Models and Algorithmic Approaches for Cooperative Multi-Robot Systems: Thesis Abstract

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1. INTRODUCTION

The subject of multi-robot systems has been thoroughly investigated in the past decade (e.g., [9, 12, 11, 7]). Current research in multi-robot systems can be divided, roughly, according to two aspects: theoretical robotics (e.g. [12]) and practical robotics (e.g. [10]). Theoretical robotics research, in many cases, make unrealistic assumptions on the robots' capabilities. For example, robots are sometime assumed to have unlimited visibility [8], or limited radius of visibility but omnidirectional [6]. In practice, it is usually not the case — robots have a limited angle of visibility along with limited radius of visibility. On the other hand, practical robotics research is driven, in many cases, by the will to solve problems, thus tend to be proven only for a specific robotic system.

In my work, similar to work done by several other researchers, I have been aiming to bridge the gap between these two disciplines by examining problems from the multi-robot domain using theoretical tools, i.e., trying to model the environment and provide computational analysis of problems and solutions while taking under consideration sensorial, motion or other limitations of the robots.

My work includes three topics. The first, multi-robot task allocation based on the cost of interaction between the team members. In the second part of my work I handled the multi-robot coverage task in which the goal was to find coverage paths such that the total time of coverage is minimized. The third topic is derived from the coverage task, and concerns multi-robot patrolling (repeated coverage) in adversarial environments. All problems are dealt using theoretical tools, for example using graph representation, graph theory algorithms, etc. The algorithms are evaluated using complexity measures, and optimality of the algorithms is theoretically proven (for non-heuristic solutions). The following sections describe the work done in each topic in more details.

2. TEAM MEMBER-REALLOCATION VIA TREE PRUNING

In the team member reallocation problem, k robots are to be extracted from a coordinated group of N robots in order to perform a new task. In our work [3], the interaction between the team members and the cost associated with this interaction are represented by a directed weighted graph. Consider a group of N robots organized in a formation. The graph is the monitoring graph which represents the sensorial capabilities of the robots, i.e., which robot can sense the other and at what cost. The team member reallocation problem we deal with is the extraction of k robots from the group in order to acquire a new target, while minimizing the cost of the interaction of the remaining group, i.e., the cost of sensing amongst the remaining robots.

In general, the innovation of the method proposed in our research is that we shift the utility from the team member itself to the interaction between the members, and calculate the reallocation according to this interaction cost. The time complexity of a brut-force algorithm for finding the optimal k robots to reassign to a new task is $\mathcal{O}(N^k)$. However, under our representation and limitations, the time complexity of our algorithm is only $\mathcal{O}(2^k)$. Therefore it is possible to find the optimal reassignment of k robots deterministically in polynomial time if $k = \mathcal{O}(\log N)$ (which is a reasonable assumption). We show that the representation of the interaction between the team members as a directed graph, along with the basic reallocation algorithm, can be used as base for other, more complicated algorithms. Specifically, we show that it is used by two algorithms that take into consideration more than one component in the utility function, one handles prioritized components and the second handles weighted components. Another advantage of our method is that it is applicable in other non-robotic domains, for example the dependency tree and warehouse assembly problems.

3. CONSTRUCTING SPANNING TREES FOR EFFICIENT MULTI-ROBOT COVERAGE

In this work, I consider the problem of building efficient coverage paths for a team of robots. An efficient multi-robot coverage algorithm should result in a coverage path for every robot, such that the union of all paths generates a full coverage of the terrain and the total coverage time is minimized. In most references to the coverage task, the location of the robots are given as input to the problem. Because the robots are typically not spread uniformly through the environment, it becomes challenging to use all robots in the system in order to cover the entire terrain in minimal time.

A method, underlying several coverage algorithms, sug-

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gests the use of spanning trees as base for creating coverage paths. This method allows creating a hamiltonian cycle, by decomposing the area into cells with several restrictions. This method was broadened for a team of robots, using the circular path for guaranteeing robustness. Current studies assume that the spanning tree is given, and try to make the most out of the given configuration. However, overall performance of the coverage is heavily dependent on the given spanning tree.

In my work [1, 2], I tackled the open challenge of constructing a coverage spanning tree that minimizes the time to complete coverage. I have shown that the choice of the initial spanning tree has far reaching consequences concerning the coverage time, and if the tree is constructed appropriately, it could considerably reduce the coverage time.

Therefore the problem is actually to find spanning trees that will decrease the coverage time of the terrain when used as base for multi-robot coverage algorithms. However, this problem is assumed to be NP-hard.

The main contributions of this research is twofold. *First*, it provides initial sound discussion and results concerning the construction of the tree as a crucial base for any efficient coverage algorithm. *Second*, it describes a heuristic polynomial-time tree construction algorithm that, as shown in extensive simulations, dramatically improves the coverage time even when used as a basis for a simple, inefficient, coverage algorithm.

4. MULTI-ROBOT PERIMETER PATROL IN ADVERSARIAL ENVIRONMENTS

In this work, I consider the problem of multi-robot patrolling around a closed area, in the presence of an adversary trying to penetrate the area. The area is divided into discrete segments, based on the velocity and sensing constraints of the robots in the area. We assume the robots can have directionality associated with their movement, and the cost of turning around is also taken into consideration.

In case the adversary knows the patrol scheme of the robots and the robots use a *deterministic* patrol algorithm, then in many cases it is possible to penetrate with probability 1. Hence we first considered a *non-deterministic* patrol scheme for the robots, such that their movement is characterized by a probability p. This patrol scheme reduces the probability of penetration, even under an assumption of a strong opponent that knows the patrol scheme. I found [4] an optimal polynomial-time algorithm for finding the probability p such that the minimal probability of penetration detection throughout the perimeter is maximized.

Planning in adversarial environments when assuming worst-case settings in which the adversary has full knowledge of the defending robots is found also in previous work. Common to all, it was shown that algorithms dealing with these worst case scenarios guarantee a "lower bound" on the performance of the team. However, an open question remains as to the impact of the knowledge of the opponent on the performance of the robots. In other words: Is preparing for the worst case scenario really the best thing to do *under all circumstances ?*. Surprisingly, the answer is strictly no.

In my work [5], I explored this question in depth and provided theoretical results, supported by extensive experiments with 68 human subjects concerning the compatibility of algorithms to the extent of information possessed by the subjects. First, we analytically examine the case of a zero-knowledge opponent—a different extreme—and show that surprisingly, this seemingly best-case scenario (from the point of view of defending robots) is optimally addressed by a deterministic, non-randomizing patrol. Moreover, we show empirically that an optimal algorithm for the full-knowledge opponent fails miserably in this case. We then address the case in which the adversary gained partial information, propose the Combine algorithm that maximizes the expected probability of penetration detection along with minimizing the deviation between the probabilities of penetration detection along the perimeter, and support the performance of this algorithm in the experiments.

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