Adaptive Cruise Control of a Passenger Car Using Hybrid of Sliding Mode Control and Fuzzy Logic Control

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ABSTRACT

This paper focuses on the design of adaptive cruise control (ACC) which was implemented on a passenger car based on sliding mode control (SMC) of throttle valve combining with fuzzy logic control of brake pedal. An important feature of the new adaptive cruise control system is the ability to maintain a proper inter-vehicle gap based on the speed of host vehicle and headway way. There are three important inputs of the ACC system, speed of host vehicle read from electronic control unit (ECU), headway time set by driver, and actual gap measured from a laser scanner. The ACC processes these three inputs in order to calculate distance error and relative velocity which are used as the two inputs for both SMC and fuzzy controller. The SMC determines throttle valve angle while fuzzy controller determines the brake command to maintain a proper gap based on current speed of the leading vehicle and the desired time headway. The experimental results show that the proposed controller can perform efficiently in ACC of a passenger car.

INTRODUCTION

Many researchers have tried to develop adaptive cruise control (ACC) using fuzzy logic controller [1], [2], [3]. These methods enable the host vehicles to follow autonomously preceding vehicles while keeping safety distance. However since fuzzy logic controller is a non-model based controller, it is designed based on experience of designer, the performance of fuzzy logic controller based ACC can be improved further if dynamics model of the vehicle is taken into consideration.

Vehicle dynamics is very important in designing high performance controller, however it is quite difficult to obtain accurate vehicle parameters. System identification of the vehicle parameters requires extensive experiment tests on the real vehicle. Nonlinearity in the vehicle model causes change in the model parameters.

Sliding mode control (SMC) is a technique derived from variable structure control. It has gradually been one of the most popular nonlinear control methods since 1977. It is widely used in many applications due to its effectiveness in nonlinear systems and robustness on model uncertainties and disturbances.

AIT INTELLIGENT VEHICLE

AIT intelligent vehicle is developed on Mitsubishi Galant GLSi, 1989. This vehicle has a 2.0 liters, gasoline engine and automatic transmission gear. The intelligent vehicle of AIT includes steering, brake and throttle value control system. The overall architecture of AIT intelligent vehicle is shown in Fig. 1. FiO-Std board is used as the
main processing unit. The vehicle speed is obtained from the average of the speeds read from two proximity sensors. These two sensors are installed inside both rear wheels. Laser scanner, SICK LMS 291, is mounted at the front bumper of the vehicle. This sensor measures the distance between the intelligent vehicle which is the host vehicle and preceding vehicle. The original throttle valve control system is modified to a drive-by-wire system so as to control the vehicle speed in the Adaptive Cruise Control (ACC) system. A 24V dc servo motor is installed to control the throttle valve position. The drive-by-wire controller is developed on an FiO-Std which receives commands from all sensors and human driver. In automatic mode, SMC determines throttle valve angle while fuzzy controller determines the brake command to maintain a proper gap. In manual mode, the driver drives the vehicle, a potentiometer is installed at the accelerator pedal to measure the pedal position of the driver.

LONGITUDINAL VEHICLE MODEL

In designing the SMC, vehicle longitudinal dynamics model is required. Actually longitudinal dynamics of the engine depends upon several factors including air/fuel ratio, exhaust gas recirculation (EGR), cylinder total mass charge, spark advance, engine speed, total load torque, as well as throttle valve angle.

The vehicle receives the input in the form of driving and/or brake torque and generates the outputs of vehicle speed, acceleration or deceleration. Vehicle speed and acceleration are also affected by road condition, aerodynamic drag and vehicle mass. The relationship between vehicle speed and transmission torque is also nonlinear.

The complexity of the vehicle longitudinal model described above makes it almost impossible to design a control law based on such model. In our approach, linearization is conducted to the vehicle dynamics in order to obtain a linear model whose parameters are functions of the operating points. Taylor series expansion with high order term negligence is used in the linearization to simplify the original vehicle nonlinear longitudinal model [4]. For a fixed gear state, the linearized model relating between vehicle speeds \( v_n \) and \( \theta_n \), can be represented by a first order transfer function.

\[
\frac{v_n}{\theta_n} = \frac{b_n}{s + a_n}
\]  

Where the coefficients \( a_n \) and \( b_n \) are function of operating point of \( v_n \) or \( (v_n, \theta_n) \) when \( n \) is state of gear transmission.

LONGITUDINAL CONTROL OF INTELLIGENT VEHICLE

Fig. 2 shows block diagram of the proposed hybrid of sliding mode control and fuzzy logic control. The electronic transmission control is an automatic transmission which uses modern electronic control technologies to control the transmission. The transmission is the same as a full hydraulically controlled transmission, however, it also consists of electronic parts; such as sensors, electronic control unit and actuators.

CONTROL OF THROTTLE VALVE ANGLE USING SLIDING MODE CONTROL

Sliding mode control is applied to control throttle valve angle. Sliding surface, \( s(t) \), in the conventional SMC depends on the tracking error, and derivative of the tracking error.

\[
s(t) = \left( \frac{d}{dx} + \lambda \right)^{n-1} e(t)
\]  

Where \( n \) denotes order of uncontrolled system, \( \lambda \) is a positive constant, \( \lambda \in R^+ \).

\[
x_R = v_H * t_{hw} + x_0, t_{hw} > 0, x_0 > 0
\]  

\[
v_R = a_H * t_{hw}
\]  

Where \( v_H \) and \( a_H \) are host vehicle speed and acceleration, \( t_{hw} \) is headway time between vehicle, \( x_0 \) is the safety distance when the
In order to define the sliding surface, the gap distance and the rate of gap distance are defined as

\[ x_L = x_p - x_H \]  \hspace{1cm} (5)
\[ x' = v_r - v_H \]  \hspace{1cm} (6)

Where \( x_p \) and \( x_H \) are the position of the preceding vehicle and the host vehicle. The preceding vehicle acceleration \( a_p \) is obtained by estimation. The tracking error between actual gap distance and reference gap distance, \( e(t) \), is defined as

\[ e(t) = x_L - x_R \]  \hspace{1cm} (7)

Time-derivative of the tracking error is derived as

\[ \dot{e}(t) = \dot{x}_L - \dot{x}_R \]  \hspace{1cm} (8)

From (8), tracking error of vehicle speed can be defined as

\[ \dot{v}(t) = v_r - a_p \times t_{hw} \].

Asymptotically stable sliding surface for longitudinal control can be expressed by

\[ s(t) = \dot{e}(t) + \lambda e(t) \]  \hspace{1cm} (9)
\[ \dot{s}(t) = \ddot{e}(t) + \lambda \dot{e}(t) \]  \hspace{1cm} (10)

In the sliding mode, where \( s(t) = 0 \), the reduced order dynamics on sliding manifold is expressed by

\[ \dot{e}(t) = -\lambda e(t) \]  \hspace{1cm} (11)

the system is stable for all \( \lambda > 0 \). This implies that in the sliding mode \( s(t) = 0 \),

\[ v_r \rightarrow \dot{x}_R, \quad x_L \rightarrow x_R \]  \hspace{1cm} (12)

From the sliding reachability condition, \( \dot{s}(t) = -Ks(t) \) [10], thus

\[ \dot{s}(t) = -K[(\dot{x}_L - \dot{x}_R) + \lambda (x_L - x_R)] \]  \hspace{1cm} (13)

Define \( \dot{s}(t) = 0 \) then

\[ 0 = -K[(\dot{x}_L - \dot{x}_R) + \lambda (x_L - x_R)] \]  \hspace{1cm} (14)
\[ 0 = v_r - a_p t_{hw} + \lambda e \]  \hspace{1cm} (15)

According to the sliding surface and the first order transfer function of the vehicle dynamics model, the control input \( \theta \) can be expressed by the following equation.

\[ \theta = \frac{1}{b_n + t_{hw}}[v_r + a_n v_m t_{hw} + \lambda e] + \beta sign(s) \]  \hspace{1cm} (16)

Where, \( \beta \) is the gain and \( sign(s) \) denotes the signum function defined as

\[ sign(s) = \begin{cases} +1 & \text{as } s > 0 \\ 0 & \text{as } s = 0 \\ -1 & \text{as } s < 0 \end{cases} \]  \hspace{1cm} (17)

CONTROL OF BRAKE ACTION USING FUZZY LOGIC CONTROL

In order to achieve high rate of deceleration of the vehicle speed, fuzzy logic controller is applied as the brake controller to decelerate the vehicle. Error of gap distance between the vehicles, called distance tracking error, and their relative speed, called speed tracking error, are the inputs and level of braking force is the output of the fuzzy controller.

The distance tracking error is determined from \( \Delta x(k) = x_L(k) - x_R(k) \) while the speed tracking error is determined from \( \Delta v(k) = v_L(k) - v_R(k) \). There are 16 brake levels varying from 0 (no brake) to 15 (full brake). Membership functions of all the

\[ \mu_i(\Delta x(k)) \]  \hspace{1cm} (18)

\[ -L_e \rightarrow -0.5L_e \rightarrow 0 \rightarrow +0.5L_e \rightarrow +L_e \]  \hspace{1cm} (19)

\[ \Delta x(k) \]  \hspace{1cm} (20)

\[ 1 \rightarrow NM \rightarrow NS \rightarrow Z \rightarrow PS \rightarrow PM \]  \hspace{1cm} (21)
The inputs and output of the brake controller are shown in Figs. 4 – 6.

![Speed Tracking Error Membership Functions](image1)

Figure 5. Speed tracking error membership functions

![Brake Level Membership Functions](image2)

Figure 6. Brake level membership functions

Based on these membership functions, the fuzzy inference rule of the fuzzy controller is shown in Table I. From the table, each rule has two antecedents and one consequent as expressed by:

\[ R_i: \text{if } \Delta x(k) \text{ is } A, \Delta v(k) \text{ is } B, \text{then } F_b(k) \text{ is } C \]

The output of fuzzy brake controller is obtained by employing the centroid defuzzifier as expressed in (18) where \( \mu_i(k) \) is the membership value of the \( i^{th} \) rule, and \( F_{b_i}(k) \) is the singleton output fuzzy set of the \( i^{th} \) rule of the fuzzy brake controller.

\[ F_b(k) = \frac{\sum_{i=1}^{N} \mu_i(k) F_{b_i}(k)}{\sum_{i=1}^{N} \mu_i(k)} \quad (18) \]

The following criteria are used for switching among the controllers.

\[ F_b(k) < F_{th} \Rightarrow \text{Throttle Valve Control} \quad (19) \]
\[ F_b(k) \geq F_{th} \Rightarrow \text{Brake Control} \quad (20) \]

Where \( F_{th} \) is the braking threshold value.

The proposed control algorithm is applied to the AIT intelligent vehicle. Two experiments are conducted. The first experiment is conducted to identify the vehicle parameters. The second experiment is conducted to test the performance of the longitudinal control.

### VEHICLE IDENTIFICATION

In the vehicle longitudinal model as expressed in (1), the parameters in the model are obtained by estimation from the experimental data. The algorithm used in this paper is the least mean square (LMS) algorithm which is used to search for two coefficients \( b_0 \) and \( a_0 \). The data of the input of throttle valve angle and the output of vehicle speed at the 1st gear are collected as shown in Fig. 9.

![Experimental Data](image3)

Figure 7. Experimental data of input of throttle valve angle and output of vehicle speed

In identifying the parameters, the least mean square (LMS) algorithm on a batch of the data is employed, then the coefficients \( a_n = 0.1416 \) and \( b_n = 0.1719 \) are obtained.
EXPERIMENTAL RESULTS OF ADAPTIVE CRUISE CONTROL

The experiment is conducted to evaluate the performance of longitudinal control for 60 sec. The headway time is selected at 1 sec and the safety distance at zero speed is 5 m. The values of the SMC parameters are selected as $\lambda = 2.512$ and $\beta = 3.627$. The preceding car accelerates during the 0th sec to the 30th sec, then during the 30th sec to the 37th sec the speed of the preceding vehicle is maintained constantly as shown in Fig. 8.

Figure 8. Preceding vehicle speed (m/s)

The longitudinal reference gap distance and the actual gap distance are shown in Fig. 9. The reference gap distance and the actual gap distance change in the same form however mostly the actual gap distance is longer than the reference gap distance. There is a delay of actual gap distance comparing with the reference gap distance.

Figure 9. Distances between reference gap distance and actual gap distance

Fig. 10 shows the results of throttle valve angle and brake level commands. The result of headway time is shown in Fig. 11. From the figure, there is a delay for about 7 sec from starting because the host vehicle does not start yet. The figure shows that the proposed control algorithm can control the vehicle to approach the desired headway time efficiently.

Figure 10. Commands of throttle valve angle and brake level

Figure 11. Desired headway time and measured headway time

CONCLUSION

The paper proposed ACC of an intelligent vehicle using hybrid of sliding mode control and fuzzy logic control. The results from the experiments have shown that the proposed control algorithm worked effectively with nonlinearity and uncertainty in the model. Since SMC is robust, the complexity of the real model can be simplified by a first-order model.

REFERENCES