Ship Patrol: Multiagent Patrol under Complex Environmental Conditions

(Extended Abstract)

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ABSTRACT

In the problem of multiagent patrol, a team of agents is required to repeatedly visit a target area in order to monitor possible changes in state. The growing popularity of this problem comes mainly from its immediate applicability to a wide variety of domains. In this paper we concentrate on frequency-based patrol, in which the agents' goal is to optimize a frequency criterion, namely, minimizing the time between visits to a set of interest points. In situations with varying environmental conditions, the influence of changes in the conditions on the cost of travel may be immense. For example, in marine environments, the travel time of ships depends on parameters such as wind, water currents, and waves. Such environments raise the need to consider a new multiagent patrol strategy which divides the given area into regions in which more than one agent is active, for improving frequency. We prove that in general graphs this problem is intractable, therefore we focus on simplified (yet realistic) cyclic graphs with possible inner edges. Although the problem remains generally intractable in such graphs, we provide a heuristic algorithm that is shown to significantly improve point-visit frequency compared to other patrol strategies.

Categories and Subject Descriptors

I.2.9 [**Robotics**]: Autonomous vehicles

General Terms

Algorithms, Experimentation

Keywords

Robot Teams, Multi-Robot Systems, Robot Coordination, Robot planning, Agent Cooperation

1. INTRODUCTION

In the problem of multiagent patrol, a team of agents is required to repeatedly visit a set of points in order to monitor possible changes in state. The growing popularity of this problem (e.g. [3, 4, 1]) comes mainly from its immediate applicability to a wide variety of domains. The points may either be in a discrete environment, a continuous 1-dimensional environment (along a line), or a continuous 2-dimensional environment (inside an area).[1]

In this paper we focus on the continuous 2-dimensional frequency-based multiagent patrol problem, with discrete points of interest, in complex environmental conditions. In this problem, we are given a graph $G = (V, E)$, and we need to define patrol paths for a team of k agents that will minimize the maximal time some vertex of the graph is left unvisited. The complexity of the environment is expressed via the cost of travel between each pair of vertices of the graph. Consider, for example, the problem of ship patrol, i.e., patrol by agents (ships) in marine environments.

Current strategies for multiagent patrol offer, roughly, two alternatives for agents' patrol paths. The first strategy, denoted herein as SingleCycle, is to create one simple cyclic path that travels through the entire area (graph), and to let all agents patrol along this cyclic path while maintaining uniform distance between them (e.g. [4, 3]). The second strategy, denoted herein by UniPartition, is to partition the area into k distinct subareas, where each agent patrols inside one area (e.g. [3]). Finding an optimal solution in both cases might be intractable, thus existing solutions concentrate on either simplified scenarios or offer heuristic solutions.

We suggest a third, more general strategy, denoted by MultiPartition, in which the graph is divided into m subgraphs, $m \leq k$, such that a subteam of agents jointly patrol in each subgraph. We define the problem of finding k (possibly overlapping) paths for the agents such that the maximal time between any two visits at a vertex is minimized, and show that the problem is $\mathcal{NP}$-Hard. We therefore investigate the problem on a special family of graphs, which are cyclic graphs with non intersecting shortcuts (diagonals), called *outerplanar graphs* [2]. Unfortunately, the time complexity of the general problem of finding an optimal MultiPartition strategy even in such graphs appears to be intractable as well.

We therefore suggest a heuristic algorithm for finding a partition of the graph into disjoint cycles in the outerplanar marine environment, and a partition of the k agents among those cycles. The evaluation of the algorithm in our custom-developed ship simulator, UTSeaSim, that was designed to realistically model ship movement constraints in marine environments, shows that the heuristic algorithm performs better compared to existing strategies.

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[1] Of course higher dimensions are also possible.

2. BACKGROUND AND MOTIVATION

The problem of multiagent patrol has become a canonical problem in multiagent (and specifically multi-robot) systems in the past several years. As such, we have decided to investigate this problem in the realistic ship simulation we have designed in our lab, UTSeaSim.

The general problem defined in graph environments requires a team of k agents to repeatedly visit all N nodes of the given graph while minimizing the longest time a node has remained unvisited by some robot. Generally, the solutions that exist in the literature for defining optimal patrol paths for a team of robots, can be roughly divided into two types: SingleCycle and UniPartition strategies, which consider the entire cyclic path, or divide thearea into k regions, each covered by one agent (respectively).

When looking at the example described in Figure 1 for three ships, we can see that there exists another strategy: Letting one ship patrol in one cycle (here points p_3, p_4, p_5, p_6), and the other two ships can jointly patrol in one cycle (points $p_1, p_2, p_7, p_8, p_9, p_{10}$). We denote this strategy MultiPartition, i.e., a partition into areas in which more than one agent can patrol in each area. In this example, the worst idleness when the sea conditions were calm (no winds or currents) was 651, 786 and 614 for the SingleCycle, UniPartition and MultiPartition strategies (respectively). When we introduced currents to the system, the advantage of using the MultiPartition strategy became more evident: the worst idleness results were 795, 792 and 613 seconds using the SingleCycle, UniPartition and MultiPartition strategies (respectively).

This example, along with other similar phenomena we have viewed in our simulator, motivated us to redefine the problem of multiagent patrol in a more general form, the MultiPartition strategy, and investigate possible solution to the problem in circular environments, but with additional shortcuts between the points of interest.

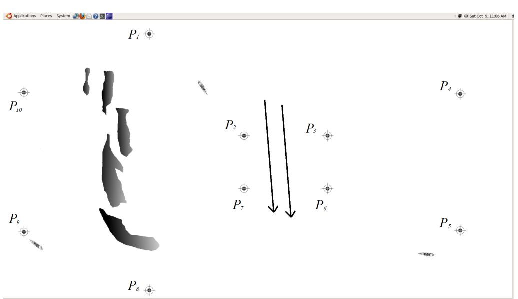

Figure 1: An example of a scenario handled by the simulator. The circles represent the points of interest (nodes of the graph), and the drop shapes are the ships. The large grey shapes are obstacles, and the drawn arrows indicate the direction of the water current.

3. PROBLEM DEFINITION AND COMPLEXITY

Definition: Multiagent Graph Patrol (MGP)
Given a graph $G = (V, E, C)$ where $|V| = N$, and $\forall(v_i, v_j) \in E, c_{ij} \in C$ is the associated cost of the edge, an integer $k < N$ denoting the number of agents and a desired maximal worst idleness criteria f, is there a division of V into $m \leq k$ cyclic paths $V_1, V_2, \ldots, V_m$ (not necessarily simple), each assigned with k_i agents such that all k_i agents visit all vertices in V_i and $\sum_{i=1}^{m} k_m = k$, such that the worst idleness wf(G) is at most f?

Theorem 1. *The* MGP *problem is $\mathcal{NP}$ complete for general k.*

The multiagent patrol problem in outerplanar graphs
Motivated by the problem of multi-robot *perimeter patrol* (e.g. [1]), we examine the MCGP problem in circular environments. However, we would like to add more realistic considerations to the environment, namely adding possible *shortcuts* between vertices that pass inside the circle. To avoid possible intersections by agents that travel along the edges, we require the inner edges not to intersect one another. The resulting graph is planar, and moreover, it is a *biconnected outerplanar* graph [2], i.e., it is a planar graph that is cyclic, and there are no nodes that are inside the cycle (all nodes in the graph are on the same outer face). In the family of outerplanar graphs, several hard problems become very easy to solve. For example finding a Hamiltonian cycle is done in linear time, as the only possible simple cycle that visits all nodes in the graph is the external cycle. Therefore also finding the optimal SingleCycle strategy is done in linear time, as the solution is unique.

Unfortunately, solving the MGP problem in such graphs is intractable is well. We therefore offer a heuristic algorithm, HeuristicDivide, for solving the problem. Algorithm HeuristicDivide works as follows. First, it examines all possible division of the given cycle into two or three cycles. If there exists one or more division that decreases the worst idleness (increases the frequency of visits), it chooses the best one. For each cycle of the best division, it runs the same procedure recursively.

We evaluated algorithm HeuristicDivide in our simulator, UTSeaSim, in two scenarios. In both we have shown that the algorithm performs better than existing SingleCycle and UniPartition strategies (the latter was computable only in small environments).

4. FUTURE WORK

Several points are left as future work. First, we would like to consider the problem of multiagent patrol in prioritized environments, i.e., where vertices of the graph should be visited with different frequencies. Second, we would like to add more learning methods for determining the cost of travel, especially in prioritized environments. We would also like to examine the possibility of generalizing our heuristic solution to general graphs.

5. REFERENCES

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