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Sampling-Based Multi-Robot Exploration

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Abstract

This paper presents a new approach for collaborative multi-robot planning issues. The main problem that arises from multi-robot exploration is waiting situations. We consider that such problem involves two or more autonomous robots in an unknown environment. The mission objective is to explore the entire map, while trying to minimize its executing time. Moreover if each robot uses the same topological graph, then it uses the same exploration path that makes waiting situations arising. To solve this problem, we propose a new approach in this paper based on sampling iteratively maps to allow interactive multi-robot exploration. Our approach has been implemented in simulation and the experiments demonstrate that the overall completion time of an exploration task can be significantly reduced by our sampling-based method.

1 Introduction

The problem of exploring an environment is one of the fundamental problems in mobile robotics. We hope it can also cover the whole exploring space more efficiently by implementing this exploration. Therefore, the key issue is how to move the robot in order to minimize the time needed to completely explore an environment [1]. In relation to a single mobile robot, in some cases, using a collaborative team of mobile robots can accomplish the exploration mission better so as to achieve the purpose of reducing the mission time. For example, looking for an object can be achieved more rapidly as each robot of a team can try different scenario simultaneously with other robots. We also believe that cooperative multi-robot systems have more adaptability than classical single ones. Figure 1 shows an example of a three robots system involved in the same map and both robots are dispatched to different destinations. Unless minimizing the global time of the exploration mission, the collaborative exploration can be smarter than a single robot exploration, if the robots communicate with each other about their position information whenever they sense each other, they could localize themselves much easier [2].

In this paper, we consider the problem of exploring an unknown indoor environment with a collaborative team of mobile robots that the mission objective is to explore the entire map but the implementation time should be as short as possible.

In order to achieve this goal, we need to focus on examining the following three questions:

a) How to identify the potential exploration targets for the map.
b) How to assign reasonably the targets calculated in previous question to each individual robot.
c) How to plan the path for multiple robots so as to avoid collision, mutual blocking, and all the other problems of waiting situation.

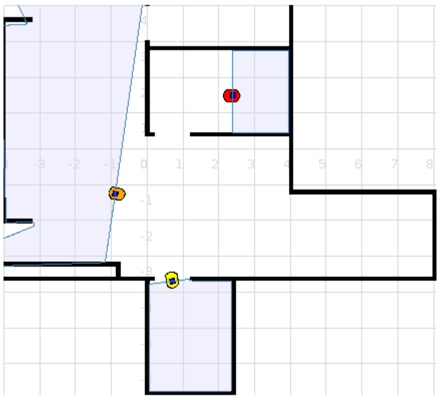

Figure 1 Example of collaborative exploration of multiple mobile robots.

For the first question, the common method is using the space partitioning by Voronoi diagram [4], [8] and [10]. The feature of this method is that, the geometry information of map can be well described by using Voronoi diagram, so it allows planning the obstacle-avoiding path effectively for mobile robots. However, in this case, since each robot uses the same topological graph, i.e. the same exploration path, the waiting situation will reasonably likely to occur. In this paper, we introduce a new approach based on sampling iteratively for multi-robot exploration. The core idea is, we sample on the basis of Voronoi Diagram, aim to build a separate topological graph for each robot, i.e. the different exploration paths, so as to avoid the defects mentioned above, and achieve the purpose of reducing the mission time. Through the simulation experiments with a group of robots and compared with others methods, the result show that the overall exploration time is significantly reduced by our method.

This paper is organized as follows. In Section 2, we state the problem, and discuss briefly some related works. Section 3 presents our approach, i.e. sampling-based multi-robot exploration. Then we present experimental results in Section 4 and a conclusion is given in last Section 5.

2 Related Work

In recent years, the question of the collaborative exploration in unknown environments using a team of mobile robots has increasingly been considered. A strategy frontier-based exploration has been presented by B. Yamauchi [3]. This approach introduced the concept of frontier defined as regions on the boundary between known spaces and unknown spaces. Mobile robots move to the nearest frontier which is the nearest unknown area.

W. Burgard *et al.* [1] presented a probabilistic approach for the coordination of multiple robots which simultaneously takes the costs of reaching a target point and the utility of target points into account.

An approach using the Hungarian method [6] to compute the assignments that determines which robot should move to which target has been presented by Ko *et al.* [5].

L. Wu *et al.* [4] presented an approach for the coordination of multiple robots which based on Voronoi space partitioning. Through experiments, they presented Voronoi-based partitioning performs better than the well-known KMeans-based partitioning.

S. A. Wilmarth *et al.* [7] presented a new method of sampling on the medial axis of the free space in probabilistic roadmap planners. This algorithm is called MAPRM. Configurations are randomly generated, free or in collision, and are retracted onto the medial axis of the free space. Retracted configurations are used to set a graph that traduces untractable free spaces and that adapts itself to grab narrow passages in C_{free}.

An approach using a segmentation of the environment for the collaborative multi-robot exploration has been presented by K. M. Wurm [8] that was designed to distribute the robots to different tasks, that means for authors to different rooms in indoor environment, so as to accomplish the exploration mission as soon as possible. This method of distribution takes the structure of the environment into account and partitions the space into segments. However, this method has only considered one topological graph for each map, especially for corridor space. This will lead to that, for a team of mobile robots, there topological graphs of exploration are partially overlapping. Then waiting situations can appear during exploration (Envisage a situation where several homogeneous robots start to move in the same direction at the same time and the same start line).

Others approaches have been developed with various policies [11], [12] and [13]. For all, the goal is to coordinate as well as possible for exploration tasks with a team of mobile robots.

In this paper, our approach, in contrast, is especially designed to build a separate topological graph for each robot, i.e. the different exploration path, so as to avoid the waiting situation. The main idea is to build simultaneously different graphs, according to each robot situation, priority according to the whole mission achievement.

3 Sampling-Based Multi-Robot Exploration

The key issue for exploration with a group of mobile robots is how to make the robots have better collaboration ability. So an important reference criterion for evaluation of effectiveness of collaboration is the time needed to cover the whole environment with the robot's sensors, i.e. the time to accomplish the overall exploration task. In this paper, our focus is, on the one hand, the exploration paths of the individual robots in the team, on the other hand, the strategy for distribution of exploration targets.

3.1 Waiting Situation

An important reason for limiting the effectiveness of multi-robot collaboration is the waiting situation. The root cause is that all robots might wholly or partly follow the same exploration path. Figure 2 depicts two types of waiting situation. The left half part of the figure shows a waiting situation when four robots move simultaneously to the same C_{free}, and the right half part shows the same problem when four robots pass to the same C_{free} in proper sequence. Figure 3 shows the two C_{free} to pass for the four robots.

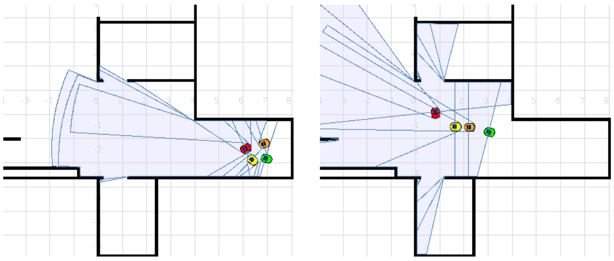

Figure 2 Two types of waiting situation.

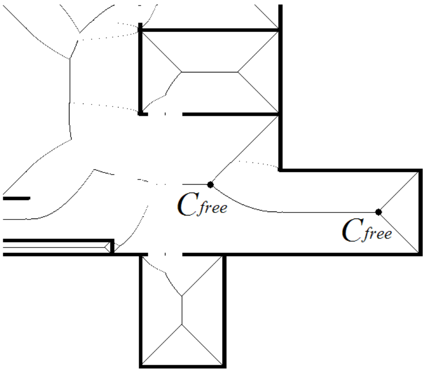

Figure 3 Two C_{free} to pass for robots.

An effective way to solve this problem, i.e. the waiting situation, is to build for each robot the different exploration path as different as possible, i.e. the overlap in topological graph for each robot as little as possible.

3.2 Sampling-Based

The sampling-based approach has dominated the research in recent years and has been applied in fields both in and out of robotics, such as automobile assembly, humanoid robot planning, and conformational analysis in drug design [9]. Although the completeness guarantees are weaker, this approach has been applied to a wide variety of robot motion planning problems [7], [14] and [15], because of his efficiency and ease of implementation.

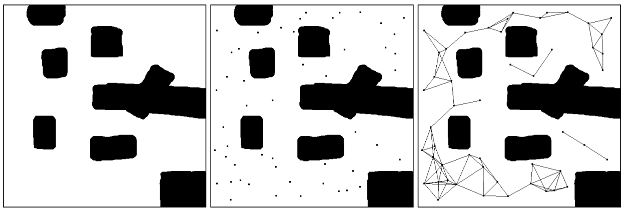

Figure 4 Generation of the Probabilistic Roadmap based on sampling approach.

The main philosophy of sampling-based approach is to avoid the explicit construction of C_{obs}. There is a large number of possible variant of sampling-based algorithm. Figure 4 illustrates the process of generating a Probabilistic Roadmap based on sampling approach for an example occupancy grid map. The left illustration shows a configuration space in which we will build a Probabilistic Roadmap, the center illustration depicts the random points in C_{free}, and the roadmap constructed by connecting nearby samples can be seen in the right illustration. With the right illustration, we can build the exploration path for mobile robot by connecting the nearest C_{free} in the roadmap.

Our algorithm [19] is designed to compute the medial axis of the free space by random sampling, and is given in Algorithm 1.

Algorithm 1 Probabilistic Medial Axis Sampling

```
$T \leftarrow$ empty;
while $T$ is not efficient
    $q_0 \leftarrow$ random in $C_{free}$;
    $q_1 \leftarrow$ nearest ($q_0$, $\delta$) in $C_{obs}$;
    $q_2 \leftarrow 2 * q_0 - q_1$;
    while $q_2$ in $C$ and $q_2$ in $C_{free}$
        $q_0 \leftarrow (q_0 + q_2) / 2$;
        $q_2 \leftarrow 2 * q_0 - q_1$;
    end while
    if $q_2$ in $C_{obs}$
        $T \leftarrow$ add($q_0$);
    end if
end while
return $T$;
```

T is defined as the graph that tries to represent as well as possible the median axis. It is based on the sampling of C_{free} and computing the approximation of the clearance between obstacles. For each random configuration, a near configuration of C_{obs} is chosen with a precision of δ. When this first configuration is defined, a last configuration is set to fix the first random at the center of the two last. While the last configuration is free, the last is pushed far from the others and the random configuration is replaced in their center. It produces self adaptive medial axis synthesis, fitted to the clearance of each local free space.

Our experiments proved that, with our sampling-based algorithm, we can effectively build a separate topological graph for each individual robot of the team.

3.3 Target assignment

In indoor environment, there are three types of structure in general, room, doorway and corridor. We consider each room like a potential exploration target. So the distribution of target means that the assignment of room to individual robots.

H.W. Kuhn [6] presented the Hungarian method for the assignment problem in 1955. It is a classical algorithm for solver the maximum matching problem in a bipartite graph. In our research, we use this method to find the best distribution of exploration target to robots. The implementation can be summarized as follows:

a) Construct a cost matrix $n \times n$, n corresponds with the count of robots. The entry in matrix corresponds with the exploration path length from robot's current position to exploration target.
b) Apply the Hungarian method on the cost matrix to find the maximum matching.
c) In terms of the above maximum matching obtain, assign the individual robots to exploration targets.

With this method, each exploration target will not be assigned to the same robot unless the count of robot is more than the count of unexplored target. In that case, we clone the target in accordance with the count of robots.

3.4 Planning

In our approach, we assign the room like a potential exploration target to different robots by taking into account both the critical points of DVG and C_{free} based on sampling. When all room is explored signifies that the overall exploration mission has been completed.

```
Algorithm 2 Sampling-Based Exploration Planning
1: Build an exploration path for one robot with DVG.
2: Build the separate exploration paths for the other robots with sampling-based algorithm.
3: while all target rooms not yet explored do
4:     Assign the target rooms to each robot using the Hungarian method.
5: end while
```

Our planning algorithm is summarized in Algorithm 2. First of all, in a configuration space, we use DVG to build an exploration path for one robot, and we find the so-called critical points [8], [16], so as indentify room, doorway and especially corridor. Second, we sample in corridor based on DVG by taking into account the critical points. After sampling, so we can build a separate topological graph for each individual robot. Then we use the Hungarian method to assign the individual robots to potential exploration targets. During the explorations, we apply dynamic planning to robots by taking into account both the critical points of DVG and C_{free} based on sampling.

4 Experimental Results

Our approach described has been implemented in a 2.5D multiple-robot simulator called Stage [17] which is a part of the Open-source software the Player Project. The simulation experiments were conducted using the Activmedia Robotics PIONEER 2 DX robot equipped with a laser range finder with 180 degrees field of view. And all our experiments were carried out on the notebook Compaq nx6125.

In our experiments, we have studied three types of skeletonizations, Voronoi diagram, straight skeleton (by library CGAL [18]), sampling-based graph, to extract information from the map. For this two first, skeleton have to be transformed to a topological graph for each robot that allows target locations assignment to each autonomous robot using the Hungarian method. To decentralize this last phase, we have tried to assign target locations to the individual robots using iteratively the Hungarian method at each step of each robot in the topological map. This additional phase decreases mission time needed and produces plans where each robot is following individually its plan to full-fill the mission.

Figure 5 and Figure 6 show two experimental maps used for the simulation. The left part show the map extracted by Voronoi diagram. The center part show the geometry information generated by straight skeleton, the red lines depict the free path which mobile robots can follow to reach the target rooms. And the right part shows the result by using our sampling-based method. Notice that we sample just for corridor, our experimental results prove that it is sufficient for solving the waiting situation for multiple robot exploration.

After identify these two experimental maps, we have tested with several robots by using different methods. The average mapping times and average planning time for all approaches corresponding to two occupancy grid maps and three or four different counts of robots are displayed in table 1, table 2 and table 3.

		Map A	Map B
Nodes		24	34
Links		23	33
Mapping time		< 1s	< 1s
Planning time	1 robot	200.0s	410.0s
	2 robots	130.2s (1.662)	267.5s (1.104)
	3 robots	102.0s (1.789)	193.5s (1.225)
	4 robots	98.6s (1.910)	151.0s (1.400)

Table 1 Voronoi Diagram

Table 1 given the results by using Voronoi diagram. The waiting situation does not exist in a signal robot. However, from two robots, the waiting problem appears. The robots have to pass C_{free} one by one because of the same exploration path.

		Map A	Map B
Nodes		21	32
Links		20	31
Mapping time		< 1s	< 1s
Planning time	1 robot	201.0s	398.0s
	2 robots	128.6s (1.496)	262.1s (1.101)
	3 robots	97.3s (1.552)	191.7s (1.134)
	4 robots	92.2s (1.661)	148.4s (1.281)

Table 2 Straight Skeleton

Table 2 given the results by using straight skeleton. The same problem like table 1, i.e. waiting situation.

Table 3 given the results by using sampling-based method. We can find that, although the mapping time required has been increased, the completion time of an exploration task has been significantly reduced by our method.

Each time is an average time computed over 10 executions. When using more than 1 robot, each executing time is followed by its standard deviation. Over all tables, the standard deviation is less than 2sec when average times vary between 100sec and 400sec.

		Nodes	Links	M. time	P. time
Map A	2 rob.	9	8	2.1s (0.700)	126.5s (0.500)
	3 rob.	18	17	4.3s (0.640)	95.2s (0.749)
	4 rob.	27	26	6.2s (0.748)	90.1s (0.831)
Map B	2 rob.	7	6	1.8s (0.600)	243.3s (0.632)
	3 rob.	14	13	3.6s (0.663)	146.7s (0.830)
	4 rob.	21	20	5.1s (0.700)	133.1s (0.900)

Table 3 Sampling-Based Method

In brief, first of all, the three tables show that, in contrast a single robot, a collaborative robots team can implement the exploration more efficiently, i.e. the time required to accomplish overall exploration task has been reduced. Secondly, by comparing the results of these three methods above, we show that sampling-based is the most effective one to eliminate the problem of waiting time. The reason is by sampling-based, we can build a separate topological graph for each robot, and each topological graph will take the other robots' topological graph into account, so that every robot has its own exploration path, and there will not be any blocks between any two of them. By this means the waiting situation problem will get resolved.

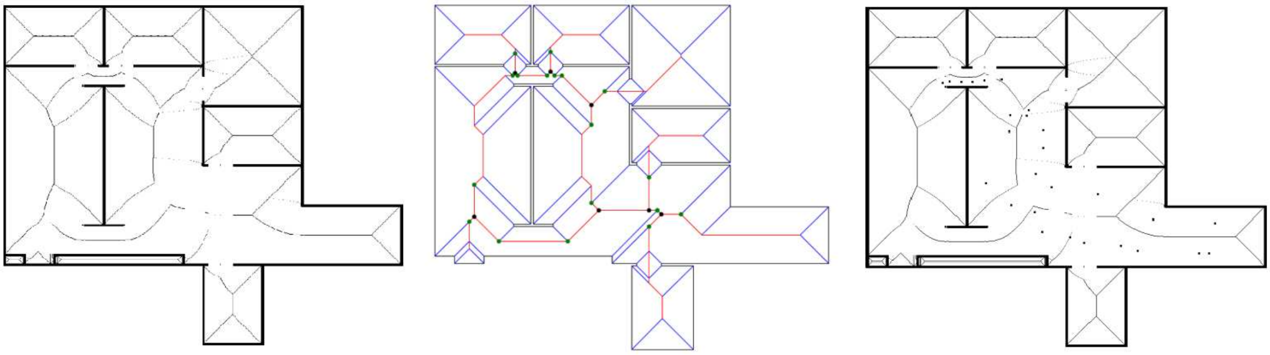

Figure 5 Map A. Left: Voronoi Diagram. Center: Straight Skeleton. Right: Sampling-Based

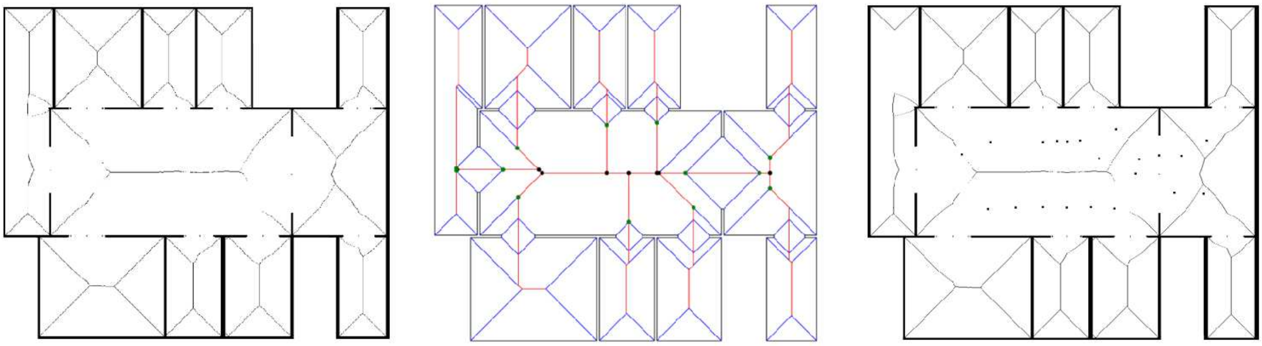

Figure 6 Map B. Left: Voronoi Diagram. Center: Straight Skeleton. Right: Sampling-Based

5 Conclusion

The experiments proved that the time needed to accomplish the exploration mission has been significantly reduced by our sampling-based method which reduces waiting situations possible occurrences. Because, in contrast with only use Voronoi diagram, adding the sampling-based graph that could be computed online, incrementally and synchronized to robot's configurations.

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