MOTION TRAJECTORY PLANNING METHOD OF LANE CHANGE FOR INTELLIGENT VEHICLE

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ABSTRACT

The motion planning method of lane change for intelligent vehicle is an important component in the autonomous vehicle field. In order to make the intelligent vehicle drive on the urban environmental road smoothly when there is a barrier in the front, a new curvature-continuous obstacle avoidance trajectory planning method was introduced. The trajectory planning method based B-spline curves and the convex hull property of the B-spline curves is used. The effection of several nonholonomic constrained conditions is considered in this method. The nonholonomic constraints include obstacle avoidance constraint, curvature constraint, rotational speed constraint, speed constraint, state constraint and so on. The intelligent vehicle's lane change reference trajectory is generated, the trajectory is collision-free and the curvature is continuous. The intelligent vehicle's lane change simulation experiment was done to test the trajectory planning method. The result showed that the feasible trajectory can be generated by use of this article's method. The curvature of the trajectory is continuous and every nonholonomic constraint condition was met.

Keywords: *Intelligent Vehicle, Motion Trajectory Planning, Continuous Curvature, Lane Change, B-spline Curve*

1 INTRODUCTION

The intelligent vehicle is an important component of intelligent transportation system, the study of intelligent vehicle is becoming more and more important[1,2]. The dynamic trajectory planning technology is the precondition of the vehicle's automatic control technology. The lane change motion trajectory planning technology of the vehicle is a key technology[3,4].

Many trajectory planning techniques for autonomous vehicles have been discussed in the literature. Among them, much of work on search algorithms provide computationally efficient way in discrete state spaces[5,6]. However, the resulting trajectories by such algorithms do not tend to be smooth and hence do not satisfy kinematic feasibility of the vehicle. Dubins trajectory is one of the most well-known methods to generate a smooth trajectory[7]. The trajectory has a drawback of discontinuity of curvature at the joint nodes connecting the lines and arcs. Tracking such trajectory requires a vehicle to stop and reposition in order to alter its steering angle. So curvature continuity is an important requirement for trajectory guidance applications. B-spline curve's curvature is continuous and some trajectory planning techniques have been discussed based on B-spline curves[8,9].

Our trajectory planning algorithm is based on the B-spline curves and the convex hull property of the B-spline curves is used. The algorithm imposes obstacle avoidance constraint, curvature constraint, rotational speed constraint, speed constraint, state constraint such that the trajectory is curvature-continuous and the vehicle can track the planned trajectory collision-freely.

2 THE VEHICLE MODEL

The simplified model of the autonomous vehicle can be expressed in the Fig. 1. Where i defines the position of the rear axle's midpoint in an Euclidean reference frame. The vehicle's front wheel is steering wheel and the rear wheel is driving wheel. The kinematics of a vehicle having axle base L can be described by a kinematic model satisfying as Eq. 1:
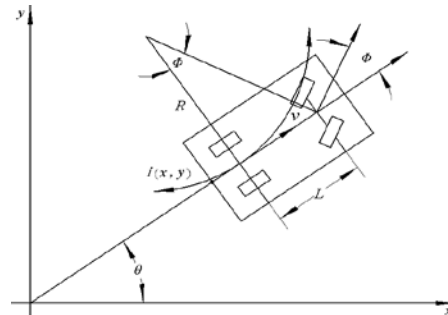

Fig 1. The Vehicle Model

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{k} \end{bmatrix} = \begin{bmatrix} \cos\theta \\ \sin\theta \\ k \\ 0 \end{bmatrix} v + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \sigma \qquad (1)$$

Where:

$$k = (1/L)\tan\varphi, \quad \sigma = \dot{k} = \omega/L\cos^2\varphi \quad (2)$$

Where θ means the orientation of the vehicle relative to the x-axis and φ is the front wheel's steering angle, R is the vehicle's curvature radius, the inputs v and ω are the vehicle's linear velocity at the point i and the steering angular velocity, respectively. The state vector is $q = [x, y, \theta, k]^T$. Furthermore, the curvature and the curvature change rate are restricted according to:

$$|k| \le k_{max} = \frac{1}{L}\tan\varphi_{max}$$

$$|\sigma| \le \sigma_{max} = \frac{1}{L}\omega_{max} \le \frac{1}{L\cos^2\varphi}\omega_{max} \qquad (3)$$

3 MAKE SURE OF THE STARTING POSITION

The parameters of lane change driving when the vehicle running on the urban environmental road is shown as Fig. 2.
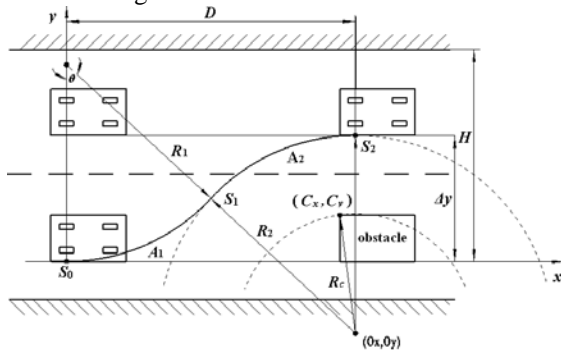

Fig.2 The Parameters Of Lane Change Driving

The lane change driving is mainly decided by three parameters: the parallel distance D between the starting and the ending positions, the arc of circumference A_2 of radius R_2 and the arc of circumference A_1 of radius R_1. The relationship equations is as follows:

$$\begin{aligned} (R_1 + R_2)\sin\theta - D &= 0 \\ (R_1 + R_2)(1-\cos\theta) &= \Delta y \end{aligned} \qquad (4)$$

Where θ and Δy are defined in Fig. 2, H is the lateral distance between the obstacle and the road side. Each value of the parameters [R_1, R_2, D] can determines a lane change driving.

The trajectory is a collision-free trajectory if the following condition is satisfied:

$$R_1 < R_{1max} \qquad R_2 \in [R_{2min}, R_{2max}] \qquad (5)$$

$$R_{1max} = \frac{C_x^2 + C_y^2 - L^2}{2P_y}$$

$$R_{2min} = \frac{|d^2 + L^2 - (H-\Delta y)^2|}{2(H-\Delta y - d)} \qquad (6)$$

$$R_{2max} = \frac{\Delta y}{1-\cos\theta_{max}} - R_1$$

Where d is the wide of the vehicle, L is the wheelbase, θ_{max} is the maximum value of θ when the trajectory is tangent to the point (C_x, C_y) and R_1, $R_2 > R_{min}$.

When $R_1 = R_{min}$ and $R_2 = R_{2min}$, the distance D of the collision-free trajectory is the minimum value:

$$D_{min} = \sqrt{2\Delta y (R_{min} + R_{2min}) - \Delta y^2} \qquad (7)$$

When $R_1 = R_{min}$ and $R_2 = R_{2max}$, the distance D of the collision-free trajectory is the maximum value:

$$D_{max} = \sqrt{2\Delta y (R_{min} + R_{2max}) - \Delta y^2} \qquad (8)$$

4 THE TRJECTORY PLANNING METHOD BASED B-SPLINE CURVE

4.1 B-Spline Curve

A *B*-spline curve is a parametric curve whose curvature is continuous even at the joints between adjacent segments. This type of curves is specified by a set of points called control vertices. Let the control polygon be composed of control vertices [V_0, V_1, . . . , V_m], the curve will be composed of $m-2$ segments. Thus, the ith curve segment is determined by four control vertices V_{i+r}, r =-2, -1, 0, 1. The coordinates of the point $Q_{i,4}(u)$ on the ith curve segment are:

$$Q_i(u) = \sum_{r=-2}^{1} b_r(\beta_1, \beta_2, u)V_{i+r} \qquad (9)$$

Where $0 \le u < 1$; $i = 2, 3, ...$, the weighting factors b_r are scalar functions evaluated at any value of the domain parameter u and on each shape parameter β_1 and β_2.

Previous works have experimentally shown that cubic splines represent the best choice. In that case, $\beta_1 = 0$, $\beta_2 = 0$ and the weighting factors are defined by:

$$\begin{bmatrix} b_{-2,4}(u) \\ b_{-1,4}(u) \\ b_{0,4}(u) \\ b_{1,4}(u) \end{bmatrix} = \begin{bmatrix} \frac{1}{6} & -\frac{1}{2} & \frac{1}{2} & -\frac{1}{6} \\ \frac{2}{3} & 0 & -1 & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \\ 0 & 0 & 0 & \frac{1}{6} \end{bmatrix} \times \begin{bmatrix} 1 \\ u \\ u^2 \\ u^3 \end{bmatrix} \quad (10)$$

One of the most significant property of the *B*-spline curves is the convex hull. If the control vertices are over an arc of circumference and the distance δ between them is regular, an important consequence can be derived[10]. Let the vertices of a *B*-spline segment be over an arc of the circumference C of radius R (see Fig. 3). If the
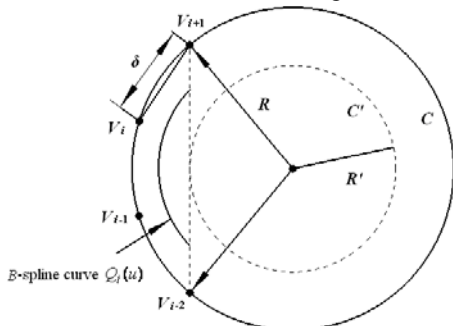

Fig.3 Sketch Of Control Vertices Over An Arc Of Circumference

distance between them is δ, where $\delta \leq (\pi/6)R$, then the *B*-spline segment is out of the circle C', whose radius R' is:

$$R' < R\cos\left(\frac{3\delta}{2R}\right) \quad (11)$$

It can be experimentally tested that the curvature radius of the segment is upper bounded by R and lower bounded by R'. Therefore, if the value of the curvature radius of the segment has to be kept between R and R', then δ should satisfy:

$$\delta < \frac{2R}{3}a\cos\left(\frac{R'}{R}\right) \quad (12)$$

This constraint also assures that the segment will be between both arcs of circumference.

4.2 Selection Of Δs
4.2.1 Collision-free constraint
According to the Fig.2, only the curve's curvature radius is between the arc of R_2 and the arc of R_c, the trajectory meet the collision-free condition. R_c is the minimum radius avoiding the collision of the vehicle's right front and right behind. The value of R_c is as follows:

$$R_c = \sqrt{\left(C_x - O_x\right)^2 + \left(C_y - O_x\right)^2} \quad (13)$$

Where (O_x, O_y) is the centre of the arc A_2. We can see from the Fig. 3 and Eq. 4 that:

$$\begin{aligned} O_x &= D = (R_1 + R_2)\sin\theta \\ O_y &= R_2 - \Delta y \end{aligned} \quad (14)$$

Then, according to Eq. 12 the trajectory is collision-free if the following sufficient condition is satisfied:

$$\delta_s \leq \delta_1 < \frac{2R_2}{3}a\cos\left(\frac{R_c}{R_2}\right) \quad (15)$$

Due to the fact that R_{2min} is the lowest value of R_2, the trajectory is collision-free if the curvature radius is over R_{2min}, according to Eq. 12, we can get:

$$\delta_s \leq \delta_2 < \frac{2R_2}{3}a\cos\left(\frac{R_{2min}}{R_2}\right) \quad (16)$$

4.2.2 Bounded curvature
The curve radius' value of an admissible trajectory has to be over the minimum radius R_{min} of the vehicle: $R_1 \geq R_{min}$, $R_2 \geq R_{min}$. Then, according to the previous section the trajectory should meet this condition:

$$\begin{aligned} \delta_s &\leq \delta_3 < \frac{2R_1}{3}a\cos\left(\frac{R_{min}}{R_1}\right) \\ \delta_s &\leq \delta_4 < \frac{2R_2}{3}a\cos\left(\frac{R_{min}}{R_2}\right) \end{aligned} \quad (17)$$

4.2.3 Steering velocity constraint
Although *B*-spline curves are curvature-continuous trajectory, the curvature's change should be smooth enough for a successful trajectory tracking. It can be experimentally illustrated that changes for lane change running. The changes of curvature can be approximated by the linear relations as Fig. 4. The curvature change need to meet the Eq. 18.
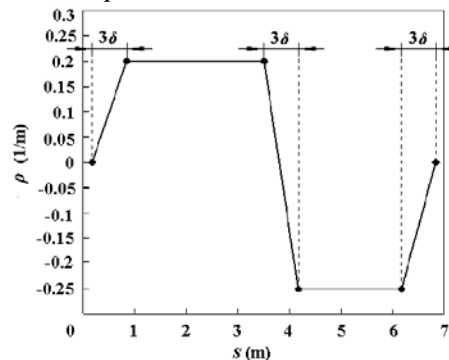

Fig.4 Change Chart Of Spline's Curvature

$$\left.\frac{d\rho}{ds}\right|_{s_0}^{s_1} < m_1 = k_1 \cdot \frac{|\rho_1|}{3\delta}$$

$$\left.\frac{d\rho}{ds}\right|_{s_2}^{s_3} < m_2 = k_2 \cdot \frac{|\rho_1| + |\rho_2|}{3\delta} \qquad (18)$$

$$\left.\frac{d\rho}{ds}\right|_{s_4}^{s_5} < m_3 = k_3 \cdot \frac{|\rho_2|}{3\delta}$$

If $v = ds/dt$ represents the vehicle linear velocity, the curvature change velocity will satisfy:

$$\left.\frac{d\rho}{dt}\right|_{t_0}^{t_1} < m_1 v$$

$$\left.\frac{d\rho}{dt}\right|_{t_2}^{t_3} < m_2 v \qquad (19)$$

$$\left.\frac{d\rho}{dt}\right|_{t_4}^{t_5} < m_3 v$$

Where $[t_0, t_1]$, $[t_2, t_3]$, $[t_4, t_5]$ represent the period of time when the curvature is changing. On the other hand, the curvature change velocity due to the steering system is:

$$\dot{\rho} = \frac{\dot{\varphi}}{L \cdot \cos\varphi^2} \qquad (20)$$

If $\dot{\phi}_{max}$ is the maximum angular velocity of the steering system, only the curvature velocity change meets Eq. 21 along the curve, the steering mechanism could properly follow the curve.

$$k \cdot \frac{|\rho|}{3\delta} \cdot v = |\dot{\rho}| \le \dot{\rho}_m = \left|\frac{\dot{\varphi}_{max}}{L}\right| \qquad (21)$$

We can gain that the value of δ_s satisfies the following constraints:

$$\delta_s \ge \delta_5 = \frac{k_1 \cdot |\rho_1| v \cdot L}{3\dot{\varphi}_{max}}$$

$$\delta_s \ge \delta_6 = \frac{k_1 \cdot (|\rho_1| + |\rho_2|) v \cdot L}{3\dot{\varphi}_{max}} \qquad (22)$$

$$\delta_s \ge \delta_7 = \frac{k_2 \cdot |\rho_2| v \cdot L}{3\dot{\varphi}_{max}}$$

Where k_1=6.6, k_2=3.2 and k_3=6.6 have been experimentally gained.

4.2.4   Make sure the value of δ_s

In order to generate B-spline curve, the value of δ_s can be accomplished from (15), (16), (17), (22):

$$\max(\delta_5, \delta_6, \delta_7) = \delta_{vel} \le \delta_s \le \delta_{col} \qquad (23)$$
$$= \min(\delta_1, \delta_2, \delta_3, \delta_4)$$

The value δ_{vel} is chosen for practical reasons. Further evaluation assures that this selection accomplishes the constraint condition $\delta_s \le \delta_{col}$. Considering that $(\delta_1, \delta_2, \delta_3, \delta_4)$ are mainly related to geometrical constraints, while $(\delta_5, \delta_6, \delta_7)$ depend on the vehicle velocity and the velocity of the steering system. It could be possible to have $\delta_{vel} > \delta_{col}$, in this case, $\delta_s = \delta_{col}$. We can see from the Eq. 22 that if the constraint condition is met then the initial velocity v_{ini} have to change. The velocity's upper bound is:

$$v \le v_1 = \frac{3 \cdot \dot{\phi}_{max} \cdot \delta_s}{k_1 \cdot |\rho_1| \cdot L}$$

$$v \le v_2 = \frac{3 \cdot \dot{\phi}_{max} \cdot \delta_s}{k_2 \cdot (|\rho_1| + |\rho_2|) \cdot L} \qquad (24)$$

$$v \le v_3 = \frac{3 \cdot \dot{\phi}_{max} \cdot \delta_s}{k_3 \cdot |\rho_2| \cdot L}$$

We choose the $v_{max} = \min(v_1, v_2, v_3)$ as the new velocity. But the value of the velocity can not lower than the minimum velocity v_{low}, if v is bellow this value, the vehicle has to perform a discontinuous curvature trajectory.

4.3   The Generation Of The Vertices

In order to generate feasible trajectory, not only the starting and ending points should belong to the B-spline curve, but also the curve has to be tangent to the vehicle orientation. Auxiliary vertices are created at each extreme in order to achieve such conditions. If the first vertex is V_0 and $\dot{\rho}_s$, $\ddot{\rho}_s$ are the first and the second derivative vector specifications, respectively. Then three phantom vertices are given by:

$$V_{-1} = V_0 + \dot{\rho}_s + \frac{1}{3}\ddot{\rho}_s$$

$$V_{-2} = V_0 - \frac{1}{6}\ddot{\rho}_s \qquad (25)$$

$$V_{-3} = V_0 - \dot{\rho}_s + \frac{1}{3}\ddot{\rho}_s$$

If V_m is the last vertex, three more vertices are defined: V_{m+1}, V_{m+2} and V_{m+3}. The values are determined by an equation similar to Eq. 25. In this paper the value $\ddot{\rho}_s$ =0 has been used.

The trajectory planning problem is changed to the selection of δ_s. The value of δ_s is ensured through considering several constraint conditions. By means of using the starting and ending point's position of the vehicle, the B-spline vertices' position is determined. So the B-spline curve's shape is ensured.

5 SIMULATION EXPERIMENTAL RESULTS

According to the urban environmental road environment, the vehicle lane change driving simulation experiment was done to test this article's method. A certain type of vehicle's length and width is 4.199 m and 1.786 m, respectively, the axle base is 2.578 m., the maximum curvature is ρ_{max}=0.165 m^{-1}, the maximum angle velocity is φ_{max}=0.4 rad/s, the initial velocity is v_{ini}=8 m/s, the minimum velocity is v_{low}=6 m/s. By means of using the trajectory planning method, the simulation experiment results of the vehicle lane change driving are shown in Fig. 5 and Fig. 6. Fig. 5 is
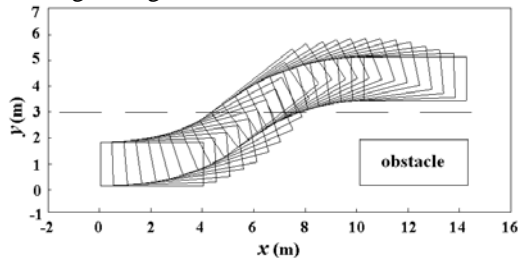

Fig.5 The Result Of The Vehicle Lane Change Driving Using This article's method
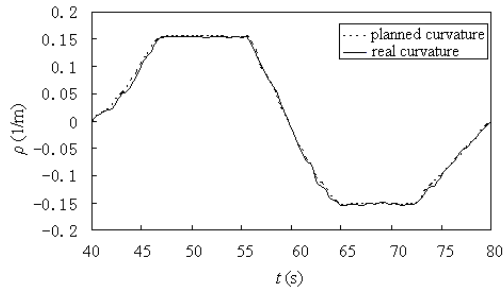

Fig. 6 The Change Of The Curvature

the result of the vehicle lane change driving using this article's method. Fig. 6 is the change of the curvature.

In Fig.5 and Fig.6, a curvature-continuous reference trajectory is generated and the vehicle can follow the planned trajectory smoothly within the constraints. In this experiment, δ_{col}=0.65 m and δ_{vel}=0.87 m. According to Section 4.2.4, the value of δ_s was chosen as δ_s=δ_{col}=0.65 m. As a consequence of not reducing the velocity, the steering system cannot follow appropriately the curvature change. Notice that a feasible driving would be obtained with v_{max}=7.7 m/s, v_{max}>v_{low}. The maximum angle velocity is φ=0.36 rad/s in this experiment, φ=0.36 rad/s<φ_{max}=0.4 rad/s. Therefore, the driving was successfully executed.

We can see from the experiment that the vehicle can follow the trajectory smoothly and collision-freely by using this article's method.

6 CONCLUSIONS

In this paper a method of lane change for intelligent vehicle to generate curvature-continuous trajectory has been presented. The conclusions can be summarized as follows:

(1) The planned trajectory is curvature-continuous by using the method. This property can ensure the vehicle to follow the planned trajectory smoothly.

(2) Several constraint conditions have been considered to assure the existence of collision-free admissible trajectory in the method. The vehicle can track the trajectory accurately.

(3) The simulation experiment results showed that this article's method is reasonable and feasible. The vehicle can follow the trajectory smoothly and collision-freely.

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