IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 15, Issue 4 Ver. V (Jul. - Aug. 2018), PP 26-33
www.iosrjournals.org

Direct Adaptive Terminal Sliding Mode Control for Lane Changing of Vehicle in Intelligent Transportation Systems

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Abstract : *In the presence of parametric uncertainty, such as the mass, inertia of vehicle about vertical axis, and tire cornering stiffness, the adaptive control method for lane changing of vehicle in intelligent transportation systems was studied. With positive and negative trapezoidal constraint for lateral acceleration, the desired yaw angle and yaw rate of vehicle was generated by the virtual lane changing trajectory. Based on the lateral dynamical model of four-wheel-steering vehicle, by applying terminal sliding mode technology, the yaw-rate tracking control law for lane changing was designed and the estimation formula for uncertain control parameters was deduced by using direct adaptive method. Based on the Lyapunov theory, the stability property of the system was obtained. By using the control law and adaptive law for uncertain parameter designed in this paper, expected control performance of asymptotic stability of tracking error and the convergence property of parameter estimation values was verified from the simulation.*

Keywords - *intelligent transportation; adaptive control; four-wheel-steering; automatic lane changing; terminal sliding mode*

Date of Submission: 13-08-2018 Date of acceptance: 30-08-2018

I. Introduction

Intelligent Transportation System is one of the most advanced research topics in the field of transportation in the world[1]. It is also the best way to solve the problems of urban traffic congestion, enhance traffic safety, improve operation efficiency and reduce air pollution. Intelligent vehicle is an important branch of Intelligent Transportation system[2]. Its research goal is to use various sensors and intelligent highway technology to realize auto self-driving and to improve ride safety and comfort. For the convenience of research on automatic driving control technology of intelligent vehicle, it is generally divided into two aspects: longitudinal control and lateral control.

Automatic vehicle lane change belongs to the research content of lateral control of intelligent vehicle, which refers to the automatic control process of vehicle entering another lane along the desired trajectory from one lane[3]. There are many methods for lane change trajectory planning. For example, when the vehicle changes lanes, the desired trajectory satisfies the constraints of arc, sine function or polynomial, the desired lateral acceleration satisfies the constraints of the positive and negative trapezoids [4]. The latter method is based on the time requirement for lane changing, combined with the vehicle dynamics characteristics to determine the lane change trajectory by selecting the desired lateral acceleration, and the application is more flexible. Regarding the design of vehicle lane change control system, literature [5] uses the optimal control theory to design the vehicle lane change controller, literature [6] uses the global positioning system to research on lane changing fuzzy control for vehicle overtaking. In literature [7], the lane change behavior for collision avoidance of vehicle is studied, and the control system is designed based on the model predictive control. Due to the uncertainty of vehicle parameters, literature [8] studied the adaptive control for vehicle lane change. In literature [9], the Kalman filter method is used to process the lane and vehicle state information when the vehicle is changing lanes. The literature [10] uses the terminal sliding mode method to study the vehicle lane change trajectory planning and tracking control on the curved road. Due to the interaction between longitudinal and lateral motions of vehicles, in literature [11], considering the strong coupling of longitudinal and lateral motions of vehicles, an integrated Backstepping method is used to design a trajectory tracking controller. The lane change described above is studied for a single vehicle. When a vehicle runs on the road, its state will be affected by the moving state of the adjacent vehicle. In order to ensure the consistency of the vehicles changing lane behavior, literature [12] research on the platoon's lane change control strategy.

The lane change studied of vehicle in the above literature is based on the front wheel steering dynamics model. However, based on the control law by using the front wheel steering model, when the trajectory tracking control of the vehicle is performed, the position tracking error and the yaw angle error cannot be guaranteed to reach 0 at the same time [13]. Literatures [14] and [15] were based on four-wheel active steering technology to study vehicle lateral control, but only involve the lane keeping control, the lane change behavior is not specifically researched. In literature [16], based on the four-wheel steering dynamics model, the vehicle lane change control is studied, and the asymptotic stability of the tracking error during changing lane process is guaranteed by designing the front and rear wheel steering angle inputs reasonably. However, the literature [16] does not consider the uncertainty of vehicle parameters. In this paper, the uncertainty of vehicle parameters such as mass, moment of inertia and tire cornering stiffness is considered. Based on the four-wheel active steering model, the terminal sliding mode control technology is used to study the control law for lane change of vehicle and the estimation formula for uncertain parameters was deduced by using direct adaptive method.

II. Vehicle Dynamics Model

The vehicle dynamics model used in this paper originates from the ideal model proposed by Ackermann, without considering the longitudinal velocity changes of the vehicle and the effects of the roll motion. According to the automobile theory [17], the lateral dynamics model of the four-wheel steering vehicle can be expressed as follows.

$$\ddot{\psi} = -\frac{2(C_f l_f^2 + C_r l_r^2)}{I_z v_x}\dot{\psi} - \frac{2(C_f l_f - C_r l_r)}{I_z v_x}\dot{y} + \frac{2C_f l_f}{I_z}\delta_f - \frac{2C_r l_r}{I_z}\delta_r \tag{1}$$

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

Where y is the vehicle lateral displacement, ψ is the vehicle yaw angle, v_x is the vehicle centroid longitudinal velocity, m is the vehicle quality, I_z is the moment of inertia of vehicle around vertical axis, l_f and l_r represent the distance from the center of mass to the front axis and the distance from the center of mass to the rear axis, respectively. C_f and C_r denote the lateral stiffness of the front and rear tires, respectively. δ_f and δ_r denote the steering angles of the front and rear wheels, respectively. Then:

$$a_1 = -\frac{2(C_f l_f^2 + C_r l_r^2)}{I_z v_x}, \quad a_2 = -\frac{2(C_f l_f - C_r l_r)}{I_z v_x}, \quad b_1 = -\frac{2(C_f + C_r)}{m v_x}, \quad b_2 = -v_x - \frac{2(C_f l_f - C_r l_r)}{m v_x} \tag{3}$$

Expressions (1) and (2) can be abbreviated as following:

$$\ddot{\psi} = a_1\dot{\psi} + a_2\dot{y} + u_1 \tag{4}$$

$$\ddot{y} = b_1\dot{y} + b_2\dot{\psi} + u_2 \tag{5}$$

Where

$$u_1 = \frac{2C_f l_f}{I_z}\delta_f - \frac{2C_r l_r}{I_z}\delta_r, \quad u_2 = \frac{2C_f}{m}\delta_f + \frac{2C_r}{m}\delta_r \tag{6}$$

III. Expected Yaw Angle and Yaw Angular Velocity

It is assumed that the lateral acceleration rate $J_d(t)$ of the vehicle is expected during the lane changing process as shown in Fig.1.

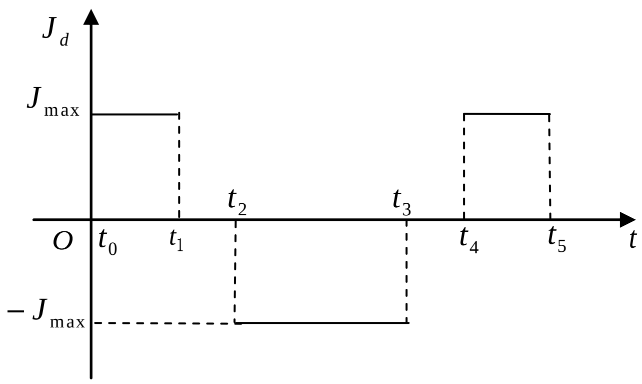


Fig.1 Desired lateral acceleration rate for lane changing

Where t_0 is the start time of lane change, t_5 is the end time of lane change, and $t_1-t_0=t_5-t_4$, $t_2-t_1=t_4-t_3$, $t_3-t_2=2(t_1-t_0)$, $J_{\max}$ is the expected maximum of lateral acceleration rate. Let $t_1-t_0=\Delta_1$, $t_2-t_1=\Delta_2$, then $t_3-t_2=2\Delta_1$, $t_4-t_3=\Delta_2$, $t_5-t_4=\Delta_1$, so the time required to change lane is $4\Delta_1+2\Delta_2$. The desired lateral acceleration $\ddot{y}_d(t)$ satisfying the positive and inverse trapezoidal constraints can be obtained from the integral of $J_d(t)$, as shown in Fig.2.

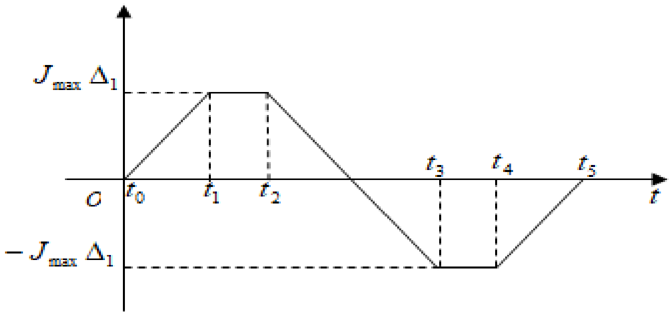


Fig.2 Trapezoidal lateral acceleration for lane changing

The longitudinal axis direction should change along the tangential direction of the desired lane change trajectory, and the vehicle yaw angle tangent function value is equal to the tangential slope of the track trajectory. Thus, the desired yaw angle and the yaw angular velocity of the vehicle are obtained as follows.

$$\psi_d(t)=\arctan\frac{\dot{y}_d}{v_x},\quad \dot{\psi}_d(t)=\frac{\ddot{y}_d v_x}{v_x^{\,2}+\dot{y}_d^{\,2}} \qquad (7)$$

IV. Control System Design

4.1 Control Law Design

We define the yaw angle tracking error for vehicle lane change as:

$$\psi_r(t)=\psi(t)-\psi_d(t) \qquad (8)$$

The switching function is designed by using the terminal sliding mode control method as following:

$$s_1=\dot{\psi}_r+p_1\psi_r+p_2\psi_r^{\,k_1/l_1} \qquad (9)$$

Where k_1 and l_1 are positive odd numbers, $p_1>0$, $p_2>0$, and $l_1>k_1$. The approach law of sliding mode $s_1 = 0$ is designed as

$$\dot{s}_1=-\alpha s_1 \qquad (10)$$

where $\alpha>0$.

Take derivative of equation (9), connecting (8), (10), and substituting (4), we can get

$$u_1=-a_1\dot{\psi}-a_2\dot{y}+\ddot{\psi}_d-p_1\dot{\psi}_r-\frac{p_2k_1}{l_1}\psi_r^{\,k_1/l_1-1}\dot{\psi}_r-\alpha s_1 \qquad (11)$$

Assuming that the vehicle parameters are unknown, and slowly changing, correspondingly, in the control law (11), there are uncertain parameters a_1 and a_2, which need to be estimated. If the estimated values are $\hat{a}_1$ and $\hat{a}_2$, then (11) is modified to

$$u_1=-\hat{a}_1\dot{\psi}-\hat{a}_2\dot{y}+\ddot{\psi}_d-p_1\dot{\psi}_r-\frac{p_2k_1}{l_1}\psi_r^{\,k_1/l_1-1}\dot{\psi}_r-\alpha s_1 \qquad (12)$$

The adaptive laws of the control parameters a_1 and a_2 are as follows.

$$\dot{\hat{a}}_1=\gamma_1\dot{\psi}s_1,\quad \dot{\hat{a}}_2=\gamma_2\dot{y}s_1 \qquad (13)$$

Where γ_1 and γ_2 are adaptive rate correction factors, which are both positive.

In order to ensure the stability of the lateral slip movement of the vehicle during the course of changing the lane, the switching function is designed as following:

$$s_2 = \dot{y} + q_1 y + q_2 y^{k_2/l_2} \qquad (14)$$

Where k_2 and l_2 are positive odd numbers, $q_1 > 0$, $q_2 > 0$, and $l_2 > k_2$. We can design the approach law of sliding mode $s_2 = 0$ as

$$\dot{s}_2 = -\beta s_2 \qquad (15)$$

Among them, $\beta > 0$.

Similarly, considering the equation (5) and (15), take the derivative of the equation (14), then, we obtain the control law as follows.

$$u_2 = -\hat{b}_1\dot{y} - \hat{b}_2\dot{\psi} - q_1\dot{y} - \frac{q_2 k_2}{l_2} y^{k_2/l_2-1}\dot{y} - \beta s_2 \qquad (16)$$

Where $\hat{b}_1$ and $\hat{b}_2$ are the estimates of b_1 and b_2, respectively. The adaptive law of control parameter b_1 and b_2 are as following;

$$\dot{\hat{b}}_1 = \gamma_3 \dot{y} s_2 , \quad \dot{\hat{b}}_2 = \gamma_4 \dot{\psi} s_2 \qquad (17)$$

Where γ_3 and γ_4 are adaptive rate correction factors, which are both positive.

4.2 Stability Analysis

Firstly, the asymptotic reachability of the sliding modes $s_1 = 0$ and $s_2 = 0$ is analyzed. Definition the Lyapunov function as following:

$$V = \frac{1}{2}s_1^2 + \frac{1}{2}s_2^2 + \frac{1}{2}\gamma_1^{-1}\tilde{a}_1^2 + \frac{1}{2}\gamma_2^{-1}\tilde{a}_2^2 + \frac{1}{2}\gamma_3^{-1}\tilde{b}_1^2 + \frac{1}{2}\gamma_4^{-1}\tilde{b}_2^2 \qquad (18)$$

Where $\tilde{a}_1$, $\tilde{a}_2$, $\tilde{b}_1$, $\tilde{b}_2$ are parameter estimation error, and $\tilde{a}_1 = a_1 - \hat{a}_1$, $\tilde{a}_2 = a_2 - \hat{a}_2$, $\tilde{b}_1 = b_1 - \hat{b}_1$, $\tilde{b}_2 = b_2 - \hat{b}_2$.

Take the derivative of equation (18), from (9) and (14), we can get as following:

$$\begin{aligned}\dot{V} &= s_1\dot{s}_1 + s_2\dot{s}_2 + \gamma_1^{-1}\tilde{a}_1\dot{\tilde{a}}_1 + \gamma_2^{-1}\tilde{a}_2\dot{\tilde{a}}_2 + \gamma_3^{-1}\tilde{b}_1\dot{\tilde{b}}_1 + \gamma_4^{-1}\tilde{b}_2\dot{\tilde{b}}_2 \\ &= s_1(\ddot{\psi} - \ddot{\psi}_d + p_1\dot{\psi}_r + \frac{p_2 k_1}{l_1}\psi_r^{k_1/l_1-1}\dot{\psi}_r) + s_2(\ddot{y} + q_1\dot{y} + \frac{q_2 k_2}{l_2} y^{k_2/l_2-1}\dot{y}) \\ &\quad + \gamma_1^{-1}\tilde{a}_1\dot{\tilde{a}}_1 + \gamma_2^{-1}\tilde{a}_2\dot{\tilde{a}}_2 + \gamma_3^{-1}\tilde{b}_1\dot{\tilde{b}}_1 + \gamma_4^{-1}\tilde{b}_2\dot{\tilde{b}}_2\end{aligned}$$

Take the equations (4) and (5) into the upper formula, we can get as

$$\begin{aligned}\dot{V} &= s_1(a_1\dot{\psi} + a_2\dot{y} + u_1 - \ddot{\psi}_d + p_1\dot{\psi}_r + \frac{p_2 k_1}{l_1}\psi_r^{k_1/l_1-1}\dot{\psi}_r) + s_2(b_1\dot{y} + b_2\dot{\psi} + u_2 + q_1\dot{y} + \frac{q_2 k_2}{l_2} y^{k_2/l_2-1}\dot{y}) \\ &\quad + \gamma_1^{-1}\tilde{a}_1\dot{\tilde{a}}_1 + \gamma_2^{-1}\tilde{a}_2\dot{\tilde{a}}_2 + \gamma_3^{-1}\tilde{b}_1\dot{\tilde{b}}_1 + \gamma_4^{-1}\tilde{b}_2\dot{\tilde{b}}_2\end{aligned}$$

Then, take the (12), (16) into the upper formula, we have

$$\dot{V} = s_1(\tilde{a}_1\dot{\psi} + \tilde{a}_2\dot{y} - \alpha s_1) + s_2(\tilde{b}_1\dot{y} + \tilde{b}_2\dot{\psi} - \beta s_2) + \gamma_1^{-1}\tilde{a}_1\dot{\tilde{a}}_1 + \gamma_2^{-1}\tilde{a}_2\dot{\tilde{a}}_2 + \gamma_3^{-1}\tilde{b}_1\dot{\tilde{b}}_1 + \gamma_4^{-1}\tilde{b}_2\dot{\tilde{b}}_2$$

In this paper, the parameters a_1, a_2 and b_1, b_2 are unknown, assuming that the rate of change of the parameters with time is 0, then we get

$$\dot{V} = -\alpha s_1^2 - \beta s_2^2 + \tilde{a}_1\dot{\psi}s_1 + \tilde{a}_2\dot{y}s_1 + \tilde{b}_1\dot{y}s_2 + \tilde{b}_2\dot{\psi}s_2 - \gamma_1^{-1}\tilde{a}_1\dot{\hat{a}}_1 - \gamma_2^{-1}\tilde{a}_2\dot{\hat{a}}_2 - \gamma_3^{-1}\tilde{b}_1\dot{\hat{b}}_1 - \gamma_4^{-1}\tilde{b}_2\dot{\hat{b}}_2$$

By substituting the expression (13), (17) in the formula, we can get $\dot{V} = -\alpha s_1^2 - \beta s_2^2 \le 0$, which shows that s_1, $\dot{s}_1$, s_2, $\dot{s}_2$, $\tilde{a}_1$, $\tilde{a}_2$, $\tilde{b}_1$ and $\tilde{b}_2$ are all bounded. Assume that $W(t) = \alpha s_1^2 + \beta s_2^2$, then $W(t) = -\dot{V}(t) \ge 0$. So we get $\int_0^t W(\tau)d\tau = -\int_0^t \dot{V}(\tau)d\tau = V(0) - V(t)$. Because $V(t)$ is a nonnegative function and $V(0)$ is bounded, so we have $0 \le V(t) < \infty$, then $\lim_{t\to\infty}\int_0^t W(t)d\tau < \infty$. Because s_1, $\dot{s}_1$, s_2, $\dot{s}_2$ are all bounded, it is easy to get $\dot{W}(t)$ is bounded. By the corollary of Barbalat's lemma, furtherly, we get $s_1 \to 0$, $s_2 \to 0$, as $t \to \infty$, hence the sliding mode $s_1 = 0$ and $s_2 = 0$ have asymptotically reachability.

Assuming that the yaw angle and sideslip displacement are not 0 when the states of system reaches the sliding mode, and the convergence of sliding mode motion is analyzed as below.

According to the switching function (9), we can obtain $\dot{\psi}_r + p_1\psi_r + p_2\psi_r^{k_1/l_1} = 0$ as $s_1 = 0$. According to the switching function (14), we can also obtain $\dot{y} + q_1 y + q_2 y^{k_2/l_2} = 0$ as $s_2 = 0$. Because $p_1 > 0$, $p_2 > 0$,

$q_1 > 0$, $q_2 > 0$, k_1 , k_2 , l_1 and l_2 are positive odd numbers as well as $l_1 > k_1$, $l_2 > k_2$, by analyzing the solution of the above two differential equations, it can be obtained that the tracking error of the yaw angle ψ_r and the sideslip displacement y will converge to 0 in finite time along the sliding mode [18].

According to formulas (13) and (17), the estimation of parameters will not change and reach the stable states when $s_1 = 0$ and $s_2 = 0$. Given the complexity of the actual vehicle model and external interference, the vehicle parameters are difficult to estimate accurately, so the paper adopts the direct adaptive method, in which the controller parameters are not calculated through the vehicle parameter estimation. The control law and parameter adaptive law are designed by the direct Lyapunov function method. Compared with the indirect adaptive control method, the method proposed in this paper is more flexible and effective.

V. Simulation Research

Assuming that lane spacing d_w is 3m, the expected value of maximum of lateral acceleration rate $J_{\max}$ is 0.05g/s, the expected value of maximum of lateral acceleration $a_{\max}$ is 0.05g, and the gravitational acceleration g is 10m/s^2. According to literature [10], it can be obtained as

$$\Delta_1 = a_{\max} / J_{\max} = 1s\text{, } \Delta_2 = -\frac{3}{2}\Delta_1 + \frac{1}{2}\sqrt{\Delta_1^2 + \frac{4d_w}{J_{\max}\Delta_1}} = 1s$$

Therefore, from $4\Delta_1 + 2\Delta_2$, the time of lane changing is 6s. The control input u_1 and u_2 can be calculated by control law (12) and (16), respectively. Assuming that initial value of sideslip displacement of the vehicle is 0.2m, the initial value of sideslip velocity, yaw angular velocity and yaw angle are all 0; the vehicle weight is 1300kg, the moment of inertia is 2800 kgm^2, the lateral stiffness of front and rear tires are 65 and 75 kN/rad, respectively, the distance from the center of mass to the front wheel is 1.35m, the distance from the center of mass to the rear wheel is 1.25m, and the longitudinal speed of the vehicle is 25m/s.

According to equation (6), the steering angles inputs of the front and rear wheel are

$$\delta_f = \frac{c_{22}u_1 - c_{12}u_2}{c_{11}c_{22} - c_{12}c_{21}} , \delta_r = \frac{c_{11}u_2 - c_{21}u_1}{c_{11}c_{22} - c_{12}c_{21}} \tag{19}$$

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

Linked to equation (3), c_{11} , c_{12} , c_{21} and c_{22} should satisfy

$$\begin{cases} c_{11}l_f - c_{12}l_r = -v_x a_1 \\ c_{11} + c_{12} = -v_x a_2 \\ c_{21} + c_{22} = -v_x b_1 \\ -c_{21}l_f + c_{22}l_r = v_x(b_2 + v_x) \end{cases} \tag{20}$$

By solving the equation (20), the estimated values of c_{11} , c_{12} , c_{21} and c_{22} can be determined:

$$\hat{c}_{11} = -v_x(\hat{a}_1 + l_r\hat{a}_2)/l \text{ , } \hat{c}_{12} = v_x(\hat{a}_1 - l_f\hat{a}_2)/l \text{ ,}$$

$$\hat{c}_{21} = -v_x(\hat{b}_1 l_r + \hat{b}_2 + v_x)/l \text{ , } \hat{c}_{22} = v_x(-\hat{b}_1 l_f + \hat{b}_2 + v_x)/l$$

Where $l = l_f + l_r$.

In the simulation, it is assumed that m , I_z , C_f and C_r are all unknown, the estimated values of a_1 , a_2 , b_1 and b_2 can be obtained by the integrals of (13) and (17), and the values of control parameters and adaptive rate correction factor are shown in Table 1.

Table 1 The values of control parameter

p_1	p_2	q_1	q_2	α	β	k_1	l_1	k_2	l_2	γ_1	γ_2	γ_3	γ_4
0.2	0.8	0.6	0.4	15	23	3	5	3	5	1.6	1.5	0.3	0.8

Fig.3 to Fig.10 are the simulation results of tracking control for lane changing. Fig.3 and Fig.4 show the changes of vehicle sideslip velocity and sideslip displacement in the process of lane changing. It can be seen that sideslip velocity and displacement are tending to zero at the end of the lane changing, which indicates that the vehicle sideslip movement is asymptotic stable when changing lane. Fig.5 and Fig.6 show the changes of the yaw angle and yaw rate, it ca be seen that the actual value of vehicle yaw angle and yaw angle rate have ideal approaching effect to the expected values. Fig.7 shows the track performance for lane change from the curve of expected trajectory and the indeed lateral position of vehicle, Fig.8 shows the change of vehicle steering angle, and it can be seen that the value of steering angle of front and rear wheels in the lane change process does not exceed 0.01rad. Fig.9 and Fig.10 show the changes of yaw angle error and lateral position error of vehicle, and it can be seen that both yaw angle error and position tracking error tend to 0 in the process of lane change, this shows that the system is asymptotically stable.

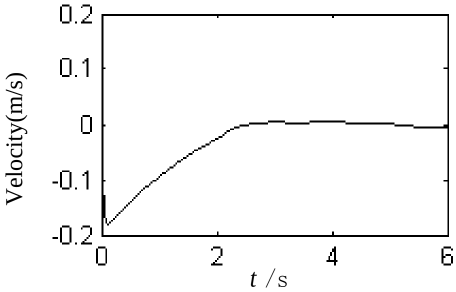


Fig.3 Lateral velocity of vehicle

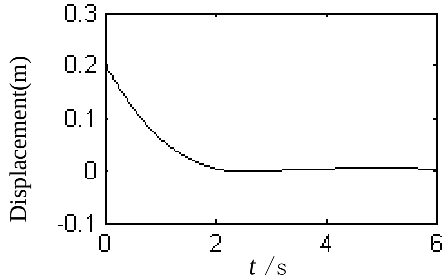


Fig.4 Lateral displacement of vehicle

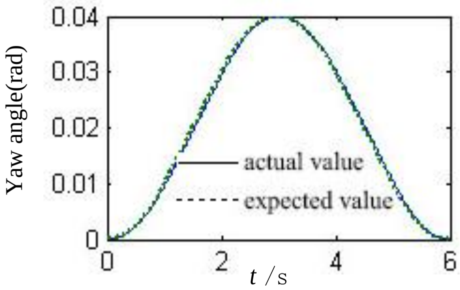


Fig.5 Yaw angle tracking for lane changing

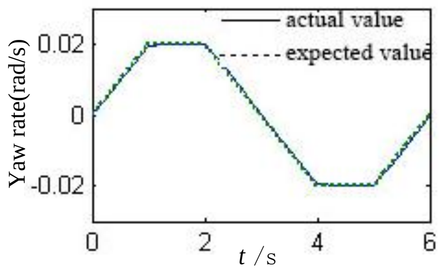


Fig.6 Yaw rate tracking for lane changing

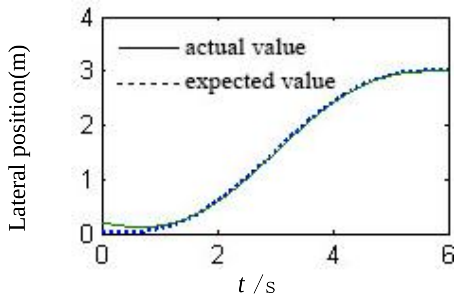


Fig.7 Trajectory tracking for lane changing

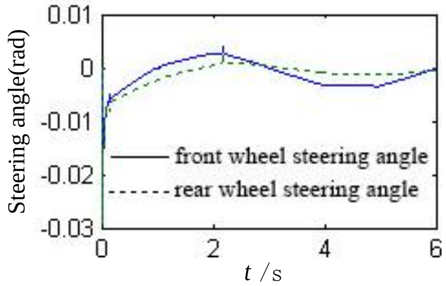


Fig.8 Control input for lane changing

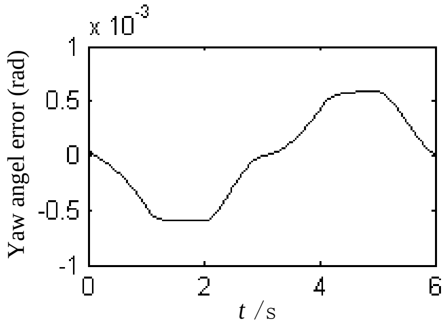


Fig.9 Yaw angel tracking error

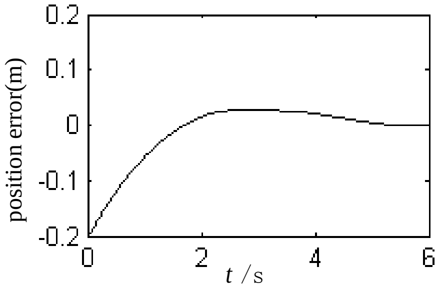
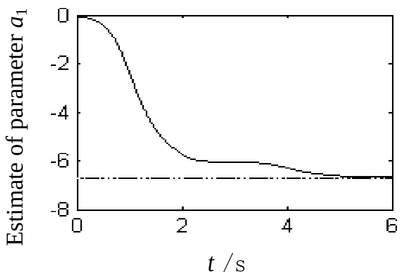
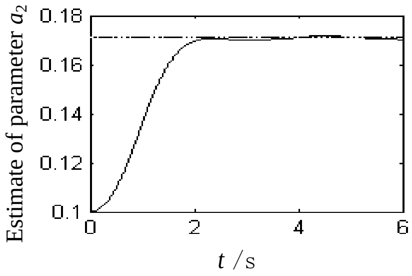


Fig.10 Position tracking error

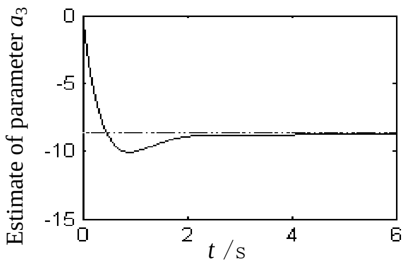
Based on the formula (3) and the vehicle parameters, it can be calculated that, $a_1 = -6.733$, $a_2 = 0.171$, $b_1 = -8.615$ and $b_2 = -24.631$. Fig.11 (a), (b), (c) and (d) show the estimation of a_1, a_2, b_1 and b_2 respectively, where the dotted line represents the actual value of these parameters, from which it can be seen that the estimation values of these parameters can converge to the actual values.



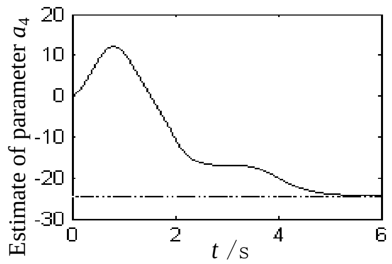
(a) Estimation of parameter a_1



(b) Estimation of parameter a_2



(c) Estimation of parameter a_3



(d) Estimation of parameter a_4

Fig.11 Parameter estimation

Conclusion

1) In this paper, it is assumed that the vehicle parameters are uncertain, but the vehicle parameters are not estimated directly, and the control parameters are not modified by using the estimated value of the vehicle parameters. On the premise of ensuring the asymptotic stability of the tracking error, it directly estimates the unknown control parameters by Lyapunov function method in real time, which is easy to apply.

2) Since only the front wheel steering is used, the asymptotic stability of the yaw angle error and the position error of the vehicle during trajectory tracking cannot be ensured at the same time. The four-wheel steering control technology is adopted in this paper to improve the tracking performance of the vehicle lane change control system. It can ensure that the vehicle yaw angle error and the lateral position tracking error both tend to zero at the end of the lane change.

3) In this paper, the terminal sliding mode control method is adopted, and the switching function is nonlinear. When the system state reaches the sliding surface, it will approach the equilibrium point in a limited time.

4) The longitudinal speed of the vehicle is assumed to be constant in the paper, however, the longitudinal speed of the vehicle often changes during a changing lane process, and the longitudinal velocity change has an effect on the lateral motion of the vehicle. It is necessary to further study the longitudinal and lateral coupling control for lane changing.

Acknowledgements

This work was financially supported by the Shandong Provincial Natural Science Foundation, China(ZR2015FM024).

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Dianbo Ren1 "Direct Adaptive Terminal Sliding Mode Control for Lane Changing of Vehicle in Intelligent Transportation Systems." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 15, no. 4, 2018, pp. 26-33