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Trajectory Tracking Control for Vehicle Lane Changing Considering Sideslip Speed

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Abstract. In this paper, based on the predetermined virtual trajectory, the reference yaw angle for lane changing was generated. From the dynamical model of front and rear wheel steering vehicle, considering the influence of sideslip speed, a track error model of vehicle for lane changing is established. By applying sliding mode technology, the tracking control law for lane changing was designed. Based on Lyapunov function method, the stability of the control system was obtained. Expected tracking performance is verified by the simulation.

Introduction

In recent years, research on the vehicle automatic lane changing mainly involves the trajectory planning for lane changing and tracking control of the planned lane changing trajectory. The modeling of tracking error should take into account the influence of the longitudinal and lateral velocity of the vehicle, but in order to facilitate studies, many researches on trajectory tracking control neglects the effect of sideslip speed, such as refs.[1,2]. Ref.[3] considers the influence of sideslip speed of vehicle when studying the trajectory tracking control of the intelligent vehicle, but the vehicle dynamics model adopted was based on the front wheel steering. According to the method of ref.[4], when the trajectory tracking control is performed on the front wheel steering vehicle, it is not guaranteed that the position tracking error and the yaw angle error simultaneously tend to 0. In ref.[5], the four-wheel steering dynamics model is used to study the vehicle lane change tracking control, which can simultaneously guarantee the asymptotic stability of position tracking error and yaw angle error. However, when planning the lane change trajectory, it assumes that the desired lateral acceleration satisfies the positive and negative trapezoidal constraints, while the longitudinal speed is fixed and does not take into account the real-time requirements of lane changing behavior on the longitudinal speed of vehicle.

In this paper, we continue to study the trajectory tracking control of vehicle for lane change on the basis of ref.[5]. According to the longitudinal and lateral movement constraints of the vehicle in the lane changing process, we designed the lane changing trajectory based on the five-order multinomial and cancelled the limitation of the assumption that the longitudinal speed is constant. Based on the dynamical model of front and rear wheel steering vehicle, consider the influence of sideslip speed, the tracking control law for lane changing was designed.

Trajectory for lane changing

The global orthogonal coordinate system XOY is established with the starting position of the lane change as the origin, in which the X-axis coincides with the longitudinal axis of the vehicle, and assumed that the direction of travel of the vehicle is positive; the Y-axis is perpendicular to the X-axis, and the direction from the starting lane to the destination lane is positive. The desired displacement of the vehicle center of mass M in the X-axis direction is $X_d(t)$, and the desired displacement in the Y-axis direction is $Y_d(t)$. The trajectory model for lane changing based on five-order multinomial can be expressed as

$$\begin{cases} X_d(t) = a_5 t^5 + a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0 . \\ Y_d(t) = b_5 t^5 + b_4 t^4 + b_3 t^3 + b_2 t^2 + b_1 t + b_0 . \end{cases} \tag{1}$$

Where a_i and b_i is undetermined coefficient, $i = 0,1,\ldots,5$. The direction of vehicle longitudinal velocity should be consistent with the tangential direction of lane changing, so the desired yaw angle of the vehicle ψ_d should be equal to the angle between the direction of the track tangent and the direction of the lane, so we have

$$\psi_d(t) = \operatorname{atan}\frac{\dot{Y}_d(t)}{\dot{X}_d(t)} . \tag{2}$$

Trajectory tracking for lane changing

From automotive theory, a longitudinal and lateral decoupled dynamics model is given by

$$\ddot{x} = \frac{1}{\delta m}\left(\frac{T_{tb}\eta}{r} - mgf - C\dot{x}^2\right). \tag{3}$$

$$\ddot{\psi} = -\frac{2(C_f l_f^2 + C_r l_r^2)}{I_z \dot{x}}\dot{\psi} - \frac{2(C_f l_f - C_r l_r)}{I_z \dot{x}}\dot{y} + \frac{2C_f l_f}{I_z}\delta_f - \frac{2C_r l_r}{I_z}\delta_r . \tag{4}$$

$$\ddot{y} = -\frac{2(C_f + C_r)}{m\dot{x}}\dot{y} - \left[\dot{x} + \frac{2(C_f l_f - C_r l_r)}{m\dot{x}}\right]\dot{\psi} + \frac{2C_f}{m}\delta_f + \frac{2C_r}{m}\delta_r . \tag{5}$$

where m is the total vehicle mass, δ is correction coefficient of rotating mass, T_{tb} is the driving or braking torque on the wheel, η is driving or braking efficiency, r is wheel radius, f is rolling resistance coefficient, C is air resistance coefficient, ψ denotes the vehicle yaw angle, y denotes lateral displacement, x denotes longitudinal displacement, I_z denotes the total vehicle inertia about vertical axis, l_f and l_r are the distance of front and rear axle from center of gravity of vehicle, respectively, C_f and C_r are the front and rear tire cornering stiffness, respectively, δ_f and δ_r are the steering angles for the front and rear wheel. Let the parameters

$$F = \frac{T_{tb}\eta}{\delta m r},\ a_1 = -\frac{gf}{\delta},\ a_2 = -\frac{C}{\delta m}. \tag{6}$$

$$b_1 = -\frac{2(C_f l_f^2 + C_r l_r^2)}{I_z \dot{x}},\ b_2 = -\frac{2(C_f l_f - C_r l_r)}{I_z \dot{x}}. \tag{7}$$

$$c_1 = -\frac{2(C_f + C_r)}{m\dot{x}},\ c_2 = -\dot{x} - \frac{2(C_f l_f - C_r l_r)}{m\dot{x}} . \tag{8}$$

$$u_1 = \frac{2C_f l_f}{I_z}\delta_f - \frac{2C_r l_r}{I_z}\delta_r,\ u_2 = \frac{2C_f}{m}\delta_f + \frac{2C_r}{m}\delta_r . \tag{9}$$

The eqs. (3)-(5) can be rewritten as

$$\ddot{x} = F + a_1 + a_2\dot{x}^2 . \tag{10}$$

$$\ddot{\psi} = b_1\dot{\psi} + b_2\dot{y} + u_1 . \tag{11}$$

$$\ddot{y} = c_1\dot{y} + c_2\dot{\psi} + u_2 . \tag{12}$$

Considering the sideslip speed, the speed of the vehicle along the axis of the global coordinate system can be expressed as

$$\dot{X} = \dot{x}\cos\psi - \dot{y}\sin\psi,\ \dot{Y} = \dot{x}\sin\psi + \dot{y}\cos\psi . \tag{13}$$

Considering eq. (13), the acceleration along the axis can be expressed as

$$\ddot{X} = \ddot{x}\cos\psi - \ddot{y}\sin\psi + w_1,\ \ddot{Y} = \ddot{x}\sin\psi + \ddot{y}\cos\psi + w_2. \tag{14}$$

Where $w_1 = \dot{x}\dot{\psi}\sin\psi - \dot{y}\dot{\psi}\cos\psi$, $w_2 = \dot{x}\dot{\psi}\cos\psi - \dot{y}\dot{\psi}\sin\psi$. Define tracking error as follows:

$$e_\psi = \psi - \psi_d,\ e_X = X - X_d,\ e_Y = Y - Y_d. \tag{15}$$

So

$$\begin{cases} \ddot{e}_\psi = \ddot{\psi} - \ddot{\psi}_d. \\ \ddot{e}_X = \ddot{x}\cos\psi - \ddot{y}\sin\psi + w_1 - \ddot{X}_d. \\ \ddot{e}_Y = \ddot{x}\sin\psi + \ddot{y}\cos\psi + w_2 - \ddot{Y}_d. \end{cases} \tag{16}$$

Applying sliding mode technology, we design the switch function as

$$S = \dot{e} + ke. \tag{17}$$

Where $\mathrm{S} = [S_\psi, S_X, S_Y]^{\mathrm{T}}$, $\mathrm{e} = [e_\psi, e_X, e_Y]^{\mathrm{T}}$, and $\mathrm{k} = \mathrm{diag}(k_1, k_2, k_3)$, is the positive definite switching function parameter matrix. Adopt the form of approaching law $\dot{S} = -\lambda S$, we have

$$\ddot{e} + k\dot{e} + \lambda S = 0. \tag{18}$$

where $\lambda = diag(\lambda_1, \lambda_2, \lambda_3)$, is the positive definite reaching law parameter matrix. Substituting eq. (16) into eq. (18), we obtain

$$\ddot{\psi} = D_1,\ \ddot{x} = D_2\cos\psi + D_3\sin\psi,\ \ddot{y} = -D_2\sin\psi + D_3\cos\psi. \tag{19}$$

Where

$$\begin{cases} D_1 = \ddot{\psi}_d - k_1\dot{e}_\psi - \lambda_1 S_\psi \\ D_2 = -w_1 + \ddot{X}_d - k_2\dot{e}_X - \lambda_2 S_X \\ D_3 = -w_2 + \ddot{Y}_d - k_3\dot{e}_Y - \lambda_3 S_Y \end{cases}$$

From eqs. (10)-(12), we have

$$\begin{cases} F = D_2\cos\psi + D_3\sin\psi - a_1 - a_2\dot{x}^2 \\ u_1 = D_1 - b_1\dot{y} - b_2\dot{\psi} \\ u_2 = -D_2\sin\psi + D_3\cos\psi - c_1\dot{\psi} - c_2\dot{y}_2 \end{cases} \tag{20}$$

Then from the above eqs. (6) and (9), we get

$$\begin{cases} T_{tb} = \delta mrF/\eta \\ \delta_f = (b_{12}u_2 - b_{22}u_1)/(b_{12}b_{21} - b_{11}b_{22}) \\ \delta_r = (b_{11}u_2 - b_{21}u_1)/(b_{11}b_{22} - b_{12}b_{21}) \end{cases} \tag{21}$$

Where $b_{11} = \dfrac{2C_f l_f}{I_z}$, $b_{12} = -\dfrac{2C_r l_r}{I_z}$, $b_{21} = \dfrac{2C_f}{m}$, $b_{22} = \dfrac{2C_r}{m}$.

Define a Lyapunov function as $V = \frac{1}{2}(S_\psi^2 + S_X^2 + S_Y^2)$, calculating the derivative of eq. (17), from eqs. (3), (4), (5) and (21), we obtain $\dot{V} = S_\psi\dot{S}_\psi + S_X\dot{S}_X + S_Y\dot{S}_Y = -(\lambda_1 S_\psi^2 + \lambda_2 S_X^2 + \lambda_3 S_Y^2) \le 0$. So the system is asymptotically stable when moving along the sliding mode.

Simulation results

In simulation, assuming that the vehicle mass m=1250kg, correction coefficient of rotating mass δ=1.1,the driving or braking efficiency η=0.95, the wheel radius r=0.32m, the rolling resistance coefficient f=0.02,the air resistance coefficient, C=0.45, the moment of inertia I_z=2800kgm^2, the front and rear tire cornering stiffness C_f=70kN/rad, and C_r=75kN/rad, the distance of front and rear axle from center of gravity of vehicle l_f=1.35m, and l_r=1.25m.

Simulation results of trajectory tracking for lane changing are given in Figures 1 to 3. Figs.1 and 2 show the tracking errors along the X-axis and the Y-axis; the yaw angle error of vehicle is shown in Fig.3. From the figures, the position tracking error and yaw angle error tend to be zero with the control method in this paper, it indicates that the control system has asymptotic stability. If ignore the influence of the side-slip speed factor in the tracking error modeling, tracking control of the car cannot guarantee that the position tracking error and the yaw angle error both tend to zero, the simulation results are shown in Fig.4.

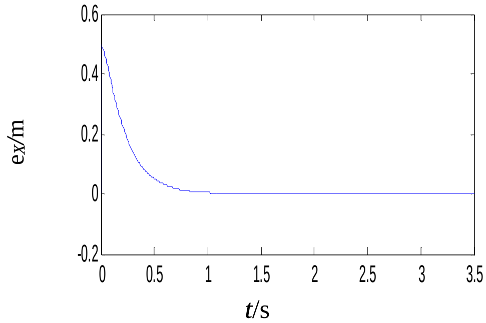

Fig.1 Position error of vehicle along X axis

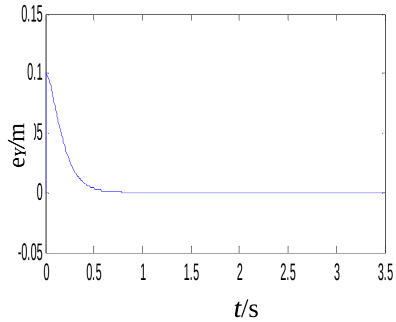

Fig.2 Position error of vehicle along X axis

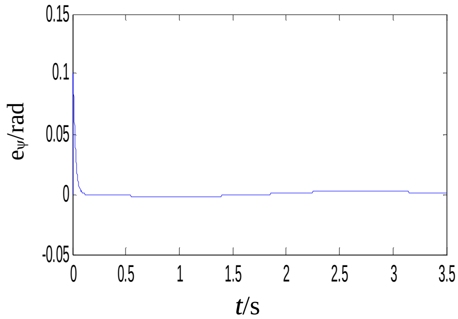

Fig.3 Yaw angle error of vehicle

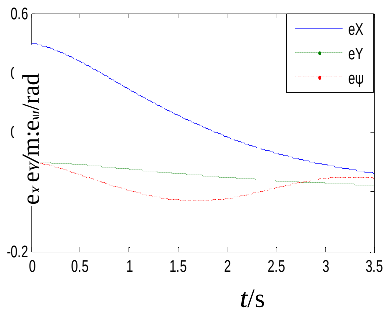

Fig.4 Vehicle position and yaw angle error

Conclusions

In this paper, the control law is designed by sliding mode method. Due to the established tracking error model takes into account the influence of side slip speed, and the dynamic model of front and rear wheels is used, the control law designed in this paper can ensure that the position error and yaw angle error asymptotically approaches zero and the longitudinal speed is not assumed to be constant, compared with the existing trajectory tracking control method, the control law is more general.

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