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A hybrid solution to the multi-robot integrated exploration problem

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ABSTRACT

In this paper we present a hybrid reactive/deliberative approach to the multi-robot integrated exploration problem. In contrast to other works, the design of the reactive and deliberative processes is exclusively oriented to the exploration having both the same importance level. The approach is based on the concepts of *expected safe zone* and *gateway cell*. The reactive exploration of the *expected safe zone* of the robot by means of basic behaviours avoids the presence of local minima. Simultaneously, a planner builds up a decision tree in order to decide between exploring the current *expected safe zone* or changing to other zone by means of travelling to a *gateway cell*. Furthermore, the model takes into account the degree of localization of the robots to return to previously explored areas when it is necessary to recover the certainty in the position of the robots. Several simulations demonstrate the validity of the approach.

1. Introduction

Exploration is the task of covering an unknown area by a mobile robot or a group of robots. Usually, they build a model of the environment at the same time. Some applications of exploration are automated surveillance, search and rescue services or map building of unknown environments as, for example, in planetary missions. Compared to the case of a single robot, the utilization of a team of cooperative mobile robots is an advantage (Cao et al., 1997; Farinelli et al., 2004): the exploration time is reduced and the precision of the maps is improved because of the redundancy of measurements (Rekleitis et al., 1997, 2001).

As stated by other authors (Stachniss et al., 2005b; Makarenko et al., 2002), the exploration problem is related to the mapping and localization tasks. Fig. 1 shows this relation and the algorithms that resolve these different problems:

- *Simultaneous localization and mapping* (SLAM) algorithms are used to create a map of the environment and to simultaneously localize the robots in it.
- *Classic exploration* algorithms decide the best movements to guide the robot to quickly create a map of the environment.
- *Active localization* algorithms guide the robots to the best positions to achieve a good localization.
- *Integrated exploration* algorithms decide the movements of the robots in order to create a map while minimizing the error in the trajectories and the obtained map.

Generally, SLAM techniques are employed simultaneously with classic exploration algorithms (Simmons et al., 2000). However, the result obtained by the SLAM algorithm strongly depends on the trajectories performed by the robots (Stachniss et al., 2005b; Makarenko et al., 2002). Classic exploration algorithms do not take localization uncertainty into account and direct the exploration in order to minimize the distance travelled while maximizing the information gained. When the robots travel through unknown environments, the uncertainty over their position increases and the construction of the map becomes difficult. Consequently, the result could be a useless and inaccurate map. Returning to previously explored areas or closing loops reduces the uncertainty over the pose of the robots and improves the SLAM process. This idea is commonly denoted as *integrated exploration* or SPLAM (simultaneous planning localization and mapping). With this technique the robots explore the environment efficiently and also consider the requisites of the SLAM algorithm.

The goal of this paper is to develop an integrated exploration algorithm. We will have to come to an agreement between the speed of exploration and the quality of the generated maps. At the same time, the algorithm must work in real time and it must be robust, thus we need a decentralized approach. One of the problems in exploration and map building is the dependence of the computational time of the exploration algorithm on the dimension of the map. For this cause, the objective of real-time processing can be difficult to achieve if we are working with large

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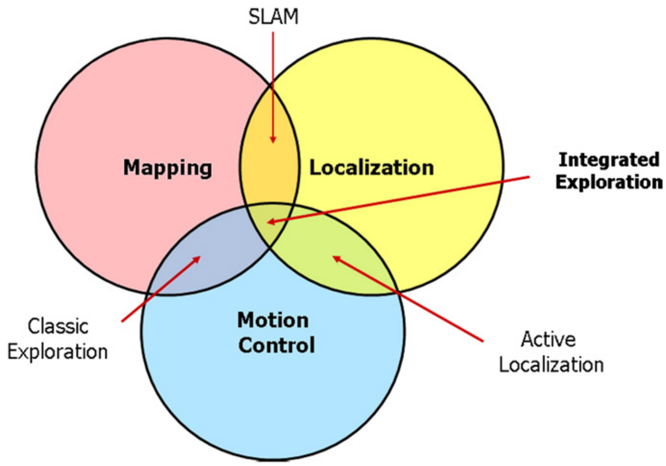

Fig. 1. The figure shows the algorithms that implement the mapping, localization and motion control task in the exploration problem. Integrated exploration algorithms decide the movements that quickly create a map while minimizing the error in the trajectories and the obtained map.

maps. In this sense, the algorithms should be independent of the dimensions of the map. For this cause, the algorithm we propose in this paper allows a robust integrated exploration because of the decentralization and the use of local maps that reduces the processing time.

Therefore, in this paper we present a hybrid solution to the multi-robot integrated exploration problem. Section 2 presents the state of the art in the field of exploration. Section 3 defines the main ideas of the approach and explains the advantages of the developed model. In Section 4 the proposed approach is explained in detail. Section 5 presents the experiments that were carried out to test the method and their results. In Section 6 our technique is compared with other integrated exploration techniques. Finally, the main conclusions are exposed in Section 7.

2. Related work

Typically, exploration techniques work basically using the frontier concept introduced by Yamauchi (1997). In a regular grid map that represents the occupation probability, as introduced by Moravec and Elfes (1985), cells can be classified as free, occupied or unknown. This information can be obtained by any kind of range sensor. Using this sort of map, Yamauchi defined the frontier cells as free cells that lie next to an unknown cell. We can see an example of occupancy grid map in Fig. 2, where the frontier cells are emphasized. Most of the exploration techniques use an occupation probability map and the frontier concept. However, there are other approaches that use other forms of identifying the regions of interest for the exploration. For instance, Wullschleger et al. (1999) and Newman et al. (2003) perform the exploration by means of directing the robots to open segments or features of the map, Murphy and Newman (2008) use a gap navigation directing the robots to the occluded zones of the sensor, and Santosh et al. (2008) lead the robots to the limits of the floor detected in images using only visual information.

Focusing on the exploration planning, we can distinguish two types of approaches to the exploration problem: deliberative and reactive.

The group of deliberative exploration methods usually employs path planning techniques (Fernandez et al., 1999) in order to direct the robots to the frontier cells. They differ in the coordination strategies used to assign a destination to each robot. A basic strategy is that the robots go to the nearest frontier as in the work of Yamauchi (1998). A cost-utility model has been also used to decide good destinations in single-robot exploration (Gonzalez-Baños and Latombe, 2002; Amigoni, 2008). In this sense, some authors have extended this kind of model to coordinate the robots (Simmons et al., 2000; Stachniss et al., 2006; Burgard et al., 2005). Normally, the cost is the length of the path to a frontier cell, whereas utility can be understood in different ways: Simmons et al. (2000) consider the utility as the expected visible area behind the frontier, Stachniss et al. (2006) use semantic information to increase the utility of the candidate destinations situated in corridors. With a higher level of coordination, Burgard et al. (2005) consider in the utility function the proximity to frontiers that were previously assigned to other robots. This way, the exploration speeds up since the robots choose different frontiers that are far from each other. Some authors include other types of representations of the environment in their approaches. For instance, Franchi et al. (2007) make the planning over a sensor-based random tree (SRT). The tree is expanded as new candidate destinations near the frontiers of the sensor coverage are selected, and it is used to navigate back to past nodes with frontiers when no frontiers are present in the current sensor coverage. In a similar way, Rocha et al. (2008) selects the best frontier from the current sensor coverage and uses also a topological map when there are no visible frontiers. Other approaches focus on the structure of the environment. The doors that divide the environment in corridors and rooms can be identified and represented in a topological map. Wurm et al. (2008) take advantage of this information for assigning optimally a different unexplored room to each robot using the *Hungarian method*. Other authors approach this issue as the *travelling salesman problem* by means of optimizing a complete route for the robots having each robot an ordered sequence of frontiers to visit. In this sense, Zlot et al. (2002) suggest using a market economy where the robots optimize their routes by means of negotiating their destinations.

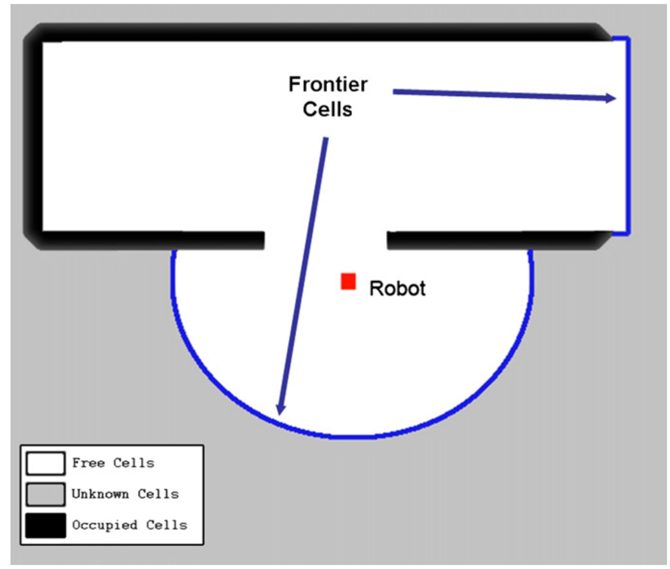

Fig. 2. The figure shows an occupancy grid map. The grey level of each cell indicates the occupation probability. The frontier cells, defined as the free cells next to an unknown cell, are emphasized in the graphic.

The other group of exploration techniques is reactive and commonly they are behavioural approaches (Arkin and Diaz, 2002; Lau, 2003; Juliá et al., 2008; Schmidt et al., 2006). The combination of a set of behavioural forces points out the advance direction. Arkin and Diaz (2002) combine an *avoid obstacles*