Multi-Robot Exploration with Communication Requirement to a Moving Base Station

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***Abstract*— Exploration is a core and important robotics area, whose applications include search and rescue robotics, planetary exploration etc. We know that this exploration task is best performed when using a multi-robot system. In this paper, we present an algorithm for multi-robot exploration of an unknown environment, taking into account the communication constraints between the robots. The aim of the robots is to explore the whole map as a pack, without losing communication throughout. The key task for us here is to allocate the target points for multiple robots so as to maximize the area explored and minimize the time and plan paths for the robots in such a way so as to avoid obstacles. A multi-robot exploration methodology is introduced similar to depth first strategy, that samples frontier points based on a metric function. This function aims to maximize the visibility gain or information gain while minimizing the distance to be travelled to the frontier points, such that the robots are within the limited communication distance of each other. The algorithm has been tested through simulation runs of various maps and results and evaluations have been presented based on it. The results effectively demonstrate that our algorithm allows robot pack to quickly accomplish the task of exploration and without the constraint ever breaking down. Here, we also present a comparative analysis of our algorithm with another exploration approach, which finds new areas based on population generation and utility calculation over the population. The results show tangible performance gain of this method over previous methods reported on exploration with limited communication constraints.**

I. INTRODUCTION

A. Motivation

Mobile Robotics is an important research area in the field of robotics. Over the years, lot of research has been done in the context of multi-robot exploration. Some of the major real world applications include search and rescue, like military actions, lunar and planetary exploration, deep ocean exploration, underground mining etc. Co-ordination among multiple robots is an important factor in achieving efficiency, robustness and reliability during exploration of an unknown environment. For the purpose of improving efficiency, it is required to minimize the overall time and distance covered by the robot. In the past, most of the strategies or approaches have focused on coordination issues, efficiency of the metric or exploration, without bringing any communication constraint between the robots. Later on, algorithms have also taken into consideration the communication constraint during multi-robot exploration using a fixed base station, where every robot tends to be in communication with a fixed robot directly or indirectly. In this paper, we extend the frontier based exploration approach where the robots move as a robot pack, and can always communicate with each other. The advantage of this algorithm over that of fixed base station is that the robots can explore the whole unknown map as a pack, and are not restricted in their approach because of the communication constraint with the fixed base station. Also, in this paper, sensing capabilities of the robots have been taken into account, through which the robots are able to explore faster compared to point wise frontier based approach. This paper builds on the work done in [1] and [2], which present an approach based on construction of a tree network for multi-robot exploration while maintaining communication constraint throughout with a fix base station.

In the current proposed work, we build on our earlier methodology [1], [2] and extend it to the case of moving base station constraints. The proposed methodology guarantees that the robots always stay in communication with each other. We propose a term called *connection graph* where it is ensured that there always exists an edge connecting every robot to at least one robot. The condition for the existence of edge is mentioned in the later section. Through optimized parametric trajectory generation, it is ensured that communication between the robots is maintained even while transiting from one candidate point to the other. Hence, the current work comes as an alternative approach to [3].

B. Previous Work

Over the past decade, a lot of work has been done in the field of mapping and exploration for single and multi-robot systems. Some of the earliest works in this field have been by [4], which introduced a new approach based on frontiers. [5] lays the foundation for the approach to multi-robot exploration and mapping using the information gain and cost of exploration. [6] presents an approach involving periodic partitions of an unknown map into several disjoint regions, using K-means clustering algorithm. Each robot then separately explores the given region. [7] proposes a distributed bidding algorithm for multiple robots. The algorithm takes information gain, travel distance and nearness measure and limited range communication into account. Multi-objective

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optimization strategy to help in determination of next best observation position during exploration has been presented in [8], whereas [9] presents an exploration strategy based on social potential field and market based approach. Extending [8], [10] shows how choosing next best observation point strategy can be merged with planning collision-free path. Further, [11] has proposed an exploration strategy where robots acts as explorers or relays and transfer information to a command centre. [12] addresses the global uncertainty regarding the robot's relative start locations. This approach also helps in estimating the probability of an overlap between the maps. More recently in our earlier efforts [1] and [2], we have presented multi-robot exploration as a two phase recursive tree propagation.

II. METHODOLOGY

Here we describe our algorithm to explore the given map, consisting of obstacles of any shape.

A. Problem Description

Given a map of *m x n* grid, consisting of obstacles, we need to explore the whole map with the help of *N* robots. Each robot has a sensing range R_s, which helps it to detect obstacles nearby without any physical contact. The robots are initially placed such that they are within communication range R_c of at least one of the robots in the robot pack. Robots have no previous information about the map to be explored. They know only the information available to them through their sensors or through their communication with other robots. Each point in our grid may have one of the following state:

Explored : A point in our map is considered to be explored if it has been seen by a robot.

Unexplored : A point is unexplored, if it has not yet been explored by any of the robots.

Frontier : A point is called frontier if it is at the boundary between the explored and the unexplored area.

Obstacle : If the point is occupied by an obstacle. Robots cannot visit these points in the map.

For simulations we will use a map of 512 x 512 grid cells. It is represented in the form of 2-D environment for the purpose of simulating.

B. Definitions

a) Visibility Gain: Visibility gain *V* is defined as the information gain of the robot, when it takes a complete 360^0 scan of areas around it. It is the fraction of unexplored areas around a point. We use the concept of ray tracing to find the visibility gain.

b) Metric Gain: Metric gain *M* at a point (*x,y*) is defined as the ratio of the Visibility Gain to the distance $d_{x,y}$, a robot has to travel from its current position to that point.

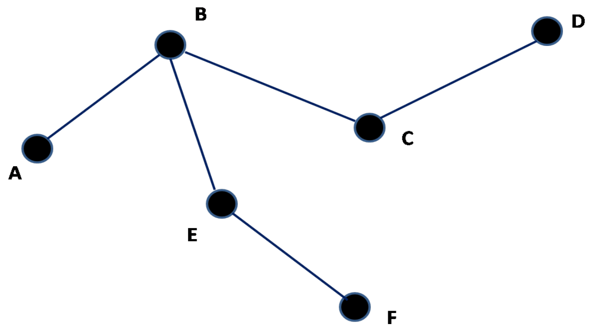


Fig. 1. Connection Graph

c) Connected: A robot *A* is said to be *connected* to another robot *B*, if the euclidean distance between the two robots is less than or equal to the communication range R_c.

d) Connection Graph: A *connection graph* refers to the topology or the layout pattern of the connected robots in a map. Fig. 1 shows a Connection Graph. An edge is said to exist between two robots in a connection graph if they are connected.

C. Algorithm

In our approach, we first find the robot through which we begin our exploration algorithm. For this, starting with the current position of each robot, we calculate the visibility gain for each of them. Among our pack of robots, we then select the robot with the maximum visibility gain. Let's call this robot *A* having coordinates (x_{At}, y_{At}). This process has been represented in Algorithm 1. Then the next instant candidate point for robot *A*, that is ($x_{A(t+1)}$,$y_{A(t+1)}$), is decided to be the point which gives the maximum visibility gain V_A for *A*. For example, consider Fig. 2, it shows how the algorithm works for a pack of 3 robots. Here, we take three robots say *A, B and C*. At any instant their initial coordinates are (x_{At},y_{At}), (x_{Bt},y_{Bt}) and (x_{Ct},y_{Ct}) respectively. The network topology is such that *A* is connected to *B* and *B* is connected to *C*, as shown in the figure. The new position of robot *A* has been represented by A^* ($x_{A(t+1)}$,$y_{A(t+1)}$).

Algorithm 1 Finding the starting robot

```
for each robot do
    calculate visibility gain
end for
find robot with maximum visibility gain value. //Call it A
```

Now, as we have the new position of starting robot, we move forward to find new positions of rest of the robots. Starting with *A*, we traverse the other robots in a depth first pattern.

1) Strategy for finding next instant position for remaining robots: We start with *A*. Let's call it root node. We find all the robots which are inside the communication range R_c of this root node. Among these, we take the first robot which has not been visited. Thus, in our Fig. 2, this robot is *B*. Now, with new position A^* as centre and communication range R_c as radius, we consider a hypothetical circle (as seen in figure) and calculate the metric gain M_B *w.r.t* initial position of B (x_{Bt},y_{Bt}), of all the points on the circumference of this circle. As for a circle of radius say 25, there will be nearly hundreds of points on its circumference and thus, finding metric gain for all the points is a tedious task and mathematically complex. Therefore to simplify, we take points at an angle of 0^0,30^0,60^0...360^0 with the horizontal to the centre. We consider points which are not occupied by obstacles and calculate metric gain of these points. We select the point with the maximum metric gain as the new position ($x_{B(t+1)}$,$y_{B(t+1)}$) for B, represented as B^* in the figure. Now, we take B as our new root node and repeat the whole process. From Fig. 2, we see that B is connected (within communication range) to C. Thus, obtaining the new coordinates ($x_{C(t+1)}$,$y_{C(t+1)}$) of C, represented as C^* in the figure. The lines connecting new coordinates of A^*, B^* and C^* in Fig. 2 depict the new topology after the iteration.

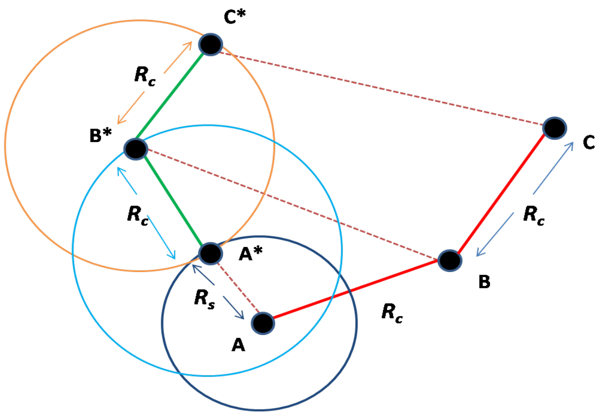


Fig. 2. Movement of Robots

Algorithm 2 DFS(A)

```
for $B$ such that $1 \leq B \leq N$ and $B \neq A$ do
    if $d_{(A,B)} \leq R_c$ and unmarked then
        for each point on the edge of circle with centre as $A$ and radius $R_c$ do
            calculate metric gain w.r.t $B$
        end for
        $NewpositionofB \leftarrow pointwithMax.metricvalue$
        mark $B$
        dfs($B$)
    end if
end for
```

Algorithm 2 illustrates the whole structure as pseudo code. This process is repeated till all the robots in our robot pack are traversed and assigned new locations to move to. We then find the shortest path, avoiding the obstacles, from initial position to new position calculated for all the robots in the robot pack. One thing that must be noted is that all the robots move synchronously from their starting positions to new positions. During the time, when they move, we make sure that the communication constraint within the robot pack is always maintained (shown in later section). The above algorithm from finding the new starting robot, to finding the new position for all robots is repeated till the whole map is explored, that is till there are no unexplored points in the map.

D. Trajectory Generation

Given the connection graph and the current location of the robots as (x_{At},y_{At}), (x_{Bt},y_{Bt}), (x_{Ct},y_{Ct}) and so on, the next instant location($x_{A(t+1)}$,$y_{A(t+1)}$) was calculated in the previous section. In this section, we generate straight line trajectories, between the current and next instant location of the robots, such that they maintain communication even when transiting. Let us first consider a two robot case, with the robots trajectory being parameterized with respect to the time as:

$$\begin{aligned} x_A(t) &= x_{At} + a_A t \\ y_A(t) &= y_{At} + b_A t \\ x_B(t) &= x_{Bt} + a_B t \\ y_B(t) &= y_{Bt} + b_B t \end{aligned} \tag{1}$$

The parameters (a_A, b_A, a_B and b_B) are solved by an optimization framework whose quality constraints are given by:

$$\begin{aligned} x_A(t) &= x_{At} + a_A t = x_{A(t+1)} \\ y_A(t) &= y_{At} + b_A t = y_{A(t+1)} \\ x_B(t) &= x_{Bt} + a_B t = x_{B(t+1)} \\ y_B(t) &= y_{Bt} + b_B t = y_{B(t+1)} \end{aligned} \tag{2}$$

The inequality constraints are responsible for maintaining communication constraints and are given as:

$$\sqrt{(x_A(t) - x_B(t))^2 + (y_A(t) - y_B(t))^2} \leq R_c \tag{3}$$

The objective function of the optimization is taken as:

$$\min u, u = t \tag{4}$$

Solving the optimization given (*2*), (*3*) and (*4*) provides parameters (a_A, b_A), (a_B, b_B) for the two robots such that they maintain communication while transiting from one candidate point to other. The variable t is free.

For systems comprising of n robots, the above optimization approach can be extended with the help of connection graph. To illustrate this, consider Fig. 1 which shows the connection graph at any particular instant.

We chose any robot pair and apply the above optimization framework to get their trajectories. Then with these trajectories as the inputs we get the trajectories for other robots which are in connection with the pair. For example in Fig. 1 we first solve for A and B and then with B

as input, trajectory of robot C is obtained and so on. The initial pair is so chosen that it contains the robot with maximum number of links (robot B in this case). **Note:** For the trajectory generation problem described above for two robots case, if the initial and final coordinates of robots are within communication constraint, then there always exist a velocity profile such that the robots can move from initial to final point without breaking communication. A trivial solution will be when both the robots move from initial to final point with equal velocity.

E. Path Planning

It has been observed that after a certain time, when significant area of the map has been explored, robots are not able to recognize new areas for exploration as they have a limited sensing range and most of the areas around them are explored. We then do path planning of the robots, to explore the unexplored regions of the map. For this, we maintain a list of frontier points, We then calculate the metric gain of all the frontier points *w.r.t* a robot of our choice say X. The point with the maximum metric gain is our required frontier point. This point is the new position of X. Now, new positions of rest of the robots are fixed at a distance equal to communication range R_c from each other in a chain form, so as to cover maximum unexplored regions. The robot pack then explores in the same way as they did before. The path planning methodology is represented in Algorithm 3.

Algorithm 3 Path Planning

```
for each point i belongs to frontier chain do
    calculate metric gain w.r.t robot j=1
end for
$Newpositionofj \leftarrow pointwithMax.metricvalue$
for robot k = j+1 and $1 \leq k \leq N$ do
    for each point on the edge of circle with j as centre and radius $R_c$ do
        calculate metric gain w.r.t k
    end for
    $Newpositionofk \leftarrow pointwithMax.metricvalue$
    $j \leftarrow j + 1$
end for
```

III. RESULTS AND ANALYSIS

We show simulations on Intel Core 2 Duo 64-bit processor running Fedora 15 with kernel version 2.6.40.3 and 2 GB RAM. The graphic interface is through QT. The sensing range R_s has been taken as 20, whereas communication range R_c of 35 units has been considered. Fig. 3 and Fig. 4 depicts a set of images showing the exploration of two different maps. In the figures, the images show how the robot pack explores the map, while avoiding different obstacles.

After running simulations over various different maps (characterized on basis of obstacle configuration such as size and quantity of obstacles), we find that the robot pack explores the whole map, while keeping the communication constraint intact, throughout the exploration. Fig. 5 shows the results for three different values of communication range R_c, that is 30, 35, 40. From the figure, we see that time taken to explore the map decreases with increase in the number of robots in the robot pack. Fig. 6 shows the percentage coverage of area by different number of robots for randomized values of time steps, at a particular communication range. It clearly shows that the area explored increases with increase in time. Also, the robots maintain communication with each other directly or indirectly throughout our exploration, and thus they are able to explore the areas which could not be explored when there was fixed base station constraint. Regarding the selection of first robot that begins the exploration,

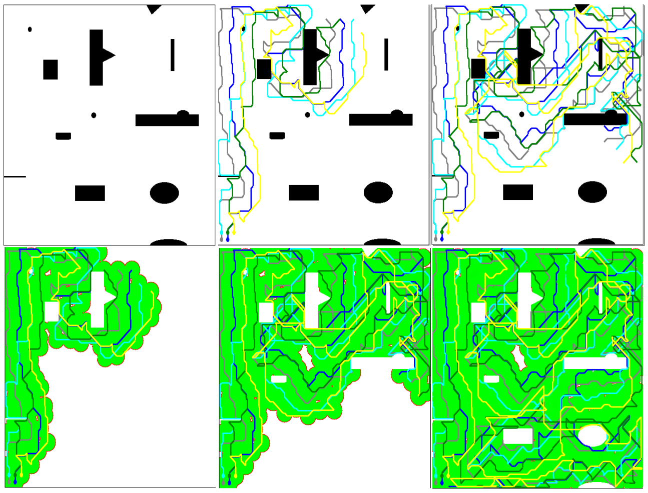


Fig. 3. Exploration process for a map with less number of obstacles, along with construction of the whole map. *Top Left*: Original map to be explored. *Top mid*: Propagation of robots after 35 time steps. *Top Right*: Propagation of robots at a later instant. *Bottom Left*: Map after 35 time steps. *Bottom mid*: Map at a later instant. *Bottom Right*: Map after 90% of the area is explored.

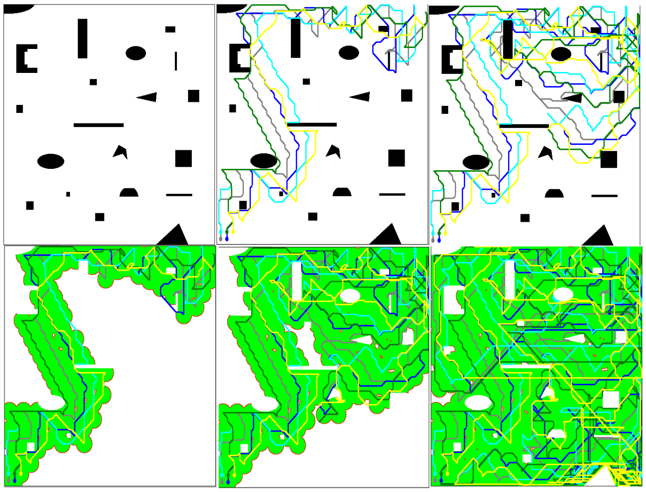


Fig. 4. Exploration process for a map with many obstacles, along with construction of the whole map. *Top Left*: Original map to be explored. *Top mid*: Propagation of robots after 35 time steps. *Top Right*: Propagation of robots at a later instant. *Bottom Left*: Map after 35 time steps. *Bottom mid*: Map at a later instant. *Bottom Right*: Map after 90% of the area is explored.

we find that our strategy based on the maximum visibility gain fairs better against the strategy where we select the robot which has maximum number of connections within the robot pack. Our approach tries to place the robots in positions where it can have maximum visibility gain or information gain and minimum distance to move to these points.

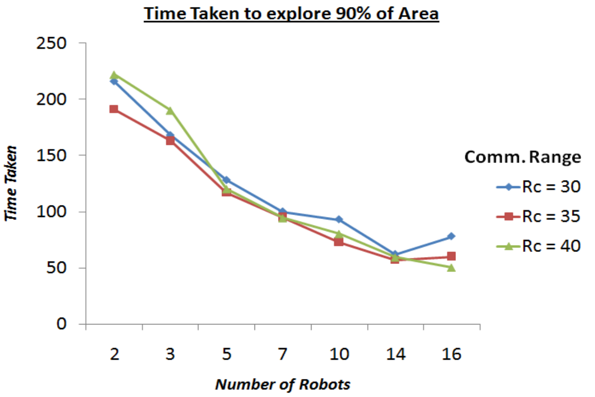


Fig. 5. Time Taken to explore 90% of Area with different number of robots for varying communication range R_c. (Our Approach)

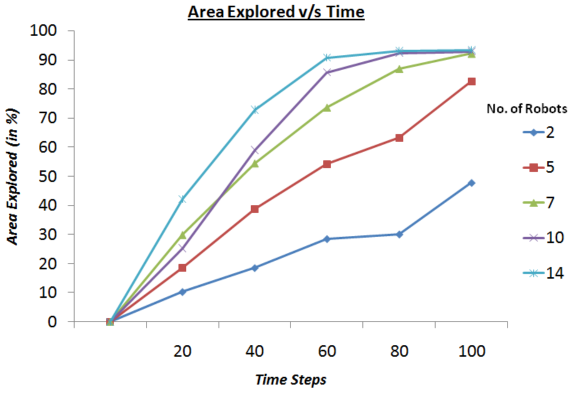
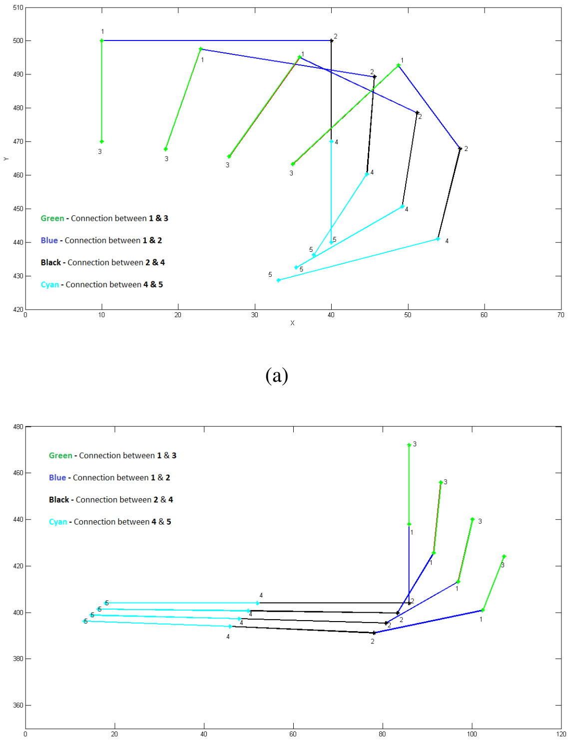


Fig. 6. Area Explored against normalized time steps for 2, 5, 7, 10 and 14 robots. Communication Range = 35. (Our Approach)

The path computation in our algorithm is performed through an optimal planner such as Djkstra's search run over visibility graph. Note that nR_c is the maximum length between one robot and the other, with n as the number of robots and R_c as communication range. Also, during the trajectory generation for the robots, we find that the communication constraint within the robot pack is maintained throughout the propagation, which was not the case in [3] and the robots reach their new locations synchronously. This has been represented in Fig. 7, where each image shows set of intermediate positions of robots and demonstrates how the robot pack progresses during transition from one position to next. The results tabulated (distance between robots) at every instant reinstate the fact that communication constraint of the robot pack is satisfied at all times.



(a)

(b)

Fig. 7. The set of two images represented for two different iterations shows evolution of a pack of five robots. It displays how the robots are connected at various instances during transition. It has been found that communication constraint is satisfied at all times. The number in each figure represents robot number. Communication Range of 35 units is considered. **Note:** The figures show connection of a robot with its nearest robot. In actual, a robot can be connected (within communication range) to more than one robot.

Compared to the approach as in [13], we find that our approach is able to explore the same map faster and also the area explored in a given time is also more. We extended the approach in [13] to include the areas visible within the sensing range and calculated the results. That is the exploration is happening by just seeing the area rather than actually visiting that area. Simulations run on the same maps show that the amount of time taken to explore the whole map using this approach is more than 8,000 time steps for a pack of three robots, which is nearly fifty times more than the time taken using our approach for the same number of robots and keeping other constraints(like R_c,R_s) same. Similar trend was found with different number of robots. Fig. 8 shows the graph of time taken to explore 80% of the map, using this approach by different number of robots for varying communication ranges. Here also, we find that time taken to explore the map decreases with increase in the communication range and increase in the number of robots.

We also find that there are no deadlocks in our algorithm, which was not the case in [13]. In [13], a population is calculated taking a large number of configurations to decide new movement of the robots. Fig. 9 shows clear comparison between the two approaches. The graph shows that the time

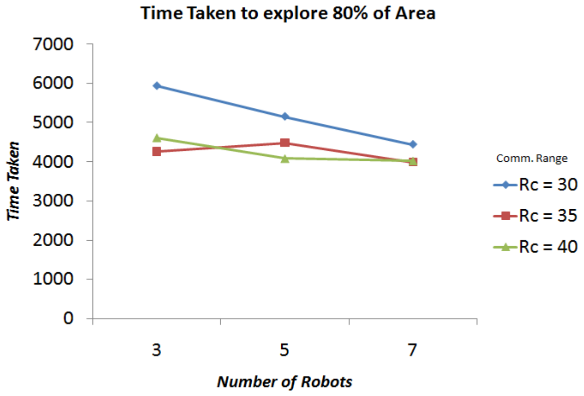


Fig. 8. Time Taken to explore 80% of Area with different number of robots for varying communication range R_c.

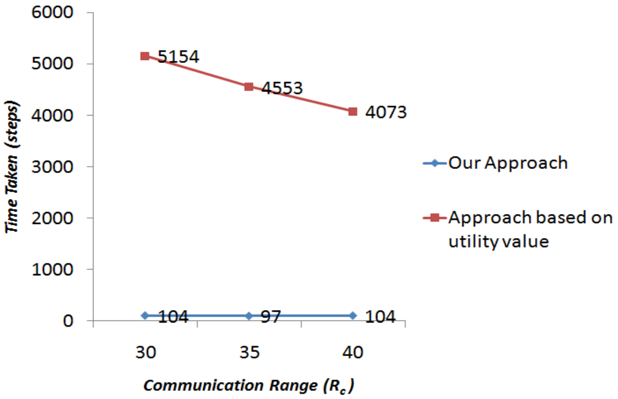


Fig. 9. Comparison Between our approach and the one based on utility value function. It shows the time taken to explore 80% of the map by five robots using both methods for three different values of Communication Range R_c. The other constraints such as Sensing Range R_s, starting positions for robots and map is same in both cases.

taken to explore the same portion of map is several times less when using our approach based on metric calculation than when using an approach where we extend the method in [13] to include the visible areas within sensor range distance.

IV. CONCLUSIONS

A metric based approach for multi-robot exploration was presented, which takes into account the limited communicative constraint of robots. Movement of robots as a pack was decided using a metric function, which considers the visibility gain and distance. In each time step, new position of robots is calculated using the metric function while satisfying the communication criteria of the whole robot pack, throughout the exploration process. The new configuration is selected such as to maximize the visibility of each robot while simultaneously minimizing the distance to move to the new point. The algorithm is able to explore the whole map effectively. We have also discussed the case of path planning of robots to a new frontier location, when the pack of robots is not able to visualize any new unexplored areas. Here, new locations are found so as to maximize the visibility of unexplored areas in the map. Experiments show that performance of our approach scales properly with the range of communication link. The robots are always in communication distance of each other through direct or indirect link. Results were computed of the utility function approach ([3]) which was extended to include sensory visible areas, and compared with our approach. Our algorithm presented significant improvements in exploring the environment as compared to the other approach. The algorithm is so designed as to avoid any deadlock situations as was evident in the utility function approach ([3]). An optimized framework presented in the paper shows that communication constraint is maintained throughout while transiting between two points. It was also observed that communication range should be more than sensing range, so as to avoid overlapping regions visible from different robots.

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