Reference Path Optimization for Autonomous Ground Vehicles Driving in Structured Environments

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***Abstract*—This paper focuses on the reference path optimization problem for Autonomous Ground Vehicles driving in structured environments. The reference path optimization algorithm is composed of three steps: data acquisition and curvature calculation, initializing straights of the reference path, using path primitives to connect the turn between the straights. In the process of data acquisition, we get the position of trajectory point and the motion data of vehicle through a probe vehicle equipped with a variety of on-board sensors. Then, the curvature information can be found using the relationship between the curvature and the steering angle of the probe vehicle, and the reference path is decomposed into a straight portion and a turn portion. In the initializing straights step, straights are fitted using the least squares method. Finally, we use clothoid curve as a path primitive to fit the remainder of the reference path. And the gradient descent method is used to improve the accuracy of the fitting path. The experimental results show that the proposed algorithm can effectively eliminate the position, heading angle and curvature noise in the reference path while greatly reducing the memory storage for saving road geometry.**

Keywords-Autonomous ground vehicle; path primitive; path optimization; gradient descent

I. INTRODUCTION

With the strong support of governments and the extensive cooperation of information technology companies, more and more automobile manufacturers and research institutions have been involved in the wave of autonomous driving technology. Autonomous driving technology has been the focus of robotics research. On the other hand, Due to the continuous development of related technologies, the application of AGVs has been greatly expanded [1]. The maturity of autonomous driving technology will improve the efficiency of traffic system and reduce the occurrence of traffic accidents [2]. But so far, the autonomous driving technology is still not mature in complex environments. The path planner plays an important role in the process of autonomous driving. However there are still many problems need to be solved for the path planning in structured environments [3]. A reference path has two important meaning in the AGV: 1) the geometric information of the reference path has a strong constraint on the local path of a vehicle. Usually, we can obtain the reference path by the environment perception information such as lane line and curbs. However, this method cannot guarantee the continuity and smoothness of curvature and heading angle, which may cause the vehicle to generate shock and overshoot in tracking control. 2) An accurate curvature has a strong constraint on the speed planning of AGVs. Therefore, it is necessary to smooth the reference path before local path planning. This paper is devoted to solving the problem of reference path optimization of an autonomous vehicle in structured environments.

II. RELATED WORK

In order to solve the problem of path planning in autonomous driving technology, a lot of research work has been carried out. According to planning objectives, the planning model can be divided into global planning and local planning [3]. The purpose of the global planning is to obtain the reference path, which provides the guidance for AGVs. The spatial scope of global path planning is large, and it needs to consider the road boundaries, road geometry, global maps and other information, so the global path is often acquired off-line [4]. There are many methods to get the reference path. One common method is using the lane line which can be obtained by perception system as reference path. Another method includes obtaining the reference path by fitting the driver's historical waypoints. In addition, the graph-search based method is also widely used [5]. However, these methods can't guarantee the continuity of the curvature and heading angle, leading to overshoot, shock and other negative effects. In order to improve the stability of tracking control, it is essential to smooth the reference path in the global planning.

Scheuer et al. used the method of polynomial curve fitting to smooth the reference path while considers the constraint of curvature continuity [6]. However, this method is sensitive to the noise in the reference path. When the high order polynomial is used to describe a smooth path, the Runge's phenomenon is easy to occur [7]. Shiller et al. used the B-spline curve to smooth the reference point [8], and the spline function uses relatively few discrete point sets, which can avoid the Runge phenomenon. The corresponding boundary conditions can be used to ensure the smoothness and continuity of the entire path. However, imposing boundary conditions on the discrete point set may lead to a large deviation between the fitting path and the actual path. Chen et al. developed the path smoothing method based on

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support vector regression(SVR) [9], but the optimization method has a high requirement for the adjustment of the kernel parameters, and the curvature constraint is not considered in the optimization process. Li et al. applied the conjugate gradient descent method to optimize the reference path, and considers the constraints of the road boundary while smoothing reference path [10]. The optimization objective function used in this method is generally obtained by experience and the design is difficult. Another way to smooth the reference path is using path primitives instead of path points [11]. The path primitives in this paper include straight lines and clothoids, which are widely used in the design of highway [12]. In order to avoid the problems caused by the use of polynomial or spline function, this paper presents a path smoothing method based on path primitives.

The remainder of this paper is organized as follows. In the Part III, we introduce the method of using straight line and clothoid curve to optimize reference path. Part IV shows the experimental results in the campus environment. The final section is a summary and with further discussion.

III. Reference Path Optimization Algorithm

In this section, we describe the proposed reference path optimization algorithm in detail. The reference path optimization algorithm consists of the following three steps. In the first step, the curvature of each way point is calculated based on the relationship between the curvature and steering angle. The second step is based on the curvature data initializing the straight part in the waypoints. In this step, we use the least squares method to fit the straight part. In the third step, the clothoid curve is used as the path primitive to fit the waypoints on the turn, and then the fitting precision is further improved by the gradient descent method.

A. *Calculating curvature of waypoints*

There are two ways to calculate the curvature of waypoints. One way to calculate curvature is based on the position information of the collected waypoints, as showing in (1), where x, y, are the position of waypoints, x', y' are the derivative of x and y respectively. In practice, since the probe vehicle is difficult to acquire waypoints information at a constant speed, the intervals between the waypoints may not be uniform. The direct use of these waypoints to calculate curvature may lead to great deviations.

$$\kappa = \frac{x'y'' - y'x''}{\left(x'^2 + y'^2\right)^{\frac{3}{2}}} \quad (1)$$

Another way is through the relationship between the steering angle of the front wheel and the curvature. The vehicle kinematics model can be built as a bicycle model in low-speed condition because the probe vehicle is based on Ackerman steering structure (Fig. 1). Thus, we can get the relationship between the steering angle of the front wheel and curvature as (2), in this paper we use the second method for simplicity.

$$\kappa = \frac{\tan\delta}{L} \quad (2)$$

Where δ denotes the steering angle of the front wheel, L denotes the wheelbase, κ is the curvature. In addition, the curvature is positive for the left turn and the curvature is negative for the right turn.

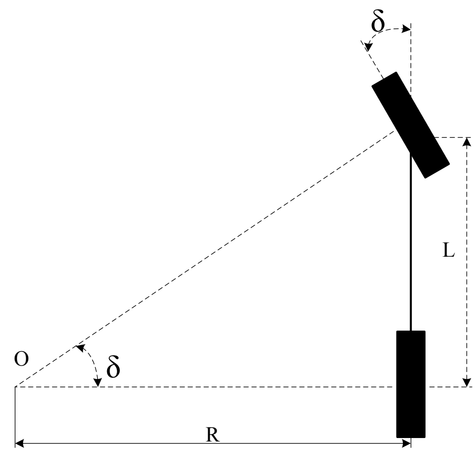

Figure 1. Bicycle model of Ackerman steered vehicle.

B. *Initialize the straights of waypoints*

A road can be divided into straights and turns. According to the curvature in the historic waypoints of the probe vehicle, waypoints can be approximated as straight when the curvature of these part is less than a certain threshold. Based on practical experience, the curvature threshold is set to $0.0035m^{-1}$. The red portion in Fig. 2 represents the curvature of the corresponding point in the straight. Then, these red waypoints are approximated as straight using the least squares method.

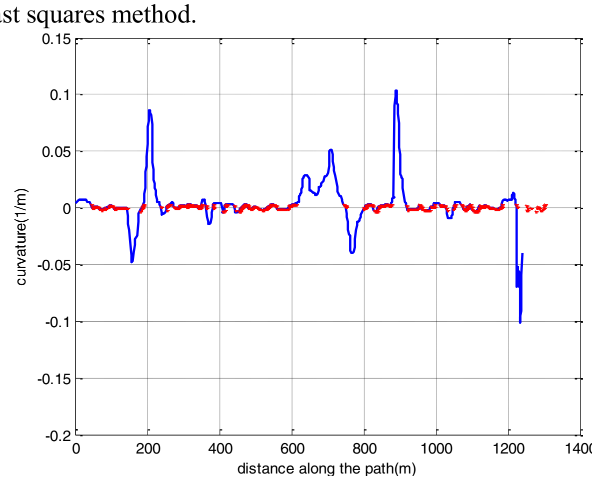

Figure 2. Waypoints and corresponding curvature.

We use the least squares method to fit a continuous point with a smaller curvature into a straight. The function of a straight is: $y = a + bx$. When estimating the parameters with