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Recent Results on Information Gathering Path Planning for Autonomous Mobile Robots

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***Abstract*—In the last decades, scientific and technological advances in autonomous mobile robotics have shown that robots can provide a valid alternative to humans in carrying out repetitive, difficult, and hazardous tasks. This is especially true for *information gathering* tasks, including exploration, search and rescue, monitoring, inspection, and patrolling. This extended abstract overviews some recent results on models and algorithms for planning information gathering paths of single and multiple autonomous mobile robots, focusing on some of the contributions that have been provided by the Artificial Intelligence and Robotics Laboratory (AIRLab) of the Politenico di Milano.**

I. Introduction

Information gathering tasks performed by autonomous mobile robots typically involve robot platforms that move in environemnts in order to take measurements (namely, to perform perceptions with their onboard sensors) that are then merged and integrated to build models representing some phenomena. For instance, in a monitoring task, robot platforms could be autonomous watersurface vehicles operating in lakes, rivers, or sea, equipped with sensors that could measure the concentration of chemical substances, the locations of the platforms, and the current time. Data collected by the robots could be merged into a spatio-temporal map of the concentration of chemical substances.

Among the different aspects involved in developing robot systems for information gathering tasks, we focus here on models and algorithms for efficient *decision-making* of autonomous mobile robots. Specifically, we consider navigation strategies used by robots, either operating individually or organized in multirobot systems, to autonomously decide *where to go* when performing information gathering tasks, in contrast to classical path planning methods [12] that are used to autonomously decide *how* to reach given locations.

This extended abstract overviews some of the recent results on models and algorithms to plan information gathering paths for single and multiple autonomous mobile robots, focusing in particular on some of those that have been developed at the Artificial Intelligence and Robotics Laboratory (AIRLab) of the Politecnico di Milano. The presentation is organized around some "canonical tasks" in information gathering, starting from the simplest tasks in which the environment is fully known, moving towards more challenging tasks in which the environment is initially unknown and the communication could be restricted, and finally discussing tasks in which opponents try to act against the robots.

II. Coverage

Given one or more mobile robots equipped with covering tools and a space E known to the robots, the basic formulation of the robot *coverage* problem asks to find paths such that, when the mobile robots follow them, all points of E fall inside the footprint of a covering tool. Usually, two objectives are considered: minimizing the cumulative length of paths or minimizing the length of the longest path (makespan). In the first case, the total effort is minimized, while in the second case the completion time is minimized.

While the general coverage problem is well studied [11], [15], some specific variants have not received much attention so far. For example, [13] provides some of the few results on optimal coverage paths that could be potentially followed by a robot even if the environment E was not known in advance. Also selecting observation paths for reaching given target locations under constraints on the amount of data that can be stored in the internal memory of the robots and that can be trasmitted to a base station is a challenging problem that have only been initially addressed [16].

III. Exploration

Given one or more mobile robots equipped with sensing tools and a space E initially unknown to the robots (at least in some of its aspects or features), the basic formulation of the robot *exploration* problem asks to find paths such that, when the mobile robots follow them, all the space E (or its unknown aspects) becomes known. Exploration is a typical on-line problem for which paths cannot be planned before the mission starts. There are two main variants of the problem: *frontier-based* exploration [19], in which the unknown features of E that are discovered by the robots are the geometry of the space and the locations of obstacles and of free space, and *information-based* exploration [17], in which the unknown features of E that are discovered by the robots are physical properties of the space, like temperature and gas concentration. In both cases, the core decision-making problem is to determine the next observation locations mobile robots should reach in a partially known environment. The mainstream approach is to apply, at each stage of the exploration mission, an exploration strategy that, given a set of candidate locations, ranks them according to an evaluation function that combines different criteria, which usually include the distance of candidate locations from robots and the expected information gain robots could get when at candidate locations.

We have provided several relevant and fundational results in this area, starting from [4], where an information-based exploration strategy is proposed for a mobile robot equipped with a laser range scanner. Moreover, decision-theoretic exploration strategies that exploit multi-criteria decision making to combine different criteria for evaluating candidate locations have been proposed [7]. A more recent exploration strategy [14] assumes that spatial semantic concepts (like 'rooms' and 'corridors') can be associated with metric entities and exploits this semantic information to push robots to explore relevant areas of initially unknown environments, according to a priori directives provided by human users. For example, in search and rescue, if a disaster happens during office hours, victims are most likely located in the offices and, thus, robots should focus on searching small-size rooms labeled as 'offices'.

Adopting teams of autonomous mobile robots to explore environments can provide significant advantages, like improved efficiency, reliability, and robustness [10]. Such advantages are obtained by employing forms of coordination between the teammates, which are often developed assuming the possibility to communicate without limitations. However, real-world missions require to deal with communication-restricted environments. In these settings, robots can share information only with teammates in a (local) communication range depending both on their transmission capabilities and on the environment itself (e.g., presence of obstacles or disturbances). Achieving a satisfactory level of coordination under such conditions is a problem that has been recently studied by the robotics community [1]. Under communication restrictions, also the basic problems of planning paths along which the robots are guaranteed to be connected [18] and of reconnection when communication is lost [5] have beeen shown to be computationally hard.

IV. Patrolling

Given one or more mobile robots equipped with sensing tools, a space E known the robots, and one or more *opponents* (which can be targets with neutral behavior or adversaries with adversarial behavior), the robot *patrolling* problem asks to find paths such that, when the mobile robots follow them, the opponents are detected or captured. The problem is also known under different names, like surveillance and target tracking. Among information gathering tasks, patrolling is arguably one of the more complex because, in order to efficiently tackle it, other agents, the opponents, should be modeled and accounted for in the development of the robots' navigation strategies. The patrolling problem is usually addressed according to two approaches: *frequency-based* patrolling [9], in which the goal of the robots is to perform a repeated coverage of E with guarantees over the time elapsed between successive visits to the same locations, or *adversarial* patrolling [2], [3], in which the behavior of the opponents is considered in planning the paths of the robots, often using tools from game theory.

Along this last direction, [8] defines the class of patrolling security games in which two players (a defender and an attacker) move in an environment in which a set of targets are protected by the defender from the attacker's intrusions. These games are modeled as extensive–form infinite–horizon games in which players act in turns and in which decision nodes are potentially infinite and algorithms are proposed to solve large instances of such games with single patroller and single intruder.

Finally, [6] presents an algorithm for coordinating a team of autonomous mobile robots equipped with limited-range sensors that keep under observation a (possibly larger) set of mobile targets. The algorithm fairly balance the distribution of attention over all the targets, avoiding that some targets are tracked for long times while some other targets are ignored.

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