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Dynamic robot path planning using an enhanced simulated annealing approach

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ABSTRACT

Evolutionary computation is an effective tool for solving optimization problems. However, its significant computational demand has limited its real-time and on-line applications, especially in embedded systems with limited computing resources, e.g., mobile robots. Heuristic methods such as the genetic algorithm (GA) based approaches have been investigated for robot path planning in dynamic environments. However, research on the simulated annealing (SA) algorithm, another popular evolutionary computation algorithm, for dynamic path planning is still limited mainly due to its high computational demand. An enhanced SA approach, which integrates two additional mathematical operators and initial path selection heuristics into the standard SA, is developed in this work for robot path planning in dynamic environments with both static and dynamic obstacles. It improves the computing performance of the standard SA significantly while giving an optimal or near-optimal robot path solution, making its real-time and on-line applications possible. Using the classic and deterministic Dijkstra algorithm as a benchmark, comprehensive case studies are carried out to demonstrate the performance of the enhanced SA and other SA algorithms in various dynamic path planning scenarios.

1. Introduction

Mobile robots are widely used in various applications; typical examples are industrial robots deployed in hazardous fields where there may be dangers for people, e.g., aerospace systems, nuclear applications, and mining equipment. Path planning for mobile robots is one of the most important aspects in robot navigation. To find an safe path in a dangerous environment for a mobile robot is an essential requirement for the success of any such mobile robot project. When an optimal path planning problem is formulated as an optimization problem, solving the problem is also of great importance in theoretical and computational investigations [1].

The main goal of the robot path planning is to search a safe path for a mobile robot, to make the robot move from the start point to the destination point without collision with obstacles. Also, the path is often required to be optimal in order to reduce energy consumption and communication delay.

Depending on the environment in which the robot is located, existing methods for robot path planning can be classified into the following two categories: (1) Path planning in a static environment with static obstacles in the map; and (2) Path planning in a dynamic environment with both static and dynamic obstacles in the map. Each of these two categories of methods could be further divided into two sub-groups depending on how much the robot knows about the entire information of the surrounding environment:

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- Path planning in a clearly known environment, in which the robot already knows the location of the obstacles before it starts to move. Because the environment is fully known, the path for the robot could be globally optimized.
- Path planning in a partially known or uncertain environment, in which the robot probes the environment using sensors to acquire the information about the location, shape, and size of the obstacles, and then uses the information for local path planning.

Dynamic path planning is the most difficult task among all path planning scenarios, and is the focus of this work.

Evolutionary computation is an effective tool for solving optimization problems. However, it demands significant computational power, limiting its real-time and on-line applications, particularly in embedded systems with limited computing resources, e.g., mobile robots. Heuristic methods such as the genetic algorithm (GA) based approaches have been shown to be a promising tool for robot path planning in dynamic environments. However, investigations into the simulated annealing (SA) algorithm, another popular evolutionary computation algorithm, for dynamic path planning are still limited mainly due to its high computational demand. This paper will develop an enhanced SA approach with integration of two additional mathematical operators and initial path selection heuristics into the standard SA for robot path planning in dynamic environments with both static and dynamic obstacles. It improves the computing performance of the standard SA significantly while giving an optimal or near-optimal robot path solution, making its real-time and on-line applications possible.

The paper is organized as follows. Following this introductory section, Section 2 discusses related work and motivations. An enhanced SA approach is developed in Section 3 for dynamic path planning. The architecture, algorithm design, and initial path selection heuristics of the enhanced SA are discussed in detail in this section. Using the classic Dijkstra algorithm as a benchmark, Sections 4 and 5 demonstrate the performance of the enhanced SA through comprehensive case studies in five dynamic environments. Finally, Section 6 concludes this paper.

2. Related work and motivations

2.1. Related work on dynamic path planning

Given the entire information of an environment in which a robot is located, the globally optimal or near-optimal path can be found by using optimization algorithms, e.g., the genetic algorithm (GA) [2]. Tarokh [3] has developed an intelligent path planning approach for highly mobile robots operating in rough environments. The approach consists of characterization of the environment using fuzzy logic, and two-stage GA planners with one being global and the other being local. The global planner determines the path that optimizes a combination of terrain roughness and path curvature; while the local planner uses sensory information, and when previously unknown and unaccounted obstacles are detected, performs on-line re-planning to get around the newly discovered obstacles. Cheng et al. [4] have proposed a path planner that combines the GA with dynamic programming to solve a path planning problem of autonomous underwater vehicles. Recently, Tuncer and Yildirim [5] have proposed an improved GA algorithm for dynamic path planning of mobile robots through using a new mutation operator to avoid infeasible paths and premature convergence.

Nearchou [6] uses the number of vertices produced in visibility graphs to build fixed length chromosomes in which the presence of a vertex within the path is indicated by setting a bit at an appropriate locus. A re-ordering operator is applied for performance enhancement; and the proposed algorithm is capable of determining a near-optimal solution.

The Dijkstra algorithm is a classic and deterministic algorithm for searching the shortest path in a graph with weighted edges. Kang et al. [7] and Wei and Liu [8] have demonstrated typical implementations of the Dijkstra algorithm for robot path planning. The main drawback of the Dijkstra algorithm is its computing inefficiency. The A* algorithm described in Russell [9] introduces heuristics into the Dijkstra algorithm to improve its computing performance with the focus on minimizing the processing time.

Evolved from the A* shortest-path algorithm, an improved algorithm is developed by Hu and Gu [10] to solve the problem of optimal route planning in vehicle navigation systems. It is based on the standard GA and the lambda-interchange local search method. It can find the optimum route efficiently without any network constraint conditions and can work well in either continuous or discrete networks.

However, in many applications such as those described in Ayers [11] and Williams and Mahon [12], it is an unrealistic assumption that a robot can get the full information of the surrounding environment at any one time because the status and movement of the obstacles in the environment may change over the time. A feasible path solution may become infeasible due to the changes in the environment. To overcome this problem, the robot should have the ability to sense the environment and to plan the path on-line and in real-time. In a dynamic environment, how to manipulate a robot to travel to the destination safely and optimally without collisions with obstacles is an important issue for both fundamental research and practical development.

Limited work has been reported on optimal path planning for mobile robots in dynamic environments. Chakravorty and Junkins [13] have introduced a methodology for intelligent path planning in uncertain environments. The method models the planning problem as a Markov decision process, which is characterized by a known, control-dependent exploration system and an unknown, uncontrollable environment. The exploration system is an intelligent adaptive control system; while the probability that governs the environment process is estimated via a Monte-Carlo-based estimation scheme using vision