New Exploration Strategy for Cooperative Mobile Robots

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Abstract: - In this paper, a frontier-based technique is used with team of cooperating mobile robots to explore unknown environment. The aim is to decrease the exploration time. The exploration algorithm explicitly coordinates the robots. It tries to maximize overall utility by minimizing the potential of overlap in information gain amongst the robots. The proposed frontier-based exploration algorithm is based on a new bidding function in which a special parameter was introduced to decrease the overlap between the robots in addition to the utility and cost parameters. The special parameter depends on the future positions of the robots. The proposed algorithm has been tested with different environments. The new technique led to promising results.

Key-Words: Multi-robot, Coordination, Mapping, Exploration, Autonomous Robot, Simulation.

1 Introduction

This paper introduces the exploring of an unknown space with a team of mobile robots. Robot teams can explore an unknown environment faster than a single robot; however this needs for specific strategies to control these robots as one team to create maps for the environment. This is an essential challenge in mobile robotics. For instance, the robots need to know what areas are worthwhile to explore and how to distribute themselves effectively in order to thoroughly map previously unknown areas [1]. Most previous work in mapping dealt with single robots. There are, however, advantages in mapping with multiple robots [2]. The most obvious is that multiple robots can often do the task in less time.

The key issue in coordinated multi-robot exploration is how to assign target locations to the individual robots such that the overall mission time is minimized. Generally, robots need the environment map to navigate effectively. Therefore, in many mobile robots applications, robots need to explore their environment themselves and arrange their sensory data to get an understandable representation for the environment. The applications may include, search and rescue, hazardous material handling, and devastated area exploration after a disaster.

The use of multi-robot systems has other rewards over single robot systems. Firstly, it increases the redundancy which makes teams of robots more fault-tolerant than only one robot. Moreover, Merging of overlapping information can help compensate for sensor uncertainty. For example, team of robots can localize themselves more precisely than one robot.

Yamauchi et al [3] presented a technique to learn maps with a team of mobile robots. He introduced the concept of frontiers between known and unknown areas in a grid map. Frontier-based exploration can be used to map indoor environments where walls and obstacles may be in arbitrary orientations. In his approach, robots shared perceptual information, however it maintain separate global maps, and make independent decisions about where to explore. This approach groups adjacent cells into frontier regions. Each robot heads for the centered of the closest frontier region, but there is no explicit coordination. As a result, the robots may end up covering the same area and may even physically interfere with one another.

In [1] Simmons et al presented a powerful technique for coordinating multiple, heterogeneous robots in their task of exploring and mapping large, indoor environments. They consider two coordination problems, creating a single global map from the sensor information of the individual robots, and deciding where each robot should go in order to create the map most effectively.

Burgard et al [2] proposed a technique in which the goal was to minimize the overall exploration time. He applied target points for the individual robots so that they simultaneously explore different regions of the environment. He presented an approach for the
coordination of multiple robots, which simultaneously takes into account the cost of reaching a target point and its utility. Whenever a target point is assigned to a specific robot, the utility of the unexplored area visible from this target position is reduced. This means different target locations are assigned to the individual robots.

In Alex et al. [4] increased research interest in systems composed of multiple autonomous mobile robots exhibiting cooperative behaviour. He analyze different topography coverage methods for robots with limited sensing and computational capabilities. More sophisticated techniques for multi-robot exploration are presented in Burgard et al [5]. He presented a statistical algorithm for collaborative mobile robot localization. His approach uses a sample-based version of Markov localization, capable of localizing mobile robots in any time. When teams of robots localize themselves in the same environment, probabilistic methods are employed to synchronize each robot's belief whenever one robot detects another. As a result, the robots localize themselves faster, maintain higher accuracy, and high-cost sensors are amortized across multiple robot platforms.

In all of the above mentioned works, there is no serious solution for the problem of overlap amongst the robots. Moreover, the presented exploration algorithms have not been tested with different environments or with different number or configuration of obstacles. In this paper a new exploration algorithm is proposed, in which the robots work in teams and coordinate their actions. Our idea depends on selecting a frontier target cell to increase the efficiency of the exploration. The proposed technique is an extension of the algorithms described in [2, 6-8]. The new technique tries to decrease the overlap between the robots as much as possible. The new exploration algorithm was tested with different environment sizes, different obstacle distributions and different obstacles numbers. Eventually, we compared the results of our exploration algorithm with the results of one of the known exploration algorithms in the literature. Promising results were obtained.

2 Exploration Method

All of our experiments were conducted using the simulation software – Netlogo [9] which is well known in the literature and employed in many published research works [10-11]. Netlog enables the computer-based investigation of the exploration process by a number of agents in an occupancy-grid-based environment. In Netlog, the environment is simulated as an m-by-n grid of square cells. Each cell has information about itself stored in variables. With Netlog, the same experiment can be repeated and results are stored in an Excel file for further analysis.

The main goal in this paper is to build a map for the unknown environment. The map is an m-by-n grid of square cells, each cell of which is allocated a number to represent its occupancy status. Zero represents that the cell is free and One to represent that the cell is occupied.

Each robot is equipped with a 360° infra red sensor, which can detect the occupancy of its eight neighbors. Also, it can distinguish weather a neighboring cell is occupied by another partner. Each robot knows its own position and the position of its partner and they move between the centers of cells. An equal amount of time (a single step in Netlogo) is required to perform a 360° scan and to move to a neighboring cell. Furthermore, robots send their new sensory data to a shared map which is updated in every step of the simulation. The communication between the robots is on, and error free. Finally, the environment edges are treated as occupied cells.

During the exploration, each cell of the map is assigned one of the states as shown in table 1 which shows the colour code used to identify each state.

<table>
<thead>
<tr>
<th>Patch Displayed Colour</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>Fresh; No Idea Yet</td>
</tr>
<tr>
<td>white</td>
<td>Free</td>
</tr>
<tr>
<td>Black</td>
<td>Occupied</td>
</tr>
</tbody>
</table>

At the beginning of each exploration, all of the cells in the environment map are colored with gray as shown in Fig.1 in which three robots (button) will explore the environment. When a robot visits a cell, all of its free neighboring cells are colored with white by scanning as shown in Fig.2. The exploration process is completed when all the cells are explored (free or occupied) as shown in Fig.3.
3 Cooperating Robots Exploration

A large number of published works in multi-robot exploration depends on the use of “frontier cells” e.g. [1-6]. Frontier cells are the borders between explored and unexplored areas. When a robot is directed to such a cell, it is expected that it will get information about the unexplored area when it arrives. Because a map may contain several unexplored areas, the challenge arises of how to plan the exploration mission by choosing the most appropriate frontier cells. In [1-6] the utility of the target frontier cell is computed. The utility of a target cell is the number of unexplored cells which can be scanned from that target cell. Then the cost of reaching that target cell is computed. The cost is a function of the target cell distance. Finally, the target cell with the maximum $[\text{Utility} - \text{Cost}]$ value wins and the robot starts moving towards its target. This is the general algorithm that guides the exploration in the above mentioned published works.

Apart from the above mentioned two factors – cost and utility, the distance of the other robot from the cell is also considered when computing the bidding value for a frontier cell. This third factor introduces potential benefit of keeping the two robots apart.

The distances in this paper (i.e between two robots, between a robot and a frontier, or between a robot and a target cell for another robot) are calculated according to the flood fill algorithm [12]. It allows us to find the shortest path to a desired point on the map.

Each robot computes the bidding value $B_i$ for each frontier cell in its shared map based on the bidding function represented in equation (1). The relative importance of each term in the formula is adjusted by a weight value.

\[ B_i = W_n N_u + W_p D_p - W_c D_r \]  \hspace{1cm} (1)

where

- $B_i$: The bidding value for the frontier cell $i$ (the target cell).
- $D_r$: The distance from the robot to the target cell.
- $D_p$: The distance from the closest robot (the partner) to the target cell.
- $N_u$: The number of unknown neighbors for the target cell.
$W_n$ (weight neighbors), $W_p$ (weight partner) and $W_c$ (weight cost) are the weight factors for $N_u$, $D_p$ and $D_r$, respectively.

Each robot scans the eight neighbouring cells around it and adds the new information (the scan information) to the shared map which is available to both robots. Then each robot computes the bidding function according to equation (1) for all of its frontier cells in the shared map. Each robot has its own bidding function values for the frontier cells in the shared map, computed from its own point of view. A cell can be a frontier cell to more than a robot. The same cell may yield different bidding value to different robots. Finally, each robot chooses among its frontier cells the one with the maximum bidding function value $\max\{B_i\}$ and starts moving towards it.

The robots explore at the same time, and make their decisions on where to go at the next step based on the same map. Equation (1) shows that we are trying to guide each robot to a cell with a large number of unexplored neighboring cells, far away from its partner, and close to its current position.

4 Experimentation and Results

The experimentation started with a free of obstacles environment of size 33-by-33 cells shown in Fig. 4. The experimentation procedure is as follows:

1- We started with one robot exploration; the time spent to finish the exploration is recorded. The experiment is repeated five times and the average is taken. This process is repeated for two, three, four … eight robots. As before, each experiment is repeated five times and the average of exploration time is recorded. The results are shown in Fig.5.

Figure 5 shows how the exploration time varies with the number of exploring robots. It is clear that as the number of robot increases the time required to finish the exploration decreases. This is due to the fact that robots explore simultaneously, and work in parallel.

2- Same procedure in 1 was repeated with the same environment but with an obstacle introduced inside the environment as shown in Fig.6. The results are shown in Fig.6.

It is clear that Fig.6 is slightly differs from Fig. 5. That means that the introduction of the obstacles has not significantly affected the exploration process.

To enhance our algorithm we adjusted the bidding function represented by equation (1). The adjustment tries aims at further reduction of overlap among robots. Instead of considering the distance of the closest robot in the bidding function, we considered the distance of the closest target cell that has been assigned by any other robot. The new bidding function tries to spread the robots in their environment. It is represented by equation (2).
The main difference between equation (1) and equation (2) is that we have the term $W_pD_p$ (weight and distance of the closest robot) while in equation (2) we have $W_tD_t$ (weight and distance of the target of the closest robot).

3- The procedure in 1 was repeated with the new bidding function in equation (2) and with the environment shown in Fig. 4. The results are shown in Figure 8.

Figure 8 shows how the exploration time varies with the number of exploring robots. As before, as the number of robot increases the time required to finish the exploration decreases. This is due to the fact that robots explore simultaneously, and work in parallel. More importantly, it is clear that considering the target cell reduced the exploration time.

5 Conclusion
We introduce new exploration algorithms to increase the efficiency of the exploration of unknown environment with team of cooperating mobile robots. The core of our algorithms is to reduce the overlap among the robots. Our algorithms were tested with different environments. The comparison with a known exploration algorithm in the literature showed that the time required to explore the environment has been significantly reduced. The main conclusions can be summarized as follows:

1- Our proposed frontier-based exploration algorithm has significantly reduced the exploration.

2- Considering the distance of the closest target cell of the closest robot in the bidding function is better than considering the...
distance of the closest robot and leads to less exploration time.

3- The exploration time slightly vary with introduction of obstacles in the environment. Actually the exploration time increases slightly with the introduction of the obstacles. This is due to the fact that the robots have to wall around the obstacle to explore the area behind them.

4- As the number of exploring robots increases, the exploration time becomes fixed. This appears to be due to the fact that when more robots are used to explore an environment, the overlap will increase and this reduces the effect of big number of robots.

References: