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Leveraging area bounds information for autonomous decentralized multi-robot exploration

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HIGHLIGHTS

- A uniform, decentralized, potential-field based approach to dispersing a team of robots to explore an area quickly.
- Leverages knowledge of the overall bounds of the area to be explored and includes a monotonic coverage factor in the field equations to avoid minima.
- Allows robot team members to become disconnected from and reconnected with the team and ongoing dispersion strategy.
- Introduces performance metrics for team speedup and efficiency in the case of adding members to teams.
- Presents both simulation and experimental robot results.

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ABSTRACT

This paper proposes a simple and uniform, decentralized approach to the problem of dispersing a team of robots to explore an area quickly. The Decentralized Space-Based Potential Field (D-SBPF) algorithm is a potential field approach that leverages knowledge of the overall bounds of the area to be explored. It includes a monotonic coverage factor in the potential field to avoid minima, realistic sensor bounds, and a distributed map exchange protocol.

The D-SBPF approach yields a simple potential field control strategy for all robots but nonetheless has good dispersion and overlap performance in exploring areas with convex geometry while avoiding potential minima. Both simulation and robot experimental results are included as evidence, and performance, speedup and efficiency metrics for each are presented.

1. Introduction

This paper addresses the problem of developing an effective control strategy when multiple robots are deployed to an unknown environment to explore and collect information about the environment. Practical examples of such missions include search and rescue, location of explosive devices, and internal reconnaissance of a structure. In a counter weapons of mass destruction (C-WMD) mission, the robot mission designer may know there is a bomb in the building. In this case, the critical point of the mission is to search as much of the area within the building as possible in the shortest time to locate the WMD so that it can be assessed. In a search and rescue scenario, where there may be injured victims in the building, the critical point of the mission is also to search, in this case to locate victims and assess their condition so as to quickly address their needs. Such missions are time-critical and detailed environment information is not needed, rather a fast, effective scan with the on-board sensors is much more crucial for the mission. It is reasonable to propose that deploying multiple robots will allow the building to be searched more quickly [1]. If multiple robots are being used to increase exploration efficiency, and all areas of the building are considered equally important, then prioritizing dispersion and reducing overlap in scanning are potential strategies to improve performance. However, if members of the team disperse within the building, then it is likely that the communications to a centralized, remote server will be intermittent. In the case of a decentralized approach, it is likely that the team members will lose and regain contact with each other from time to time as they explore. For simplicity and efficiency, it is preferred to have the robots depend and communicate with each other as little as possible, and for the control strategy of the robots to be as uniform as possible.

In prior work [2], we proposed the following as reasonable and useful assumptions to make about the mission: (1) the robot mission designer knows something about the environment, but not ev-

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erything. (E.g., the rough dimension of the building to be searched is known but not the indoor floor map details); and (2) some inter-robot communication is possible, but only a minimum amount of data transfer is preferred. That work did not address the decentralized communication between members of the robot team. In this paper, a decentralized system architecture and map update algorithm is proposed and evaluated using a simple and uniform potential field dispersion and navigation mechanism based on that in [2].

In the next section relevant prior literature is reviewed. Section 3 presents the proposed decentralized map update and navigation control algorithm. It begins with a review of the potential field mechanism proposed and evaluated in [2] as well as the modifications added for the decentralized implementation evaluated in this paper. Section 4 reports a series of evaluation results, where the algorithm is evaluated in simulation using a number of metrics and compared to existing work, as well as the results of implementation on a pair of Pioneer 3-AT robots. Section 5 concludes by summarizing the results and discussing future challenges.

2. Prior work

Burgard et al. [1] introduced a centralized approach to multi-robot exploration that assigns target location goals to team members by locating a robot and frontier point (a point on the boundary of explored and unexplored space) that balances exploration utility and travel cost. Rogers et al. [3] develop a centralized scheme to coordinate frontier-based exploration by large robot teams and investigate which robot coordinate strategies are effective. Decentralized schemes have been introduced by Visser & de Hoog [4] and Chand & Carnegie [5] for heterogeneous teams by assigning different roles to team members.

Potential field methods have been leveraged for robot navigation (e.g., [6–8]) because they offer intuitive and efficient implementations. While primarily used to describe single robot motion (e.g., Arkin [6]), the potential field approach was also used to specify manipulator configurations (e.g., robot manipulators, Khatib [7]; dexterous hands, Lyons [8]). Multirobot exploration offers challenges beyond single robot exploration [1]. More recently potential field approaches have been extended to handle multiple robot exploration (e.g., Arkin and Diaz [9], Lau [10]), formation (e.g., Schneider [11]) and map improvement (e.g., Julia et al. [12]). Our motivation in pursuing a potential field approach is its potential for an intuitive and efficient solution.

Our focus in this paper is addressing the multirobot exploration problem by leveraging a distributed potential-field method. Similar approaches include that of Lau [10], Julia et al. [12], Renzaglia [13], Baxter [14], Cepeda [15] and Popa [16]. Baxter [14] presents a potential field approach in which the field is shared among robots. Cepeda [15] proposed a behavior based approach for multi-robot exploration, but such an approach has difficulty in robot exploration status synchronization. Popa [16] uses potential fields for dispersion of sensor networks, but does not discuss exploration or path-planning. Batalin [17] presents an approach with good dispersion results but which is not as strong on path-planning and searching. Min [18], Mi [19] and Schwager et al. [20] all provided novel topological approaches for dispersion and coverage of multi-robot exploration, and Jensen [21] proposed using wireless signals for the same purpose; however the detailed path-finding strategy is not part of the solutions.

One of the key issues that any potential field method must address is how local minima in the field are handled [22]. These are undesirable locations at which the field sums to zero, resulting in robots being stuck or stalled, delaying or halting exploration. Arkin [6] uses random noise, to eject robots from minima, and spin fields, to move robots along the surface of obstacles, to address minima issues. Julia et al. [12] and Renzaglia [13] use the potential field method for decentralized robot control, and a frontier-based approach for breaking out of potential field minima. Julia et al. [12] represent the space to be explored using an occupancy grid map enhanced so that each cell also represents the degree of exploration of that area. Each cell generates an attractive force on each robot inversely proportional to the amount of exploration of the cell. Furthermore, landmark locations for landmarks not yet precisely enough known generate attractive force. Whenever a local minimum is detected, the robot plans a path to the nearest frontier cell. Renzaglia [13] has two classes of robot: one (follower) which is potential-field driven, and one (leader) which is always planning the path to the frontier. The follower robots are influenced by the explored area and the position of the other robots, whereas the leader robots are uninfluenced by the other robots (and hence local minima). In both schemes, communication and calculation of information shared between the robots, as well as the transition between roles of leader and follower (Renzaglia) or detection of minima (Julia et al.), become crucial and risk failure if any link in this cooperation fails.

The approach proposed in this paper is similar to that of Julia et al. in maintaining an extended occupancy grid with cumulative sensor coverage information per cell, and to Renzaglia's potential field for dispersing follower robots. However, no frontier is maintained, and only one class of robot exists; a substantial simplification. Potential minima will be handled by adding a monotonic coverage factor to the potential field equations of Renzaglia, and by the noise and vortex methodology of Arkin. Furthermore, the exchange of information between robots will be explicitly formalized here in terms of transfer of extended occupancy grids.

In [23] Ozisik et al. described an occupancy-grid based SLAM method, however it was not optimized for multiple robot efficiency. In [24] Birk shows how to merge occupancy grid maps from multiple robots, as does Herath [25]. However they focus on feature-recognition and merging data from multiple robots. Lyons et al. [26] discuss grid-based methods to combine maps so as to avoid transitory readings from other robots. In this paper, the occupancy grid contains information about obstacles sensed and information about exploration coverage. However, no SLAM module will be included; this simplification is made to focus on the coverage, rather than the mapping, issues of the problem.

3. Decentralized navigation

The proposed approach is presented in two components. The first is the decentralized navigation algorithm—which is based on our prior work [2]. The second component is the decentralized communication and map update.

3.1. The space-based potential field approach

The potential field approach [6] has been used previously for directing robot motion toward a goal while avoiding obstacles. A key aspect of the approach, as introduced in our prior work [2], is that the unexplored area needs to act as an attractive goal for robots. The unexplored area is not modeled as a frontier as in [13,12] but rather the unexplored area *itself* exerts an attractive force on all robots. Because we assume we know the overall bounds of the area, we know the maximum area to be explored and can calculate the attractive field. All robots are drawn to the unexplored areas of the map.

The proposed approach represents space by a map divided into multiple grids/cells, where each cell has a *potential level* representing the level of exploration or scanning by each robot's sensors. Initially the potential level for each cell is zero. The effect of a zero potential is to generate an attractive force on all robots. As robot sensors cover an area of the building once or more, the