ATLANTIS PRESS

Advances in Computer Science Research, volume 87

3rd International Conference on Mechatronics Engineering and Information Technology (ICMEIT 2019)

Simulation Research on Vehicle Stability based on Sliding Mode Variable Structure Control

Liyuan He[1, a], Chenghui Yang [1, 2, b, *] and Junfeng Wang[1, c]

[1]School of Electrical Engineering, Northwest University for Nationalities, Lanzhou 730124, China;

[2]Laboratory of Electronic Materials, Northwest University for Nationalities, Lanzhou 730124, China.

[a]1072421307@qq.com , [b,*]yangchenghui36@163.com , [c]1637689017@qq.com

Abstract. This paper aims to explore a vehicle stability control strategy based on sliding mode variable structure control theory. The smart car is used as the simulation object, and the vehicle's centroid angle and control system are mathematically modeled and controlled. The research was carried out and joint simulations were carried out with three typical working conditions: icy road surface, wet asphalt road surface and dry concrete. The simulation results show that the designed control algorithm can significantly improve the lateral stability of the vehicle, so that the vehicle has strong adaptability to the road surface and different driving speed under different working conditions, thus improving the braking of the car as a whole. Performance, drive performance and steering performance.

Keywords: sliding mode variable structure control; yaw angle; pose error; vehicle stability; simulation.

1. Introduction

As we all know, the safety performance of cars during driving has always been the focus of academic attention. With the upgrading of science and technology, the driving speed of automobiles has been greatly improved, and the density of vehicles on the road has gradually increased. This has undoubtedly led to the trend of increasing traffic accidents year by year. Based on such status quo, reducing or even avoiding traffic accidents as much as possible has become a top priority in the field of traffic control.

On the other hand, the Vehicle Stability Control System (VSC), begins to enter people's daily lives. The system not only maintains the directional stability of the vehicle during steering, but also prevents the wheels from slipping during braking or driving, thereby effectively improving the active safety performance of the vehicle. As a mechatronics product, the control algorithm of vehicle stability control system has become an academic hotspot in the field of traffic control at home and abroad.

2. Basic Theories of Sliding Mode Variable Structure Control

As a special variable structure control, the sliding mode variable structure control utilizes a variable structure controller to drive the system state from the initial state and maintain it on a hyperplane determined by the switching function within a certain period of time. Sliding mode variable structure control is widely used in nonlinear systems due to the superiority of the system over the robust control, and the advantages of simple construction algorithm and easy design of the controller. Different from the optimal control, the sliding mode variable structure control is unique under certain conditions. In addition, the diversified design of the control law provides more choices for the control of large systems.

3. Establishments of Vehicle Models

3.1 Kinematic Model and Pose Error Model

Based on the directionality of the motion of the intelligent vehicle, the world coordinate system and the local coordinate system are used to describe the position vector of the vehicle at a certain time [1].

As shown in Fig. 1, at a certain moment, the position of the vehicle center of mass in the world coordinate system oxy is (X_C, Y_C), and the angle between the longitudinal axis of the vehicle and the x axis is ϕ_c. Then in the world coordinate system oxy, the kinematic model of the vehicle is expressed as follows:

$$\begin{bmatrix} \dot{X}_C \\ \dot{Y}_C \\ \dot{\phi}_C \end{bmatrix} = \begin{bmatrix} \cos\phi_C & 0 \\ \sin\phi_C & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_c \\ \omega_c \end{bmatrix} \tag{1}$$

In Equation 1:v_c and ω_c are the linear velocity and yaw rate of the vehicle's center of mass, respectively.

It can be seen from Equation 1 that the linear velocity and the yaw rate of the vehicle center of mass determine the position vector of the vehicle. According to the centroid speed, the traveling path of the vehicle can be controlled by changing the yaw rate. The pose error of the vehicle is not caused by the lateral deviation and the azimuth deviation at the center of mass, but the deviation value at a point p in front of the vehicle. The point p here is called the prediction point, and the distance between the centroid and the predicted point is called to predict the distance. Assuming that the predicted distance of the vehicle is x_e, in the vehicle local coordinate system, the distance between the predicted point and the tangent to the road centerline is the lateral deviation y_e, and the angle between the vehicle centerline and the tangent of the road centerline at the predicted point is the azimuth deviation ϕ_e, according to The geometric relationship shown in 1 is, in the local coordinate system, the pose error $p_e = [x_e \; y_e \; \phi_e]$ can be expressed as:

$$\begin{bmatrix} x_e \\ y_e \\ \phi_e \end{bmatrix} = \begin{bmatrix} \cos\phi_C & \sin\phi_C & 0 \\ -\sin\phi_C & \cos\phi_C & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_P - X_C \\ Y_P - Y_C \\ \phi_P - \phi_C \end{bmatrix} \tag{2}$$

In Equation 2, $[X_P \; Y_P \; \phi_P]$ is the pose of the point on the road ahead of the vehicle in the world coordinate system.

In order to realize the trajectory tracking of intelligent vehicles, this paper dynamically plans the virtual driving trajectory based on the local coordinate system between the vehicle center of mass and the predicted point, assuming that the virtual driving trajectory is a cubic polynomial curve:

$$y = n_1 + n_2 x + n_3 x^2 + n_4 x^3 \tag{3}$$

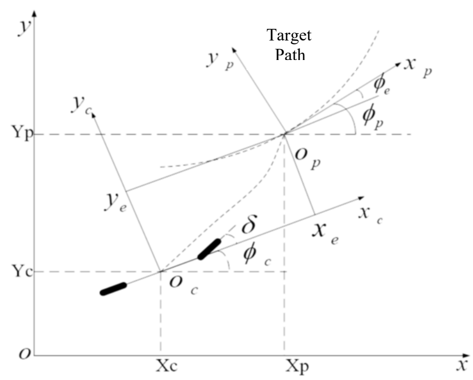

Fig. 1 Schematic diagram of vehicle pose error

The curve satisfies:

$$\begin{cases} y(0)=0 \\ \dot{y}(0)=0 \\ y(x_e)=y_e \\ \left.\dfrac{\ddot{y}}{(1+\dot{y}^2)^{3/2}}\right|_{x=0}=\psi \end{cases} \tag{4}$$

Where $\psi=\frac{\omega_c}{v_c}$ is the driving curvature of the vehicle. The trajectory equation for solving the virtual driving path is:

$$y(x)=\frac{\omega_c}{2v_c}x^2+\frac{y_e-\frac{\omega_c}{2v_c}x_e^2}{x_e^3}x^3 \tag{5}$$

Let the center of gravity of the intelligent vehicle stably track the planned trajectory curve equation in an unbiased form. At a certain moment, the position of the vehicle centroid on the curve equation is (x,y), the speed is v_c, and the speed direction is consistent with the tangential direction of the curve, that is, the driving curvature of the vehicle is the same as the curvature of the current point of the planning curve. For the ideal yaw rate, you can get:

$$\omega=v_c\gamma \tag{6}$$

The changing rate of the curvature of the planning curve at the current point is as follows:

$$\dot{\gamma}=\frac{d\left(\frac{\ddot{y}}{(1+\dot{y}^2)^{3/2}}\right)}{dx}\frac{dx}{dt}=v_c\frac{\dddot{y}(1+\dot{y}^2)-3\ddot{y}^2\dot{y}}{(1+\dot{y}^2)^{5/2}} \tag{7}$$

The ideal yaw rate of change is:

$$\dot{\omega}=\dot{v}_c\gamma+v_c\dot{\gamma}=\dot{v}_c\gamma+v_c\dot{\gamma} \tag{8}$$

Combine the above various equations, take the value of the origin of the local coordinate system, and push the ideal yaw rate of the car to travel along the virtual trajectory:

$$\dot{\omega}\big|_{x=0}=\dot{v}_c\psi+v_c\dot{\psi}=\frac{\dot{v}_c\omega_c}{v_c}+6v_c^2\frac{y_e-\frac{\omega_c}{2v_c}x_e^2}{x_e^3} \tag{9}$$

The ideal yaw rate of change indicates the trend of the yaw rate as the vehicle tracks the target trajectory at the current speed. The expected yaw rate is:

$$\omega_r=\omega_c+\alpha\dot{\omega}\big|_{x=0}=\omega_c+\alpha\left(\frac{\dot{v}_c\omega_c}{v_c}+6v_c^2\frac{y_e-\frac{\omega_c}{2v_c}x_e^2}{x_e^3}\right) \tag{10}$$

In Equation 10: α is a scale factor.

3.2 Dynamics Model

Strong coupling and uncertainty are two typical characteristics of intelligent vehicles appearing as nonlinear systems. In order to facilitate the discussion of the characteristics of vertical and horizontal motion and yaw motion of the vehicle during trajectory tracking, the vehicle traveling on the plane with small curvature is simplified into a three-degree-of-freedom vehicle model. The following assumptions are made about the model:

(1) The vehicle is a rigid body moving in a plane with a small curvature parallel to the ground (excluding suspension effects);

(2) The lateral acceleration of the vehicle is kept within 0.4g, and the lateral deflection characteristic of the tire is linear;

(3) The difference between the side-to-side characteristics of the left and right tires is neglected, and the front wheel angle is used as an input [2].

Based on the above assumptions, the longitudinal and lateral coupling dynamics models of three-degree-of-freedom vehicles are as follows:

$$\begin{cases} \dot{v}_x = -f_R g + \dfrac{c_x v_x^2}{m} + v_y \omega_c - 2C_f \dfrac{v_y + a\omega_c}{m v_x}\delta_f + \dfrac{F_x}{m} \\ \dot{v}_y = \dfrac{2(C_f + C_r)}{m v_x} v_y + \dfrac{2(C_f a - C_r b)}{m v_x}\omega_c - v_x \omega_c - \dfrac{2C_f}{m}\delta_f + \dfrac{c_y v_y^2}{m} \\ \dot{\omega}_c = \dfrac{C_f a - C_r b}{I v_x} v_y + \dfrac{C_f a^2 + C_r b^2}{I v_x}\omega_c - \dfrac{C_f a}{I}\delta_f \end{cases} \tag{11}$$

In Equation 11:

m −vehicle mass (kg); v_x, v_y −the speeds along x, y axis(m/s);

F_x −drive, braking force (N); ω_c −vehicle yaw rate (rad/s);

a, b −the distance from the center of mass of the vehicle to the front and rear axles (m);

δ_f −the front wheel angle of the vehicle (rad);

c_x, c_y −air longitudinal and lateral resistance coefficient;

f_R −rolling resistance coefficient; g −gravity acceleration (m/s^2);

C_f, C_r −the lateral stiffness of the front and rear tires of the vehicle (kN/rad);

I −the moment of inertia of the vehicle ($kg \cdot m^2$);

4. Control Methods of the System

Aiming at the problem of controlling the lateral stability of the car during driving, this paper proposes a comprehensive control method combining sliding mode variable structure control and fuzzy predictive control. The input of fuzzy predictive control adopts the sliding mode surface switching function and its rate of change. First, it ensures that the sliding mode variable structure control can still exhibit superior robustness when there are uncertain factors in the system and the control parameters fluctuate. Sex, on the other hand, inherits the advantages of general fuzzy control independent of the precision system model, so this method can be used to soften the control signal and thus reduce the chattering effect caused by the sliding mode variable structure control.

5. Selection of the Sliding Mode Function

Define the sliding mode switching function:

$$s = \omega_c - \omega_r \tag{12}$$

Where ω_c is the current yaw rate, ω_r is the expected value of the yaw rate;
Simplification is available:

$$s = \omega_c - \omega_r = f_2 + g_3\delta_f - \omega_r \tag{13}$$

The control law of the sliding mode controller is generally divided into two parts, namely equivalent control and switching control. The former keeps the state of the control system constant on the sliding surface, and the latter aims to keep the state of the control system sliding on the sliding surface which makes: $s\dot{s} \leq 0$. Equivalent control is (by $s = 0$):

$$\delta_{eq} = (-f_2 + \dot{\omega}_r)/g_3 \tag{14}$$

This paper uses the exponential approach law to design the switching control δ_{sw}, then:

$$\delta_{sw} = (-\varepsilon_1 \operatorname{sgn}(s_1) - k_1 s_1)/g_3 \tag{15}$$

Where: $\varepsilon_1, k_1 > 0$;
Control volume δ_f is:

$$\delta_f = \delta_{eq} + \delta_{sw} \tag{16}$$

6. Algorithm Verification

Using the established three-degree-of-freedom vehicle model, the lateral stability control of the intelligent vehicle was simulated on MATLAB /Simulink. Here, a car runway composed of two straight lines and a fifth-order polynomial curve is used as a road trajectory for simulation calculation. In order to meet the goal, the configuration parameters are as follows:

The longitudinal speed of the vehicle is $8m/s$, the vehicle's preview distance x_e is $5m$, the proportional coefficient α takes zero, the initial values of the vehicle lateral displacement and lateral velocity are $2m$ and $0.2m/s$,, respectively, the initial values of the vehicle's yaw angle and yaw rate are respectively for $0rad$ and $0.2rad/s$. Other parameters involved are as follows.

Table 1. vehicle model parameter table

Vehicle parameters	Numerical value
Vehicle mass(kg)	2010
Moment of inertia of the whole vehicle around the Z axis(kg·m^2)	2280
The distance from the center of mass to the front and rear axles(m)	1.335/1.265
Cornering stiffness of front tires (KN/rad)	40
Cornering stiffness of rear tires (KN/rad)	40
Track(m)	1.395
Rolling resistance coefficient	0.02
Air resistance coefficient	0.35/0.4

It can be seen from the Fig.2 that the vehicle can better track the desired motion trajectory during the whole process. From the partial enlargement, it can be seen that the vehicle can track its desired motion trajectory after 20m longitudinal travel [3].

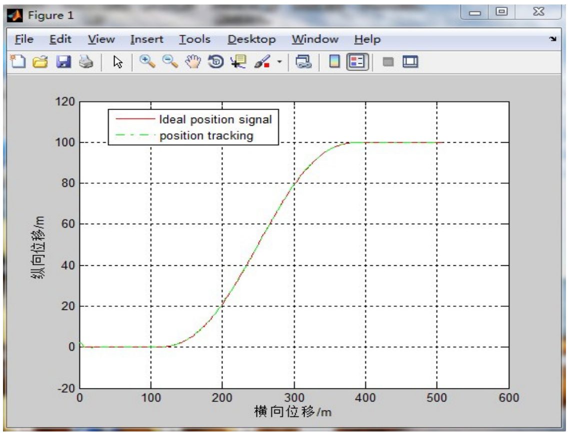

Fig. 2 Intelligent vehicle lateral control trajectory tracking curve

It can be seen from the figure that when the curvature of the desired trajectory is zero, it is expected that the yaw rate will quickly converge to zero. When the curvature of the desired trajectory changes, the yaw rate will also change, which indicates that the yaw rate can be very high. Properly approaching the desired yaw rate improves the handling stability and safety of the vehicle to a certain extent.

The vertical and horizontal vehicle speed and other signals are used as the input of the vehicle control system. The upper half is the lateral deviation curve. It can be seen that the lateral deviation of the vehicle at the intersection of the straight track and the curved runway has a certain fluctuation, but the whole tracking In the process, the lateral deviation is always controlled within the error range of $\pm 0.1m$; the lower half is the direction deviation curve, the direction deviation asymptotically converges to zero at nearly $5s$, and there is no large jitter in the whole process. It can be seen from the analysis of the above two graphs that both the lateral deviation and the azimuth deviation are kept in a constant interval and show a relatively stable trend, which means that the control algorithm can stably track the reference paths of different curvatures, so that it can be better It is consistent with the vehicle dynamics model established in this paper.

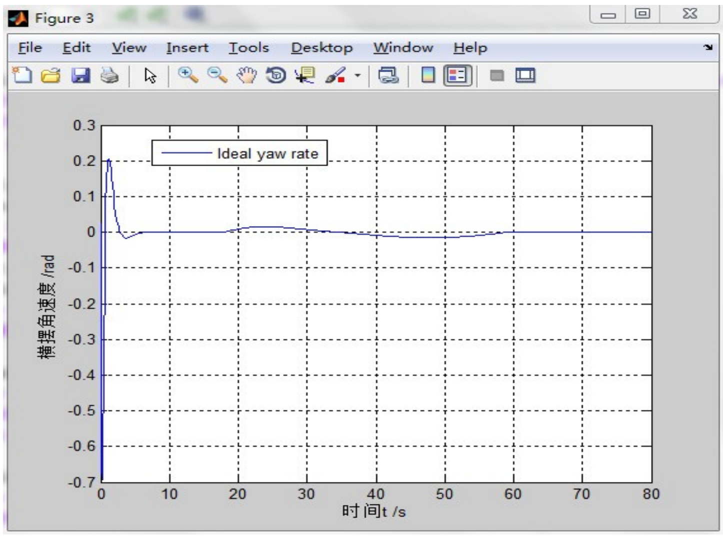

Fig. 3 The yaw rate and expected value of the intelligent vehicle

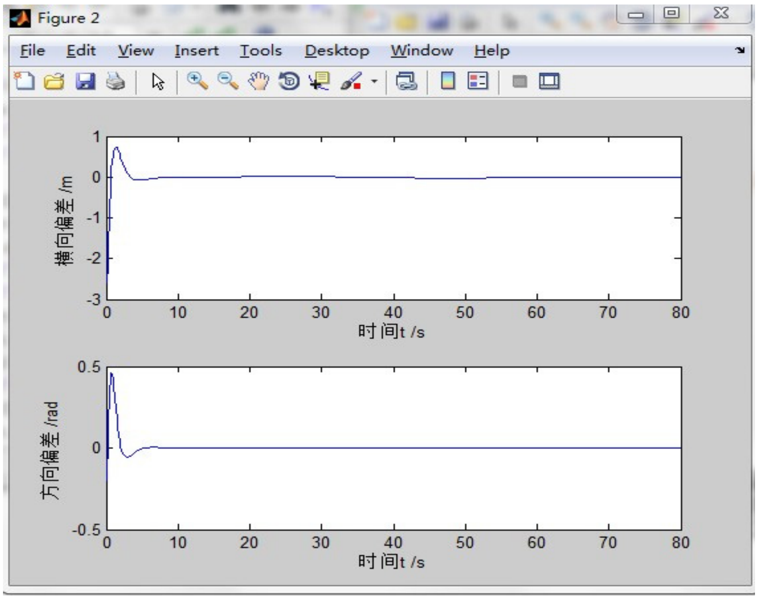

Fig. 4 Simulation curve of tracking error of vehicle longitudinal and lateral motion

When the time is between $18\sim58s$, the expected value of the curvature of the trajectory changes, thus causing the opposite direction of the front wheel rotation to change. From the figure, it can be seen that the front wheel rotation angle shows a relatively stable trend, and no large fluctuations occur. Therefore, when the intelligent vehicle is driving on the road, the front wheel drives the rear wheel to rotate in the same direction, which can quickly change the speed of the vehicle, and the vehicle body does not cause a large swing, which improves the safety of the vehicle during driving to some extent.

The front wheel angle is used as the input of the vehicle model and the output of the control system. The vehicle's position, vertical and horizontal vehicle speed and other signals are used as the output of the vehicle model and the input of the control system. It is not difficult to find through the simulation results. The trajectory tracking controller has better control performance, which can keep the lateral deviation and direction deviation of the intelligent vehicle within a certain range, and make the response curve tend to be stable[1].At the same time, the synovial controller combined with fuzzy predictive control is easy to achieve the target of small yaw angular velocity control error, and improves the steering stability and path tracking ability of the vehicle steering while maintaining the original vehicle speed constant.

7. Conclusion

The algorithm based on sliding mode variable structure control can significantly improve the lateral stability of the vehicle, and it also has better adaptability to the road surface and different driving speed under different working conditions, which verifies the feasibility of the control algorithm; using computer simulation The technology builds the vehicle stability control system, and the deep optimization of the sliding mode variable structure control theory as the core achieves good vehicle maneuverability and stability, which confirms the effectiveness of the vehicle pose model; through continuous simulation, optimization, The research results obtained by the test improve the braking performance, driving performance and steering performance of the vehicle as a whole, which witnesses the wide application prospect of the sliding mode variable structure control strategy.

Admittedly, in order to facilitate the calculation, this paper has been simplified to a certain extent when establishing the vehicle motion model. This part of the later exploration needs to be further improved to improve the accuracy and scientific of the simulation research results.

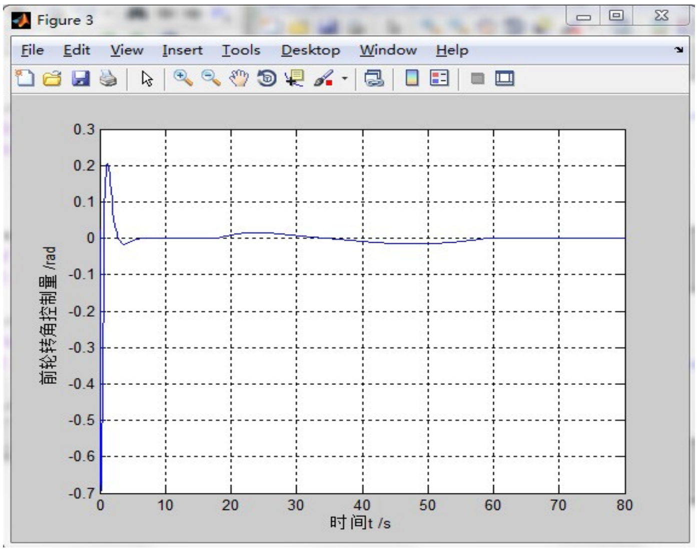

Fig. 5 Front wheel angle control input of the vehicle

Acknowledgements

Open Laboratory Project of Northwest University for Nationalities in 2019: SYSKF-2019026.

The Undergraduate Scientific Research Innovation Project of Northwest University for Nationalities in 2019.

References

[1]. Bing Li: Research on intelligent vehicle path tracking control based on co-simulation (Master, Dalian University of Technology, China 2014). p.36.

[2]. Xijin Feng, Yintao Wei and Chunsheng Ma. Several Mechanical Problems in Automotive Engineering. Mechanics in Engineering. Vol. 34 (2012) No. 4, p.1-7.

[3]. Lie Guo. Tracking control of intelligent vehicle detouring lane change based on inversion method. Journal of Jilin University (Engineering Science). Vol. 43 (2015) No. 2, p.56-61.

[4]. Shihao Li, Yan Wu and Yu Lu. Research on adaptive cruise control strategy based on fuzzy PID. Automotive Practical Technology. (2018) No. 23, p.176-177.

[5]. Bo Liu. Simulation of vehicle stability control system based on Simulink. Times Agricultural Machinery. Vol. 44 (2017) No. 8, p.100-102.

[6]. J. He, L. Xiong, Z. Yu and Y. Feng. Study on stability control of 4WD EV based on sliding mode control. 2013 IEEE International Conference of IEEE Region 10 (TENCON 2013). Xi'an, 2013, p. 1-4.

[7]. Bin Wang. Development of full-speed segment distance control system based on synovial variable structure control. Shanghai Automotive. (2018) No. 7, p.34-39.

[8]. Chunyan Gao. A dynamic surface adaptive synovial membrane control strategy. New Technology and New Process. (2015) No. 3, p.119-121.