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Dynamic path planning for autonomous driving on various roads with avoidance of static and moving obstacles

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ABSTRACT

This paper presents a real-time dynamic path planning method for autonomous driving that avoids both static and moving obstacles. The proposed path planning method determines not only an optimal path, but also the appropriate acceleration and speed for a vehicle. In this method, we first construct a center line from a set of predefined waypoints, which are usually obtained from a lane-level map. A series of path candidates are generated by the arc length and offset to the center line in the $s-\rho$ coordinate system. Then, all of these candidates are converted into Cartesian coordinates. The optimal path is selected considering the total cost of static safety, comfortability, and dynamic safety; meanwhile, the appropriate acceleration and speed for the optimal path are also identified. Various types of roads, including single-lane roads and multi-lane roads with static and moving obstacles, are designed to test the proposed method. The simulation results demonstrate the effectiveness of the proposed method, and indicate its wide practical application to autonomous driving.

1. Introduction

Autonomous driving has been the focus of significant interest from academia, industry, and the military in recent years [1–3]. Demonstrations on California highways in 1997 proved that autonomous driving was possible in cases restricted to a dedicated lane on a highway with magnets [4,5]. The Defense Advanced Research Projects Agency (DARPA) Grand Challenge and Urban Challenge have stimulated research interest in the field. Moreover, Google driverless cars have been tested on more than 1,600,000 miles of American roads. Tesla has equipped its MODEL S car with a self-driving system "autopilot system. Although Google cars, Teslas, and vehicles developed for the DARPA challenges have shown great autonomous driving performance, significant challenges still remain for the commercialization of autonomous vehicles in terms of technology and price [6,7]. There are many issues associated with autonomous driving systems in practical applications. However, these issues can be solved in the near future [8,9].

Current research on autonomous driving encompasses different fields, including perception, planning, and control [10–12]. The goal of perception is to obtain information for autonomous vehicles from their environments [13], while the goal

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of control is to determine the appropriate parameters for veer, throttle, or brake systems in order to make the autonomous vehicles follow the planned path [14]. Planning is the decision making stage between perception and control. In particular, critical decision making in autonomous driving is the key to autonomy. This can be realized through planning algorithms incorporated into the middleware of the navigation system of an autonomous vehicle, situation understanding, and decision making modules. The main purpose of planning is to provide vehicles with a safe and collision-free path towards their destinations, accounting for vehicle dynamics, maneuvering capabilities in the presence of obstacles, and traffic rules and road boundaries [15,16]. Path planning methods are typically studied to allow mobile robots and autonomous vehicles to avoid obstacles [17,18]. Existing path planning algorithms can be divided into two stages: global planning and local planning. In the global planning stage, global routes and the vehicle states are determined from a digital map and localization system. In the local planning stage, a local path can be achieved based on a global route and surrounding information obtained from sensors such as cameras or radars [4,7]. In this paper, we focus on designing a local path planning method for autonomous vehicles on the basis of a predefined global route.

In recent years, many studies have been conducted on dynamic path planning. These studies can be divided into four primary categories: grid-based approaches, potential field approaches, sample-based approaches, and discrete optimization approaches.

In grid-based approaches, the environment is mapped to a set of cells, where each cell represents the presence of an obstacle at that position in the environment [19]. Optimal search algorithms such as A∗ and D∗ are typically used to find the global optimal path that connects the initial position of each cell to the goal position, while also avoiding obstacles. In recent years, some improved grid-based methods treating nonholonomic constraints have been proposed, by adapting applications such as executing U-turns on a blocked road, parking, and navigating roads in unstructured environments [20,21]. Path planning for first responders in the presence of uncertain moving obstacles based on algorithm A∗ is proposed in [22]. Zuo developed a novel hierarchical path planning approach for mobile robot navigation in complex environments [23]. This type of method has all future path information known after planner execution and before vehicle motion [24]. However, the incremental nature of search algorithms causes problems with the exponential growth of computing complexity. Grid-based approaches perform well for path planning in low-speed applications, but they are not suitable for high-speed driving.

In potential field approaches, the repulsive forces to obstacles and attractive forces to the goal position are virtually assigned [25,26]. The gradient of a potential field is constructed by virtual forces. A path can then be achieved along the steepest gradient of the potential field. Ref. [27] introduces a path planning method based on a potential field where stream functions are used to plan the paths of autonomous vehicles. Daily proposed a harmonic potential field path planning approach for high speed vehicles in [28]. These potential-field-based approaches are advantageous, because their trajectories can be produced with little computation. However, in some scenarios the approaches can become trapped in the local minima of a potential field, in which case the obtained path is not optimal or a path may not be found.

Path planning approaches based on sampling are appropriate for planning in high dimensional spaces. In such approaches, a collision-free path from the initial position to the destination is constructed by sampling the configuration describing the position and orientation of a vehicle. Rapidly exploring random trees (RRTs) and RRT variants are widely used in nonholonomic path planning [29]. Obermeyer used this method to deal with a path planning problem for a single fixed-wing aircraft performing a reconnaissance mission [30]. In [31], an adaptive path planning algorithm was proposed for multiple AUVs to estimate the scalar field over a region of interest. Devaurs developed two efficient sampling-based approaches combining two RRT variants (RRT∗ and T-RRT) to solve a complex path planning problem [32]. An efficient state-space sampling-based trajectory planning scheme was employed to smoothly follow the reference path in [16]. These approaches easily handle problems with obstacles and differential constraints (nonholonomic and kinodynamic), and have been widely used in autonomous robotic path planning [33,34]. Nevertheless, path planning approaches based on RRTs for real-time implementation require efficient guiding heuristics for their sampling configurations.

Path planning approaches based on discrete optimization have achieved great success in the field of autonomous driving in recent years. Methods that apply a finite set of paths can reduce the solution space; this allows for real-time implementation [35]. An efficient path planning method was developed with an autonomous vehicle in [36]. In this method, the planner defines the lateral offset as the perpendicular distance to a fixed-base line, enabling a vehicle to travel a road parallel to the base line. To select the optimal path, the cost function penalizes running over obstacles and distance from the current road center. The authors in [37] proposed a similar path planning approach for autonomous vehicles to avoid obstacles on roads. Phung proposed an enhanced discrete particle swarm optimization path planning for unmanned aerial vehicle (UAV) vision-based surface inspection [38]. These methods can provide a safe and smooth path for autonomous vehicles or UAVs. However, it can only treat static obstacles. Moving obstacles are not considered in these methods.

In this paper, we propose a path planning approach based on discrete optimization for autonomous vehicles. This approach can select an optimal path from a finite set of path candidates, and simultaneously determine appropriate vehicle acceleration and speed. The method uses a global route from the digital map that is obtained prior to local path planning. A center line representing the global route is constructed using a cubic spline. To generate the path candidates, a $s-\rho$ coordinate system is introduced and the directional information for the global route is blended with the maneuvering of the vehicle by adjusting the lateral offset to the center line. A novel cost function is designed and used to select an optimal path from multiple path candidates. The proposed method in this paper considers dynamic safety costs and allows a vehicle to avoid moving obstacles. Appropriate acceleration and speed for every planning can be simultaneously provided for autonomous