COMPLETE AND SCALABLE MULTI-ROBOT PLANNING IN TUNNEL ENVIRONMENTS

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Abstract: This paper addresses the challenging problem of finding collision-free trajectories for many robots moving to individual goals within a common environment. Most popular algorithms for multi-robot planning manage the complexity of the problem by planning trajectories for robots sequentially; such decoupled methods may fail to find a solution even if one exists. In contrast, this paper describes a multi-phase approach to the planning problem that guarantees a solution by creating and maintaining obstacle-free paths through the environment as required for each robot to reach its goal. Using a topological graph and spanning tree representation of a tunnel or corridor environment, the multi-phase planner is capable of planning trajectories for up to $r = L-1$ robots, where the spanning tree includes L leaves. Monte Carlo simulations in a large environment with varying number of robots demonstrate that the algorithm can solve planning problems requiring complex coordination of many robots that cannot be solved with a decoupled approach, and is scalable with complexity linear in the number of robots.

Keywords: mobile robots, efficient algorithms, path planning, trajectory planning

1. INTRODUCTION

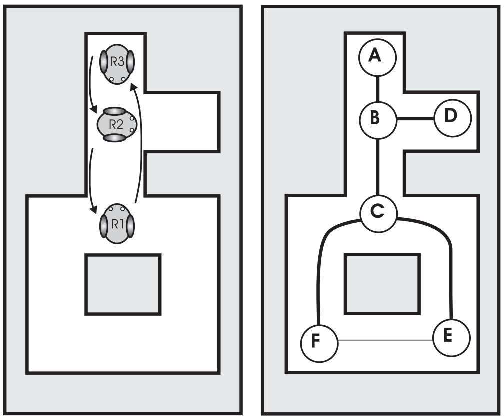
The use of multiple mobile robots in a common environment is required for the automation of many operations, such as underground mining and warehouse management. In such applications, multiple vehicles are required to drive autonomously between different locations, preferably taking the shortest possible route while avoiding collisions with static objects and other vehicles. This paper presents an algorithm for efficiently determining collision-free paths for many vehicles in environments composed of tunnels or corridors, as may be found in these applications. The problem addressed by this research is demonstrated by the multi-robot planning task pictured in Figure 1(a).

In this scenario, the environment is constructed of corridors or tunnels that are wide enough for only a single robot to travel, and we assume differential drive robots that can rotate in place. The objective in this example is to shift the positions of each robot, such that robot R_1 moves to the initial position of R_3, R_3 to the position of R_2, and R_2 to the position of R_1. Our goal is to find an algorithm that can solve the simple problem shown in Figure 1(a), yet is scalable to a large number of robots (> 100) densely situated in a large environment.

Many methods have been proposed for planning the motion of one or more robots; refer to (Latombe, 1991) and (LaValle, 2006) for detailed reviews. Planning algorithms can be evaluated in terms of completeness (whether they are guaranteed to find a solution if one exists), complexity, and optimality.

Most multi-robot planning algorithms fall into one of two categories, *coupled* and *decoupled*. *Coupled* algorithms, such as (Svestka and Overmars, 1998), plan the trajectories of all robots in the environment concurrently. By combining the states (poses) of the individual robots together into a system state representation, a sequence of state transitions can be found that will move all robots to their respective goals. Using complete search methods, such as A*, coupled algorithms can achieve completeness and optimality, and can solve the problem shown in Figure 1(a). Their limitation is in searching the large configuration space that grows in dimension as each additional robot is added to the environment. One approach to reducing the size of the search space is to create probabilistic roadmaps (PRMs) through the environment; this method was shown in (Svestka and Overmars, 1998) to be probabilistically complete and demonstrated in simulation for up to 5 robots.

Decoupled methods plan for the motion of individual robots, rather than planning the motion of all robots simultaneously. Such methods may use a decentralized architecture, allowing independent planning based methods such as maze-searching (Lumelsky and Harinarayan, 1997) or potential fields (Ge and Cui, 1997), or they may use a centralized architecture planning for all robots with a single processor, allowing for coordination of collision-free plans for all robots. Centralized decoupled planners typically determine individual trajectories sequentially and combine the plans of all robots to avoid collisions, as in (Erdmann and Lozano-Perez, 1987), (Bennewitz *et al.*, 2001) and (Guo and Parker, 2002). By planning the motion of robots sequentially, decoupled methods have lower complexity and greater scalability than a coupled planner; however, this comes at the cost of completeness and optimality. The problem in Figure 1(a) for example cannot be solved by a sequential planner. By selecting the optimal plan for any robot independently, an obstacle is created in the space-time map that cannot be avoided by the other two robots.



(a) A planning problem (b) Graph-based map

Fig. 1. A multi-robot planning problem requiring coordination of 3 robots, and a graph-based representation of the environment.

This paper presents an alternative *multi-phase* planning method that can solve these coordinated planning problems, and is scalable to a large number of robots in a large environment. A graph representation of the environment is first created, and a spanning tree through the graph is selected. For the tunnel and corridor environments considered here the segments are only one lane wide, reducing the complexity of a suitable topological map generation process compared to the general case. A multi-phase planning approach then takes advantage of the properties of the graph and spanning tree to create and maintain obstacle-free paths while robots move to their respective goals.

2. MAP REPRESENTATION

Occupancy grids are a common map representation for robot navigation, and are easily derived from range sensor measurements. However, for motion planning problems, graph representations such as topological maps and roadmaps are often more efficient.

For the simple example of Figure 1(a), a topological graph G can be constructed as shown in Figure 1(b), consisting of $N = 6$ nodes and $E = 6$ edges. We assume that the initial and goal positions of all robots lie on the nodes of the graph; in this representation, the goal positions of robots R_1, R_2, and R_3 are nodes A, C, and B respectively.

Given the graph representation, we can also select a spanning tree T^* in the graph, that is, a subset of edges connecting all nodes without forming any loops. A given spanning tree has L *leaf nodes*, and $N - L$ *interior nodes*. A suitable spanning tree for the example is shown in Figure 2 where node C, closest to the geographic center of the map, is selected as the root. Selecting all edges except for $E - F$ into the spanning tree as shown gives