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Acceleration estimation method and sliding mode control design for car-following distance control

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Abstract

Vehicle following for traffic safety has been an active area of research. Car-following distance control is key for vehicle following mode in autonomous cruise system. Sliding mode control has been applied in vehicle longitudinal distance control. But most of them ignore or simplify acceleration information and reduce control performance. The purpose of this paper is to design sliding mode control method considering relative acceleration parameter to control car-following distance for autonomous cruise control (ACC). Meanwhile, tracking-differentiator is designed to estimate acceleration information as the control parameter and enhances the control system performance. Theoretical analysis and computer simulation prove that the designed linear tracking-differentiator can effectively estimate the relative acceleration and sliding mode control method considering relative acceleration parameter can also effectively control headway distance.

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Keywords: Tracking-differentiator; Acceleration estimation; sliding mode control; car-following distance

1. Introduce

Autonomous cruise control system includes cruise mode and following mode. For the cruise mode, no vehicle exists before the subject vehicle and the subject vehicle run according to the setting speed. For the following mode, the headway distance between the subject vehicle and the lead vehicle is controlled.

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According to the parameters obtained by sensor, the system controls the headway distance between the subject vehicle and the lead vehicle by PID、LQ and sliding mode control methods [1], [2]. But most of them ignore or simplify acceleration information and reduce control performance. In this paper tracking-differentiator is designed and applied for the headway distance sliding mode control system. It provides the relative acceleration information needed in calculating the subject vehicle desired acceleration for headway distance sliding mode control system.

2. Sliding mode vehicle following control system design

2.1. Constant time-headway policy

General speaking, there are mainly two strategies for headway control. One is to keep constant spacing between the host vehicle and the preceding vehicle. The other is to maintain constant headway time. The Constant spacing is for inter-vehicle communication situation. The constant time-headway policy is commonly suggested as a safe practice for human drivers and is frequently used in ACC designs. Therefore the constant time-headway policy is adopted in this paper. It can be expressed as follows,

$$R_{des} = \tau \cdot v_f + L \tag{1}$$

Wherein τ may be viewed a following time or time-headway between vehicles, L is the separation distance when the vehicle is at standstill.

2.2. Sliding mode vehicle following control model

Most control systems use velocity and distance as the control parameters for vehicle following mode and have poor response capability for the quick change of the lead vehicle velocity. Sliding mode control (SMC) method considering acceleration parameter can improve the response capability. The structure of an ACC system is showed in figure 1.

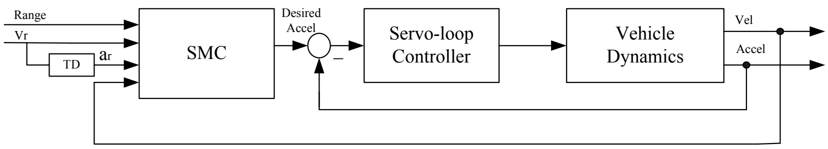

Fig.1 The structure of an ACC system

A main loop SMC controller determines the proper acceleration based on measured range, range rate, velocity and acceleration signals. A sub-loop controller then manipulates engine and brake actuators to achieve the desired acceleration or deceleration. Since the emphasis of this study is on the tracking differentiator and SMC, the servo-loop is ignored. Sliding surface is defined for the vehicle following mode control in paper[3] as followed,

$$R = x_l - x_f \tag{2}$$

$$S = \dot{R} + \lambda(R - R_{des}) \tag{3}$$

$$\dot{S} = \ddot{R} + \lambda(\dot{R} - \dot{R}_{des}) \tag{4}$$

$$\dot{S} = -KS \tag{5}$$

Wherein R is the headway distance, R_{des} is the desired distance between two vehicles, x_l and x_f are the positions of the lead vehicle and the subject vehicle respectively. If the differential of relative velocity namely relative acceleration a_r can be estimated real-timely, the desired acceleration is expressed by

$$a_{des}=\frac{1}{\lambda\tau}\cdot(KS+\lambda v_r+a_r) \tag{6}$$

As mentioned above, the relative acceleration information is needed in order to calculate the desire acceleration in equation (6). But only the distance R and the relative velocity v_r can be obtained directly by measurement system. Note that the relative acceleration parameter a_r is the differential of relative velocity v_r. So the key to realize the above control is whether the relative acceleration parameter a_r can be effectively obtained only according to the relative velocity data measured by millimeter-wave radar.

3. Relative acceleration estimation

About the moving target parameters estimation or tracking, the estimation model is built by numerical differentiation [5]. Tracking-differentiator is designed which tracks the position information and obtain the velocity information at the meantime [6]. Tracking-differentiator has two output signals and one input signal. The one of output signal tracks the input signal and the other estimate the difference signal of the input signal [7]. In real life, distance, velocity, and acceleration are related to each other. Due to the massive weight of the vehicle, acceleration can not be changed dramatically. Based on these assumptions, the linear tracking-differentiator is adapted for the headway distance control in the vehicle following model. It is used to track the velocity measured by millimetre-wave radar at the meantime estimate the relative acceleration. The tracking-differentiator is expressed as follows:

$$\begin{cases}\dot{v}(t)=a(t)\\ \dot{a}(t)=m_1R^2[v(t)-u(t)]+m_2R\cdot a(t)\\ y(t)=v(t)\end{cases} \tag{7}$$

wherein $m_1, m_2>0$, $m_2{}^2-4m_1>0$, $R>0$, $v(t), a(t)$ are system sate variable and $v(0), a(0)$ are system initial sate variable and bounded. $u(t)$ is the relative velocity measured by radar and it is system input signal. The Laplase transformation is done for system (7) and finally get

$$\lim_{R\to+\infty}G(s)=\lim_{R\to+\infty}\frac{Y(s)}{U(s)}=\lim_{R\to+\infty}\frac{V(s)}{U(s)}=\lim_{R\to+\infty}\frac{1}{1+\frac{m_2}{m_1R}\cdot s-\frac{1}{m_1R^2}\cdot s^2}=1 \tag{8}$$

According to the above analysis, the conclusion that the system (7) is asymptotically stable can be obtained. So, when $R\to+\infty$ $\lim\limits_{R\to+\infty}v(t)=u(t)$, $v(t)$ tracks the velocity signal $u(t)$ and $a(t)$ is the differential of $u(t)$ (acceleration signal). $v(t)$ and $a(t)$ are the parameters needed by sliding mode control system. But in fact for computer, the linear discrete-time tracking-differentiator form is selected. According to the description [9], the tracking performance of the discrete-time tracking-differentiator is proved in this paper. The system (7) can be changed into

$$\begin{bmatrix}\dot{v}\\ \dot{a}\end{bmatrix}=\begin{bmatrix}0 & 1\\ m_1R^2 & m_2R\end{bmatrix}\cdot\begin{bmatrix}v\\ a\end{bmatrix}-\begin{bmatrix}0\\ m_1R^2\end{bmatrix}\cdot u(t) \tag{9}$$

The solution of discrete-time form of the linearity system (9) is

$$x(k)=e^{\begin{bmatrix}0 & 1\\ m_1R^2 & m_2R\end{bmatrix}\cdot l(k-k_0)}x(k_0)-\sum_{n=k_0}^{k-1}e^{\begin{bmatrix}0 & 1\\ m_1R^2 & m_2R\end{bmatrix}\cdot l(k-n-1)}\int_0^l e^{\begin{bmatrix}0 & 1\\ m_1R^2 & m_2R\end{bmatrix}\tau}d\tau\begin{bmatrix}0\\ m_1R^2\end{bmatrix}\cdot u(n) \quad (10)$$

Wherein l is sampling time interval and $0<l<1$, $x(k)=[v(k) \quad a(k)]^T$ is system sate variable at time k. Therefore,

$$\lim_{R\to+\infty} v(k)=\left(\lambda_2 e^{\lambda_1\cdot l}-\lambda_1 e^{\lambda_2\cdot l}+\sqrt{m_2^{\;2}+4m_1}R\right)\cdot\frac{1}{\sqrt{m_2^{\;2}+4m_1}\cdot R}u(k-1)=u(k-1) \quad (11)$$

So, tracking-differentiator has good tracking performance and its output signal can tracks the relative velocity signal and estimates acceleration signal.

4. Simulation and anlysis

In order to verify the correctness and test the tracking performance of the designed linear tracking-differentiator, simulation is performed and the intelligent vehicle headway sliding mode control simulation is also performed. The parameters of linear tracking-differentiator system are selected as following $m_1=0.5, m_2=8, R=350, l=0.05$. Furthermore, the filtered relative velocity measurement signals are used as the input signal of linear tracking-differentiator to test the tracking performance of the designed linear tracking-differentiator. These signals measured by Fujitsu millimetre-wave radar and are filtered by kalman filter method in paper [10]. The initial state vector to vehicle headway distance control system is $x(0)=[v(0) \quad a(0)]^T=[0 \quad 0]^T$. Fig2 and Fig3 show the simulation results .

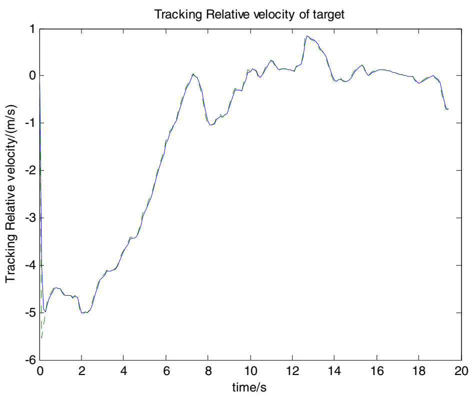

Fig 2. Relative velocity and its tracking output signals

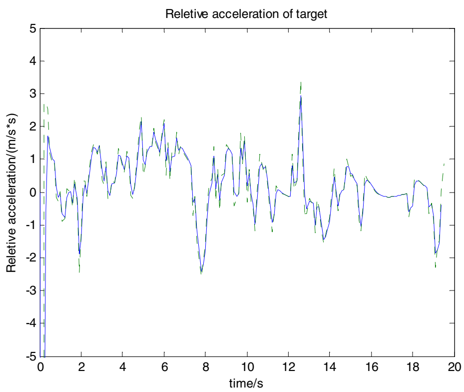

Fig 3. Output signals of relative acceleration estimation

Figure 2 illustrates vehicle relative velocity and its' tracking output signals. The real line is the tracking output signal of relative velocity and the imaginary line is the relative velocity signal. It shows that the designed linear tracking-differentiator can track the change of vehicle relative velocity thoroughly. In Figure 3, the real line is the estimation value of relative acceleration and the imaginary line is the theory value of relative acceleration signal. It shows that linear tracking-differentiator can effectively estimate the relative acceleration and the error is small for very short sample-time. Then intelligent vehicle headway sliding mode control simulation is also performed. Control input signals data are still obtained from paper [8]. The parameters of control system are selected as following, $\tau=2.5, \lambda=0.55, K=0.5$.

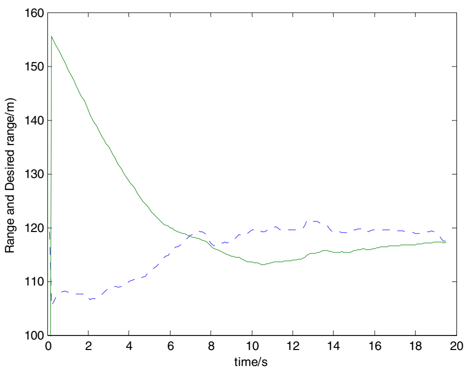

Fig 4. Range and desired range of vehicles

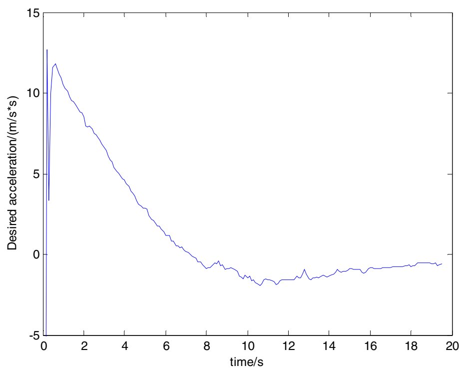

Fig 5. Desired acceleration of the following vehicle

In fig4, the real line is the range curve and the imaginary line is the desired range curve.The simulation results in Fig4 and Fig5 show that sliding mode intelligent vehicle headway distance control system based on tracking differentiator can effectively control headway distance.

5. Conclusions

In this paper, sliding mode control method considering relative acceleration parameter has been introduced for the headway distance control. Meanwhile the linear tracking-differentiator has been designed for tracking the relative velocity signal and estimating the value of relative acceleration. Theoretical analysis and computer simulation prove that sliding mode control based on tracking differentiator approach can effectively control intelligent vehicle headway distance.

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