Towards Safest Path Adversarial Coverage

(Extended Abstract)

Roi Yehoshua, Noa Agmon and Gal A. Kaminka *
Computer Science Department
Bar Ilan University, Israel
roi.yehoshua@biu.ac.il, agmon@cs.biu.ac.il, galk@cs.biu.ac.il

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1. INTRODUCTION

Coverage is a fundamental problem in robotics, where a robot is required to visit every part of a given area as efficiently as possible ([1], [3], [4], [5], [6], [8]). Coverage has many applications in various domains, from automatic floor cleaning to humanitarian missions such as search and rescue and field demining. The coverage problem is analogous to the traveling salesman problem (TSP), which is known to be $\mathcal{NP}$-complete [1]. However, it is possible to find solutions to the coverage problem that are close to optimal in polynomial or even linear time through heuristics and reductions (e.g., [1], [3], [5], [8]).

Almost all previous studies of the coverage problem dealt with non-adversarial settings, where nothing in the environment is hindering the robot's task. However, in many occasions, robots and autonomous agents need to perform coverage missions in hazardous environments, such as operations in nuclear power plants, exploration of Mars, demining and surveillance of enemy forces in the battle field.

In the adversarial coverage problem [9], the target area contains locations with potential threats of harming the robot, in addition to obstacles which the robot cannot go through. The robot's task is to cover the *entire* target area as quickly as possible without being damaged by a threat point. In the offline version of this problem, a map with the locations of the potential threats is given in advance, therefore the coverage path of the robot can be determined prior to its movement.

In this paper we focus on the problem of finding the safest coverage path in an adversarial environment, i.e., we are concerned about the survivability of the robot and not the coverage time. Nevertheless, the algorithms we propose will also try to minimize the coverage time, in cases where the robot's safety is not compromised. We will refer to this problem as the *Safest Coverage Path Problem.*

2. BACKGROUND

The problem of robot coverage has been extensively discussed in the literature (see Galceran and Carreras [4] for a recent exhaustive survey). Grid-based coverage methods, such as we utilize here, use a representation of the environment decomposed into a collection of uniform grid cells (e.g., [3], [6]).

Papers that took into account the presence of an adversary in the environment such as [2], [10] present algorithms and methods for risk avoidance. For example, the patrol problem, where a multi-robot team needs to patrol around a closed area with the existence of an adversary attempting to penetrate into the area, has been discussed in [2].

The offline adversarial coverage problem was formally defined by us in a recent study [9]. There we proposed a simplistic heuristic algorithm that generates a coverage path which tries to minimize a cost function, which takes into account both the survivability of the robot and the coverage path length. However, the heuristic algorithm worked only for obstacle-free areas, and without any guarantees, or analysis of the problem complexity, in contrast to the novel algorithms and analysis suggested in this paper.

As a basis for our safest path coverage planning algorithm, we chose to use the Spiral Spanning Tree Coverage (Spiral-STC) algorithm. This algorithm, introduced by Gabriely and Rimon [3], provides close-to-optimal coverage paths in a uniform grid based terrain. Spiral-STC assumes that a single robot is equipped with a square shaped tool of size D placed on grid. The grid is then coarsened such that each new cell is of size $2D \times 2D$, and a spanning tree is built over this new coarse grid. Then the robot follows the edges of this spanning tree, while covering each $2D$-cell internally. The main result is that Spiral-STC covers any planar grid in $O(n)$ time using a path whose length is at most $(n + m)D$. Here, n is the number of D-size cells and $m \leq n$ is the number of cells that share at least one point with the grid boundary.

Other optimization problems related to adversarial coverage include the Canadian Traveller Problem (CTP) [7],

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in which the objective is to find a shortest path between two nodes in a partially-observable graph, where some edges may be non-traversable. In contrast, here the graph is fully-observable and the agent must visit every node in the graph (some of them may stop the robot).

3. SAFEST COVERAGE PATH PROBLEM DEFINITION

We are given a map of a target area T, which contains obstacles and also points with threats, which may stop the robot. We assume that T can be decomposed into a regular square grid with n cells, whose size equals the size of the robot. Some cells in T contain threat points. Each threat point i is associated with a threat probability p_i, which measures the likelihood that the threat will stop the robot. The robot's task is to plan a path through T such that every accessible free cell in T is visited by the robot at least once.

Figure 1 shows an example map of the world. Obstacles are represented by black cells, safe cells are colored white and dangerous cells are represented by 5 different shades of purple. Darker shades represent higher values of p_i (more dangerous areas).

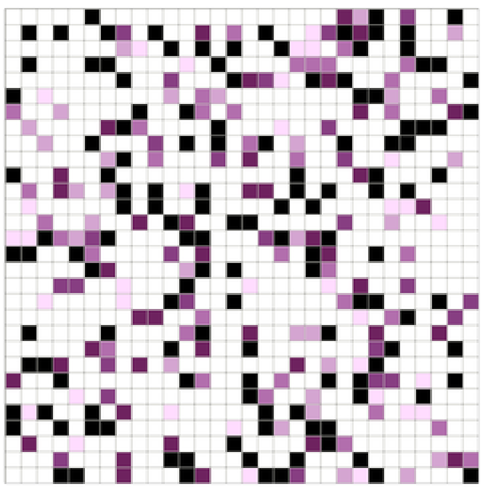

Figure 1: An example map of the world. Obstacles are colored black and dangerous cells are colored purple. Darker purple cells represent more dangerous areas.

In this paper, two objective functions are considered with respect to the safest coverage path problem:

1. Minimize the total accumulated risk along the coverage path (i.e., maximize the probability of covering the whole target area).
2. Maximize the coverage percentage of the target area before the robot is first hit (i.e., maximize the expected coverage percentage).

Note that for the first objective, the order of visits of the cells is not important, as long as the number of visits of threat points along the coverage path is minimized (ideally, visiting each threat point only once). On the other hand, for the second objective, the visit order of the cells is crucial, since the robot is trying to cover as much as possible before getting hit by a threat (ideally, covering all the safe cells before visiting a threat point).

4. ALGORITHMS FOR SOLVING THE SAFEST COVERAGE PROBLEM

In the paper we prove that the safest coverage path problem (both objectives) is $\mathcal{NP}$-complete. We therefore suggest two polynomial-time approximate solution algorithms.

We provide optimality bounds on these algorithms and evaluate them in various types of environments: maps with randomly scattered threat points vs. contiguous dangerous areas and maps with randomly scattered obstacles vs. contiguous areas of obstacles. For each type of environment we report on the probability of the robot to complete the coverage, its expected coverage and the coverage path length.

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