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Smooth path and velocity planning under 3D path constraints for car-like vehicles

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HIGHLIGHTS

- A path-smoothing model was described as the vehicle moves under 3D path constraints.
- A 3D path-smoothing method similar to the road design method was constructed.
- A velocity profile generation model that takes into account comfort constraints was constructed.
- In contrast, path planning can essentially be seen as the limit state of road design.

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ABSTRACT

Existing path and velocity planning methods for car-like vehicles, the paths of which are subject to constraints on the derivative of the curvature in the horizontal plane, do not accurately express the relationships among position, velocity and acceleration in 3D space. Moreover, velocity planning algorithms are efficient only when the curvature and derivative of the curvature have the same velocity demand. As efficiency and comfort are two key issues in promoting planning algorithms, in this paper, the vehicle is allowed to know the nearly shortest-length path and to set a continuous velocity and acceleration profile to track the trajectory reference while taking into account bounds on acceleration (including lateral acceleration) and jerk that are consistent with comfort. First, to construct a nearly shortest path, the 3D path surface is mapped onto the horizontal, profile and frontal planes, and a 2D path smoothing method is applied to solve the 3D path smoothing problem. This method has been used in highway design, but the theoretical understanding of its performance remains limited. This limitation is addressed from the viewpoint of 3D path smoothing in this paper. In addition, the jerk, acceleration, velocity, steering angle and steering angular acceleration profile are merged into a trajectory tracking task to provide a new velocity planning method to find the time-optimal path. Finally, the capabilities of the path and velocity planning methods within general planning schemes are also demonstrated.

1. Introduction

The goal of a path-planning problem is to produce a continuous path that connects a starting point and an ending point while avoiding collisions with known obstacles. The goal of the geometric design of highways is to find a path between the starting point and ending point based on standards and constraints. The basic objectives are to optimize efficiency and safety while minimizing cost. The problems differ in terms of their description and objectives, but both aim to find an optimal path between the starting and ending points. It is useful to improve highway construction in life cycle assessments because of their efficiency, lack of CO_2 emissions, safety, and comfort [1,2], and the vehicle is forced to follow certain navigation laws connected with the geometric design, invariant of the path, to improve efficiency and reduce users' travel times. To these ends, both a time-optimal path-planning algorithm and an accurate control system are necessary.

As the instantaneous motion of the vehicle in 3D space occurs on a plane, some closed-loop techniques for the control of a non-holonomic car in 2D inspired by the nonlinear control theory can be used to track the path as closely as possible to both the planned path and the planned velocity; e.g., the robust flatness-based control strategy [3], the VFO (Vector Field Orientation) controller [4,5], and an approximate decoupling method based on the transverse function [6]. Therefore, the focus of the present work is to construct a smooth path for car-like vehicles based on geometric design invariants in 3D environments that are consistent with given comfort and safety requirements and then to generate an optimal velocity profile that takes into account the previously smooth path and some additional drivability constraints.

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Three problems remains, which should be considered for the purpose of generating time-optimal path planning:

- How to describe the 3D path-planning problem under the constraints of a car-like vehicle moving along a 3D path.
- How to solve the 3D path-planning problem and generate an effective trajectory considering the constraints.
- How to generate a velocity profile combined with the 3D path smoothing method to ensure that the path is time-optimal.

1.1. State of the art

Considering a running car moving on a road surface is useful for describing the 3D path-planning problem with the constraint that the car-like vehicle moves along a 3D path surface. In 2D highway design, the road is divided into three types of alignments on the horizontal, profile, and frontal planes. Constraints on vehicle motion are usually described in terms of these three types of alignments. The model does not require the highway to be a continuous road surface. Past 3D road surface analyses with digital terrain models, such as ADAMS and Carsim, focused on the vehicles, and the path surface was modeled as a set of discrete triangular patches [7,8]. As this path surface model cannot be described by a continuous function that takes the road geometric design invariants as parameters, we can describe the vehicle motion only through the profiles generated by simulations and not via velocity planning based on these geometric design invariants. The vehicle runs on a 3D road surface. This surface has the characteristics of bending and torsion, and its characteristics cannot be unified in a planar rectangular coordinate system. To describe the geometric characteristics of the road surface in a 3D space, the Darboux frame is introduced [9–11]. The Darboux frame has fixed directions, which are tangential and perpendicular to the surface. When the Darboux frame moves along the road, it carries the geometric design invariants of the road as the basis of a vector space over to other types of geometrical spaces, and the vehicle motion can be described in a vector space.

The next stage is to solve the 3D path-planning problem and generate an effective trajectory considering the constraints.

Path planning has historically been conducted in the 2D plane. Motivated by the development of optimal control techniques using Pontryagin's maximum principle (PMP) [12,13], Dubins' algorithm [14] obtained the shortest path between two points in a plane based on straight line segments and arcs of circles and taking into account the maximum turn rate of car-like vehicles. Because the curvature of the path is discontinuous, the vehicle operation is discontinuous at segment connections [15,16]. To address this issue and to control the path "smoothness", Kanayama and Hartman [17] proposed two types of cost functions to smooth the path: path curvature and the derivative of path curvature. Concatenations of clothoids and cubic spirals are proposed through these two functions to solve the path-planning problems. Consistent with this strategy, B-splines [18], fifth-degree polynomials [19], polar splines [20], cardioids [21], G2-splines [22,23], η3-splines [24], and Bézier curves [25], whose coordinates have closed expressions, have been proposed for vehicle path planning. Additionally, clothoids [26] and intrinsic splines [27], whose curvature is a function of their arc length, have also been proposed. However, most of these approaches focused on curve smoothness but not on ensuring that the paths were time-optimal. Fraichard and Scheuer [28] presented a path-planning algorithm with a CC path. The clothoids provided to smooth the angular velocity were generated to connect straight-line segments and circular arcs. As clothoids are curves whose curvatures change linearly with curve length and act as transition segments between circular arcs and straight lines, the resulting paths are the shortest-length paths subject to a constraint on the derivative of the curvature [29].

Fewer articles have addressed vehicle path planning in 3D space, and most of the literature considers unmanned aerial vehicles (UAVs). In 3D space, because the momentum of UAV is through the air, a UAV cannot perform sharp angular movements or rapid stops. Therefore, the planned path should not include vertexes, and the curvature should be continuous to maintain a steady velocity and acceleration [30]. Studies have proposed path-planning algorithms utilizing various curves (quadratic curves [30], Pythagorean hodograph curves [31], B-spline curves [32] and cubic Bézier spiral curves [33]) to obtain various suboptimal paths to perform 3D trajectory smoothing. These algorithms were used to satisfy curvature or torsion constraints but are disadvantageous for real-time implementation [34]; that is, they suffer in terms of simplicity and feasibility. In 3D road path planning, these curves are difficult to design and measure during actual construction. To simplify this problem, the 3D workspace was resolved into horizontal and vertical planes by Belkhouche and Bendjilali [35], and the pitch angle and heading angle were expressed as linear functions of the visibility line angles. When the distance between the initial and final positions on the horizontal plane is much larger than that in the vertical direction, the algorithm is efficient and not far from optimal. Therefore, an improved algorithm [36,37] was generated based on the 2D Dubins curve trajectory. On one hand, the projection of the path on the horizontal plane was a straight line, and the Dubins curve satisfied the curvature radius and pitch angle constraints. On the other hand, another single Dubins curve was exploited to change the flight angle. However, this method did not address the constraint on the continuity of the curvature.

Indeed, the horizontal alignment and vertical profile in the highway design process can be seen as a 3D path-planning algorithm as described previously because the distance between the initial and final positions on the horizontal plane was sufficiently large to adopt the method of plane projection to obtain a suboptimal path. However, the question of whether a path constructed using existing highway design is optimal for vehicles could not be given a reasonable theoretical answer from a 3D perspective previously. In contrast to UAVs, vehicles move under 3D path constraints, and momentum is gained from the ground. Many forces, such as gravitational, centrifugal and inertial forces, obstruct stable movement in a real physical environment. These forces have a greater effect on movements in 3D space; however, as long as slippage does not occur and the path is continuous, the effects of these forces can be neglected [30,38]. Compared with the constraints in the vertical direction, side slip accidents caused by momentum along the path surface are common when the centrifugal force is greater than the lateral force. Moreover, vehicles cannot perform sharp angular movements or rapid stops. Together, these issues necessitate the development of a new method to solve the 3D path-planning problem.

Finally, when the velocity has a certain range of values, the optimal path corresponding to different velocity ranges is different, and the time required also differs; therefore, finding the time-optimal path using the velocity profile is necessary. On the other hand, a velocity planning of the path can be useful to help the driver understand the path to be followed in an efficient, safe, and comfortable way. Indeed, rough command signals could cause wheel slippage and worsen the accuracy of path tracking. To maintain command smoothness, the longitudinal velocity of the car-like vehicle must be continuous and differentiable. Therefore, a longitudinal jerk bound was introduced to generate velocity profiles. M. Lepetič [39] and R. Solea et al. [40] noted that an optimal velocity profile is required to satisfy safety and comfort constraints to a certain degree. That is, velocity, longitudinal and lateral accelerations, and jerk should be upper-bounded. To this end,