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Incremental algorithms for Safe and Reachable Frontier Detection for robot exploration

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HIGHLIGHTS

- Incremental algorithms for efficient frontier detection in 2D occupancy grid maps.
- Maintains reachability and mapped free space boundary information separately.
- Reachability is incrementally maintained through a safe-patch graph.
- Boundary cells are efficiently maintained as contours in a modified MX-Quadtree.
- Reachable contours are reported as valid frontiers improving detection accuracy.

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ABSTRACT

Majority of the autonomous robot exploration strategies operate by iteratively extracting the boundary between the mapped open space and unexplored space, *frontiers*, and sending the robot towards the "best" frontier. Traditional approaches process the entire map to retrieve the frontier information at each decision step. This operation however is not scalable to large map sizes and high decision frequencies. In this article, a computationally efficient incremental approach, Safe and Reachable Frontier Detection (SRFD), that processes locally updated map data to generate only the safe and reachable (i.e. valid) frontier information is introduced. This is achieved by solving the two sub-problems of a) incrementally updating a database of boundary contours between mapped-free and unknown cells that are safe for robot and b) incrementally identifying the reachability of the contours in the database. Only the reachable boundary contours are extracted as frontiers. Experimental evaluation on real world data sets validate that the proposed incremental update strategy provides a significant improvement in execution time while maintaining the global accuracy of frontier generation. The low computational footprint of proposed frontier generation approach provides the opportunity for exploration strategies to process frontier information at much higher frequencies which could be used to generate more efficient exploration strategies.

1. Introduction

Autonomous exploration of an unknown environment is a major research problem in robotics. Robotic missions such as autonomous search and rescue [1], planetary mapping [2], underwater mapping [3] require the robot to autonomously map the surrounding unknown environment. During exploration, the robot must sense the environment at a sequence of points until the entire environment is mapped. As planning for the optimal sequence of sensing locations is known to be NP-hard [4,5], all the exploration strategies are reduced to iteratively finding and moving to the next best sensing location. Heuristically, it can be understood that it is best to move the robot towards the boundary between the mapped free space and the unmapped space to expand the map where maps can be represented metrically using grids [6,7] or poly-lines [8,9]. The exploration strategy that generates and evaluates candidate target points based on this heuristic on metric grids is called Frontier Based Exploration [7] and the boundaries identified are called the *frontiers*. This strategy has become the baseline approach for developing exploration missions due to its simplicity and scalability in multi-robot systems.

Frontier based exploration strategy and its many variants have relied on Occupancy Grid Maps [6] to extract the frontier information and have focused mainly on better ways to quantify the desirability of frontier points for robot's next sensing task

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[4,10,11]. Efficient generation and management of frontier information has largely been ignored in the research literature due to the way the frontier information is traditionally being used by exploration strategies. In these strategies, the selection of a frontier point as the next sensing target location is done only when the robot reaches and finishes sensing at currently selected location. Therefore it does not require frequent generation of frontiers, hence efficient generation of frontiers has not been a major consideration.

While frontiers are extracted sporadically, almost all exploration strategies employ continuous sensing/mapping with map updates occurring at a certain frequency or based on the change of motion (e.g. at 1 Hz or update every 0.5 m motion or 0.1 rad rotation) [12,13]. This continuous mapping results in a frequent evolution of frontiers in the occupancy grid map. It is suggested in the literature that making use of these frequently evolving frontier information could lead to more efficient exploration strategies [14–16]. Having access to frequently evolving frontiers allow robots to quickly uncover dead-end situations and traps. It also allows a robot to discover when the target location assigned is fully or substantially explored by another robot due to unintentional crossing of paths during multi-robot missions [15]. These early discoveries of undesirable situations during exploration missions reduce unnecessary motions for robots thus improves the overall efficiency of missions [17]. Therefore frequent extraction of frontier information from the map is vital in developing more efficient exploration strategies. However, the traditional approach of frontier extraction processes the entire occupancy grid map. Processing the entire map at high frequency and regenerating all frontier cells at each step is not scalable with increasing map sizes along missions. While improving the processing capability of robots is a possible solution, it is not applicable for many robots with computing and payload limitations. Therefore development of efficient algorithms for frontier generation is considered in this work.

The work described in this paper proposes to manage and extract frontier information in an efficient and incremental way by processing only the modified sections of the map at each update step. At each update step, the boundary cells between mapped-free and unknown cells that are safe for the robot are updated using a global database of boundary contours. The reachability of the mapped space is also incrementally updated and is then used to retrieve only the safe and reachable boundary contours as frontiers. This approach alleviates the need to process the entire mapped grid space to compute the reachability of frontiers to filter invalid frontiers (i.e. phantom-frontiers) that are generated due to mapping through small openings or due to errors in mapping as depicted in Fig. 1. Thus it provides a complete incremental approach to generating valid frontier cells.

The rest of the article is organized as follows. In Section 2, the traditional frontier extraction approach is summarized and a review of related incremental algorithms is provided. Section 3 provides the basic definitions used throughout the article. Section 4 details the incremental extraction of safe boundary information between mapped-free and unknown grid-cells. Section 5 formalizes the operations to incrementally maintain the reachability of the mapped area by the robot. Section 6.1 details the implementation of the reachability maintenance operations provided in Section 5 and Section 6.2 details the database used to manage the boundary contour information. Section 7 provides details of the experiments and analyzes the results and Section 8 concludes the article.

2. Literature review

2.1. Traditional frontier cell generation

Most of the exploration strategies require frontier information sporadically with long time intervals in between. Therefore these strategies employ trivial processing of the entire map to generate the frontiers. Initial works [7] describe the generation of frontier cells to be analogous to edge detection and region extraction in computer vision. These steps are clearly described and illustrated in Fig. 3 of [18]. Initially the safe regions in the map are extracted. This involves filtering out grid cells classified as *free* that lead to collisions. Various collision checking algorithms can be employed to extract the safe regions. Approximating the robot's footprint to a circle and dilating obstacles using the radius of this circle [19] can be done to identify the unsafe regions that lead to collisions. The free cells that do not intersect the dilated/inflated obstacle cells can be then retrieved as safe. This is a simple and common approach used for retrieving safe cells for mobile robots operating at slow-medium speeds [20]. Next, only the reachable safe-regions need to be considered to extract frontier information. The reachability of safe-cells could be calculated by either a flood-fill operation [21] with robot's position cells as the seed or by using a distance calculation operation from robot's current position, such as Dijkstra's shortest path algorithm [22] or Lee's algorithm [23]. Then, the boundary between the reachable safe-region and unknown regions are extracted. This could be done by convolving the map with a kernel similar to a one used for edge detection in images. The implementation referred to as the *traditional approach* (TRA), throughout this article, uses obstacle inflation to retrieve safe-regions, Lee's algorithm to retrieve reachability information and finally uses a convolving operation to extract the boundary of reachable safe regions as frontiers.

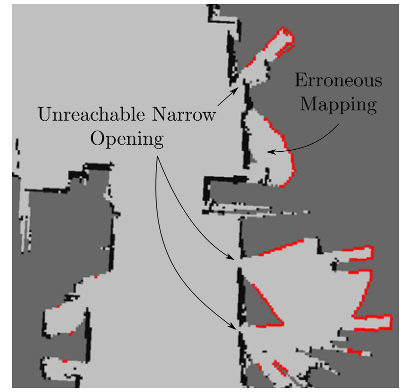

Fig. 1. A section of an occupancy grid map illustrating phantom-frontiers due to erroneous mapping and mapping through narrow openings. (White—free space, Black—Obstacles, Gray—Unknown space, red—phantom frontiers). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Different usage of frontier information

Frontier exploration strategies use extracted frontier cell information in different ways. A large collection of exploration strategies use the frontier cell information as it is and evaluate cells individually [24,14]. However, evaluating groups of frontier cells for better exploration performance has also been explored. These include clustering frontier cells based on cluster size [7,25], clustering based on environment segmentation [26,27], representing frontiers cells as contours [28,18] and improving clustering of frontier cells based on semantic information about map features [29,30].

All of the above mentioned clustering/grouping of frontier cells require additional processing after the extraction of initial frontier cell information. Regenerating all frontiers at each update step would thus lead to re-computation of all the cluster information, making frontier extraction process even more computationally inefficient. Recent work on incremental generation and management