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Short Note

Sliding mode lane keeping control based on separation of translation and rotation movement

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ABSTRACT

The lane keeping problem of automatic driving for vehicles was studied based on the simplified linear lateral dynamic model which was divided into a translation subsystem and a rotation subsystem. The rotation subsystem was defined as an inner loop and the translation subsystem was defined as an outer loop. With the separation design strategy of inner loop and outer loop, a kind of angle stable controller was designed to make the rotation subsystem stable. The inner angle stable subsystem was driven by the outer translation subsystem which was controlled by the error signal of vehicle position. The inner loop was cascaded with outer loop and both loops were designed by the sliding mode method. At last, detailed numerical simulations were done and simulation results were compared with other three methods to explain the physical meanings of design and its three advantages.

1. Introduction

In recent years, the related technology of automatic driving for vehicles had attracted the interest of scholars at home and abroad. The lane keeping control is one of the key technologies of automatic driving for vehicles. By the offset between the actual direction of vehicle moving and the central direction of the lane, this technology calculates the corner of the steering wheel with corresponding control algorithm, based on which the vehicle is controlled to drive safely following the lane.

The approximated linear model of the lateral motion for vehicles described in the literatures [1–10] included two main equations, which are the equation of angle rotation and the equation of centroid mass translation. And in most literatures, the control law was designed mainly for the equation of centroid mass translation in the problem of lane keeping. While in literatures [12,13], compound control strategy was proposed which combined the position of centroid mass to the angle, but it was only a simple compound program which, based on adopting the weighted factor lied between 0 and 1. Furthermore, it was pointed that both variables could not converge simultaneously when the curvature of the path was not 0. In this paper, first based on the equation of angle rotation, the angle stability was assured by designing the inner loop, then the outer loop was constructed by the information of the error of the centroid mass. The inner loop was drived by the outer loop, which made both control missions, angle control and position control, and could be realized without contradiction. This control program, with the chief advantage of beautiful stability, was similar to the traditional design for flight control system. This method considered the key point that the rotation made the stability losing easily, so the inner loop was designed independently for angle stability, which provided enough stability margin for system. Meanwhile, the thought, converting the error of distance to the error of angle, accorded with the people's driving habits. And the realization of designing the inner loop and the outer loop separately also accorded with the physical law that the fast loop and the slow should be designed respectively.

In literatures [5–9], the methods of adaption, fuzzy control, neural network and sliding mode control were used separately for trial to realize the robust control for lane keeping, considering the perturbation, which were produced from the parameters in the model of vehicles influenced by the outside disturbance during the motion. In this paper, based on the sliding mode control, a kind of simple design program was put forward, whose control law did not include the parameters of model of vehicles completely. Thus this program possessed good robustness because the influence resulting from the perturbation of the parameters was small.

In literature [10], the dynamic characteristic of the steering of vehicle was considered furthermore on that basis. The first-order inertial component with its time constant of 0.1 s was chose to simulate the physical delayed characteristics of the steering, and the bipolar sigmoid function was adopted instead of the sign function

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in the conventional sliding mode control, then the sliding mode controller with self-correction was designed to improve the buffeting phenomenon in the output of the sliding mode controller. In literature [11], the direct adaptive control scheme was proposed, but its speed of convergence was slow. In the final part of this paper, the sliding mode control with double loops proposed in this paper was compared with the method introduced in literature [11]. The results showed the former was more swift.

The maximum rotation angle of the front wheel could not exceed the limit value due to physical factors, which was the typical problem of control saturation. However, the strategy of anti-saturation was seldom considered for lane keeping in current documents. The double sliding mode control law put forward in this paper, realized the strategy of anti-saturation for the front wheel, by using the softening function and bipolar Sigmoid function.

2. Model description

On the premise of assuming the rotation angle of wheel as a small angle, the lateral position error and the lateral yaw angle error were chosen as the basic state variables to describe the model of lateral motion for vehicles. The mode was written in the following formula [9–11]:

$$\ddot{y} = -\frac{2(C_f + C_r)}{mv_x}\dot{y} - \left[v_x + \frac{2(C_f l_f - C_r l_f)}{mv_x}\right]\dot{\psi} + \frac{2C_f}{m}\delta_z \tag{1}$$

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

where,, ψ was shown as the lateral yaw angle; y was shown as the lateral position; I_z was described as the moment of inertia for vehicle; v_x was indicated as the longitudinal velocity for vehicle; m was meant for the mass of the vehicle; l_f and l_r were shown as the distance from the centre of mass to the front axle and the back axle respectively in vehicle; C_f and C_r were written as the stiffness of the front wheel and the back wheel; δ was shown as the rotating angle of the front wheel.

Referenced as literatures [3–7], if exploration strategy was assumed to be used, then two lateral sensors were installed at the front and rear bumpers. In this way, the lateral offset of the wheel from the central line and the angle between the moving direction of vehicle and the tangent of the path could be both measured. Let the explored distance be taken as d, the lateral moving model in geometry of vehicles could be shown as follows:

$$\dot{y}_s = \dot{y} + v_x\psi_r + d\dot{\psi}_r \tag{3}$$

$$\ddot{\psi}_r = \ddot{\psi} - \ddot{\psi}_d \tag{4}$$

where, ψ_r was shown as the lateral yaw angle error, that was the angle between the moving direction of vehicles and the tangent of the path; y_s was shown as the lateral position error off the central line; ψ_d was the desired yaw angle, χ was the curvature of the centre line in the lane, that the equation $t\dot{\psi}_d = v_x\chi$ could be obtained.

3. The transformation and hypothesis of the model

According to Eqs. (1)–(4), the related variables were defined as follows:

$$a_1 = C_f + C_r,\ a_2 = C_f l_f - C_r l_r,\ a_3 = C_f l_f^2 + C_r l_r^2 \tag{5}$$

$$a_{11} = \frac{2a_2}{I_z},\ a_{12} = 2\left[\frac{da_2}{I_z v_x} - \frac{a_3}{I_z v_x}\right] \tag{6}$$

$$a_{13} = -\frac{2a_2}{I_z v_x},\ b_1 = -\frac{2C_f l_f}{I_z},\ d_1 = -\frac{2a_3}{I_z v_x}\dot{\psi}_d - \ddot{\psi}_d \tag{7}$$

$$a_{21} = 2\left[\frac{a_1}{m} + \frac{da_2}{I_z}\right],\ a_{22} = 2\left[\frac{da_1}{mv_x} - \frac{a_2}{mv_x} + \frac{d^2a_2}{I_z v_x} - \frac{da_3}{I_z v_x}\right] \tag{8}$$

$$a_{23} = -2\left[\frac{a_1}{mv_x} + \frac{da_2}{I_z v_x}\right],\ b_2 = 2\left[\frac{C_f}{m} + \frac{dC_f l_f}{I_z}\right] \tag{9}$$

$$d_2 = -\left[v_x + \frac{2a_2}{mv_x} + \frac{2da_3}{I_z v_x}\right]\dot{\psi}_d - d\ddot{\psi}_d \tag{10}$$

Then the lateral moving model of vehicles could be described as the following form:

$$\begin{bmatrix}\ddot{\psi}_r \\ \ddot{y}_s\end{bmatrix} = \begin{bmatrix}a_{11} & a_{12} & 0 & a_{13} \\ a_{21} & a_{22} & 0 & a_{23}\end{bmatrix}\begin{bmatrix}\psi_r \\ \dot{\psi}_r \\ y_s \\ \dot{y}_s\end{bmatrix} + \begin{bmatrix}b_1 \\ b_2\end{bmatrix}\delta_z + \begin{bmatrix}d_1 \\ d_2\end{bmatrix} \tag{11}$$

With $\dot{\psi}_r = \omega$ and $\dot{y}_s = v_y$ defined, the above model could be written as standard state-variable mode.

$$\begin{bmatrix}\dot{\psi}_r \\ \dot{\omega} \\ \dot{y}_s \\ \dot{v}_y\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0 \\ a_{11} & a_{12} & 0 & a_{13} \\ 0 & 0 & 0 & 1 \\ a_{21} & a_{22} & 0 & a_{23}\end{bmatrix}\begin{bmatrix}\psi_r \\ \omega \\ y_s \\ v_y\end{bmatrix} + \begin{bmatrix}0 \\ b_1 \\ 0 \\ b_2\end{bmatrix}\delta_z + \begin{bmatrix}0 \\ d_1 \\ 0 \\ d_2\end{bmatrix} \tag{12}$$

Considering the practice and complexity in the problem of lane keeping, the hypothesis was made for model with reference to literature [11].

Hypothesis 1. The variables m, I_z, l_f, l_r, C_f and C_r of vehicles are all unknown.

Hypothesis 2. The curvature χ of the pavement was also the unknown parameter, but its value was bounded.

4. The design of sliding mode control law for inner loop based on the stability of rotating angle

First, the expected yaw angle error was assumed as ψ_{rd} and the tracking controller was designed as follows. The error variable was defined as $e_\psi = \psi_r - \psi_{rd}$, then the following formula could be got.

$$\dot{e}_\psi = \dot{\psi}_r - \dot{\psi}_{rd} = \omega - \dot{\psi}_{rd} \tag{13}$$

Define the sliding mode surface as below:

$$s = c_1 e_\psi + \dot{e}_\psi \tag{14}$$

The derivation of this sliding mode surface was written as:

$$\dot{s} = c_1\dot{e}_\psi + \ddot{e}_\psi = c_1(\omega - \dot{\psi}_{rd}) + \dot{\omega} - \ddot{\psi}_{rd} \tag{15}$$

By substituting the model equations in the above differential formula, the following relation could be obtained.

$$\dot{s} = c_1(\omega - \dot{\psi}_{rd}) - \ddot{\psi}_{rd} + a_{11}\psi_r + a_{12}\omega + a_{13}v_y + b_1\delta + d_1 \tag{16}$$

The control law δ was designed as below:

$$\delta = \frac{1}{b_1}\left[-c_1(\omega - \dot{\psi}_{rd}) + \ddot{\psi}_{rd} - a_{11}\psi_r - a_{12}\omega - a_{13}v_y - d_1\right] + \Omega_1 \tag{17}$$

where,

$$\Omega_1 = -k_1 s - \frac{k_2 s}{|s| + \varepsilon} - k_3\frac{1 - e^{-\varepsilon s}}{1 + e^{-\varepsilon s}} \tag{18}$$

Considering the uncertainty of these parameters in system, when the control gain k_1, k_2 and k_3 were large enough, the control law could be simplified further as follows.

$$\delta = \Omega_1 \tag{19}$$