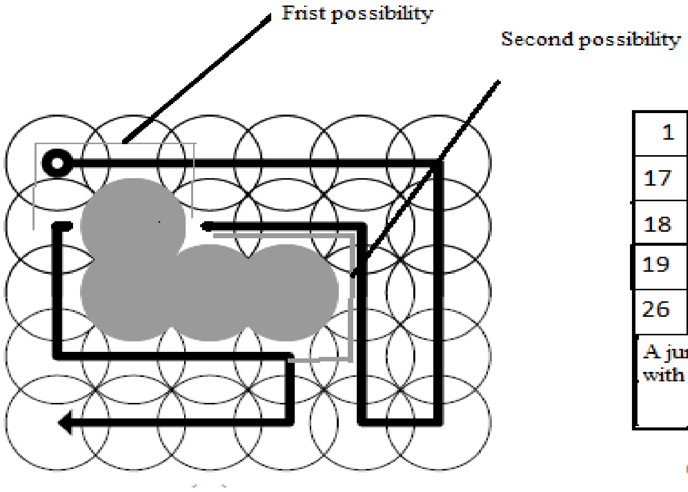
| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 19 | | | |
| | | 20 | 9 | 18 | | |
| | 21 | 10 | 3 | 8 | 17 | |
| 22 | 11 | 4 | P2 | 2 | 7 | 16 |
| | 23 | 12 | 1 | 6 | 15 | |
| | | 24 | 5 | 14 | | |
| | | | 13 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 13 | | | |
| | | 14 | 5 | 24 | | |
| | 15 | 6 | 1 | 12 | 23 | |
| 16 | 7 | 2 | P3 | 4 | 11 | 22 |
| | 17 | 8 | 3 | 10 | 21 | |
| | | 18 | 9 | 20 | | |
| | | | 19 | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 19 | | | |
| | | 18 | 9 | 20 | | |
| | 17 | 8 | 3 | 10 | 21 | |
| 16 | 7 | 2 | P4 | 4 | 11 | 22 |
| | 15 | 6 | 1 | 12 | 23 | |
| | | 14 | 5 | 24 | | |
| | | | 13 | | | |

Fig.7 Neighbour-disk prioritization patterns

Based on the priorities assigned in above patterns, the movements of robots are decided. Now let us assume a practical example as illustrated in fig.7.



(a)

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 17 | xx | 16 | 15 | 14 | 7 |
| 18 | xx | xx | xx | 13 | 8 |
| 19 | 20 | 21 | 22 | 12 | 9 |
| 26 | 25 | 24 | 23 | 11 | 10 |
| A jump from 16 to 17 occurs with three double-visited disks | | | | | |

(b)

| Chromosome.1 | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gens | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
| Neighbo-ur | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 1 | 1 | 1 | 4 | 4 | 11 | 3 | 3 | 2 | 2 | 2 | 3 | 4 | 4 | 4 |

(c)

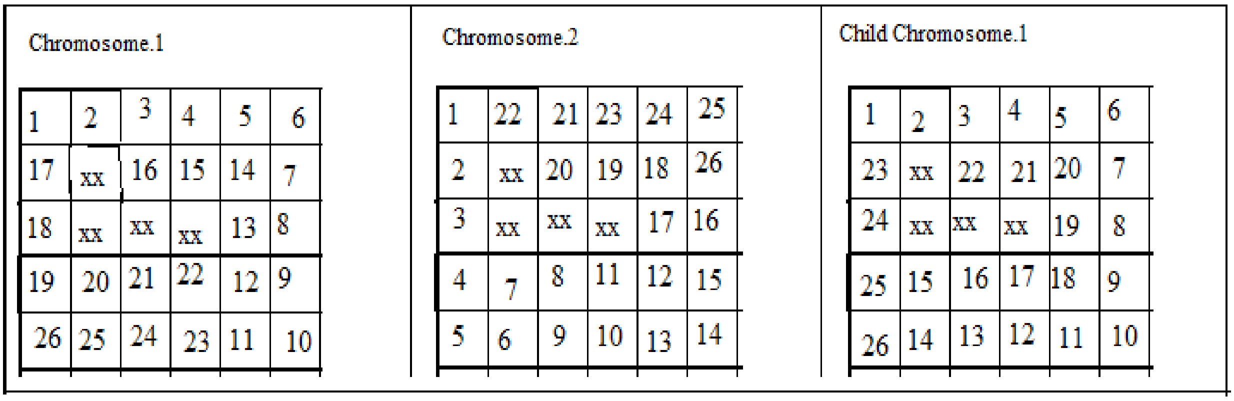
Fig.8 (a) sample environment (b) Decoded chromosome (c) Genetic representation

Here the whole area has been divided into small circles first and then the traversing starts on the basis of PP (P1 in this case). When a obstacle comes in the path, the robot calculates the shortest distance which it needs to cover to reach at an unexplored circle. Two possibilities have been shown in fig.8 among which the shortest path will be chosen and the robot may travel through a path in which already explored circles may include. Now in second step this methodology is used on the basis of all available PP's i.e. total eight. This is done to find out the shortest path that may differ in each pattern. One complete transverse movement of robot corresponds to one chromosome and each cell to gene. In next step the crossover of these chromosomes are done, for which one is transferred according to other and two chromosomes are intermixed as shown in fig.9.

| Genes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chrom. 1 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 1 | 1 | 1 | 4 | 4 | 11 | 3 | 3 | 2 | 2 | 2 | 3 | 4 | 4 | 4 |
| Chrom. 2 | 1 | 1 | 1 | 1 | 4 | 3 | 4 | 1 | 4 | 3 | 4 | 1 | 4 | 3 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 11 | 4 | 4 | 1 |
| Conv. chrom. 2 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 3 | 2 | 2 | 2 | 3 | 2 | 1 | 1 | 4 | 1 | 4 | 4 | 1 | 4 | 7 | 2 | 2 | 3 |
| Mask | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Child.1 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 4 | 2;4 | 3;4 | 2;4 | 1 | 1;2 | 4;2 | 1;2 | 4;1 | 4;1 | 1;4 | 4 | 11 | 2;3 | 2;3 | 3 |

Fig.9 Illustration of the modified parametric crossover for two chromosome with masking probability.

After this step, the mutation is done which drastically changes the behaviour of exploration and reduces the turns as shown in fig. 10.



Chromosome.1

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 17 | xx | 16 | 15 | 14 | 7 |
| 18 | xx | xx | xx | 13 | 8 |
| 19 | 20 | 21 | 22 | 12 | 9 |
| 26 | 25 | 24 | 23 | 11 | 10 |

Chromosome.2

| | | | | | |
|---|---|---|---|---|---|
| 1 | 22 | 21 | 23 | 24 | 25 |
| 2 | xx | 20 | 19 | 18 | 26 |
| 3 | xx | xx | xx | 17 | 16 |
| 4 | 7 | 8 | 11 | 12 | 15 |
| 5 | 6 | 9 | 10 | 13 | 14 |

Child Chromosome.1

| | | | | | |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 23 | xx | 22 | 21 | 20 | 7 |
| 24 | xx | xx | xx | 19 | 8 |
| 25 | 15 | 16 | 17 | 18 | 9 |
| 26 | 14 | 13 | 12 | 11 | 10 |

Fig.10 Path generation based on the crossover of the sample chromosome

## V. SUMMARY OF ALGORITHMS

Summary of all the algorithms is given in table.1.

TABLE.1. COMPARISON OF MULTI-ROBOT AREA EXPLORATION ALGORITHMS

| Year | Author | Technique | Method | Parameter summery |
|---|---|---|---|---|
| 2012 | Flavio Cabrera-Mora | A flooding algorithm for multirobot exploration[1] | Multi-robot Depth first search non cyclic branch | Exploration time reduce up to $2e/K_m \leq t_c \leq 2e$ |
| 2011 | Peter Brass | Multi-robot Tree and Graph Exploration [3] | Multi-robot Depth first search for cyclic Branch with different length | $T_c=1/k(2e+2\sum\mu(e_i))$ $\mu(e_i)$ reduced up to 50% for wide tree and 30% for long tree |
| 2011 | Yiheng Wang,Alei Liang | Frontier-based Multi-Robot Map Exploration Using Particle Swarm Optimization [4] | Grid based technique | Minimization of walking time |
| 2004 | Weihua sheng, Qingyan yangn, song Ci, Ning Xi | Multi-Robot Area Exploration With Limited Range Communications.[12] | bidding algorithm | Reducing traverse distance<br>And avoided collision |
| 2013 | Ali Marjovi and Lino Marques | Multi-robot Topological Exploration Using Olfactory Cues[9] | Finding odour source | Optimum use of finite no of robot for exploration. |
| 2009 | Metin Ozkan, Ahmet Yazici, Muzaffer Kapanoglu, Osman Parlaktuna | Genetic algorithm for task completion time minimisation for multi-robot sensor based coverage.[8] | Back Tracking Spiral Algorithm (BSA) | Minimize traverse distance, Exploration time minimized through reduction of turn. |

## VI. CONCLUSIONS AND FUTURE WORK

The field of exploration has been drastically increased due to use of multi robot which means under most of the situations having unknown terrain, the robots can efficiently transverse the area in an optimum way. Various parameters can be taken into consideration and algorithms have been developed on parametric basis. Some reduces time, while other reduces distance and at the same time some algorithms target on the effective communication. Meanwhile there are algorithms which are especially suitable for extreme conditions like fire or searching of an odour source. Some approaches discuss about combining the two ways of traversing to find the best way. It is concluded that no algorithm has discussed any method to find the exact number of robots required during a particular traversing. If such a method could be developed by which a robot from a node could tell the centralized CPU about the requirement of robots based on the number of edges outgoing from any node then it will not only help to find out exact number of robots but it will also reduce the traversing path (yet to be proven). Further if an algorithm is capable of focussing maximum number of parameters (among available five) could be developed.

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