

Vehicle Longitudinal Control Algorithm Based on Iterative Learning Control

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ABSTRACT

Vehicle Longitudinal Control (VLC) algorithm is the basis function of automotive Cruise Control system. The main task of VLC is to achieve a longitudinal acceleration tracking controller, performance requirements of which include fast response and high tracking accuracy. At present, many control methods are used to implement vehicle longitudinal control. However, the existing methods are need to be improved because these methods need a high accurate vehicle dynamic model or a number of experiments to calibrate the parameters of controller, which are time consuming and costly. To overcome the difficulties of controller parameters calibration and accurate vehicle dynamic modeling, a vehicle longitudinal control algorithm based on iterative learning control (ILC) is proposed in this paper. The algorithm works based on the information of input and output of the system, so the method does not require a vehicle dynamics model. Due to ILC's self-learning ability, the controller parameters don't need to be calibrated. Then the proposed algorithm has been built in the study and tests of the control algorithm have been carried out. Finally the results show that the vehicle longitudinal control algorithm based on ILC can accomplish the target longitudinal acceleration tracking well and its control performance is better than PID controller and model-based controllers.

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INTRODUCTION

In recent years, intelligent vehicle and Advanced Driver Assistance Systems (ADAS) have been paid more and more attention [1,2,3,4]. As a typical function of ADAS, Adaptive Cruise Control System (ACC) is being actively developed in automobile research areas. The vehicle longitudinal control algorithm (VLC) is one of the most important parts of ACC, which provides both safety and driving comfort. The main task of the vehicle longitudinal control algorithm is to translate the desired acceleration into appropriate throttle or brake control actions so that the vehicle speed and the headway distance track the desired values [5,6].

Many scholars devoted themselves to the topic of ACC. However, the researches of ACC mainly concentrate on the development of the decision algorithm, which is the upper layer above vehicle longitudinal control algorithm. With respect to vehicle longitudinal control, current literature is rare. The vehicle longitudinal control is in the scope of tracking control. A vehicle is the plant of the controller, with regard to the realization of vehicle longitudinal control. There are some difficulties in the widely varying non-linear dynamic behavior of the vehicle. The classical control method such as the PID controller does not need mathematical model of the plant. So the PID controller has been used to implement the vehicle longitudinal control at the beginning. Additionally, the look-up table

based control method has been adopted for the vehicle longitudinal control because it doesn't need the plant mathematical model. Then the vehicle longitudinal dynamics model has been involved in the vehicle longitudinal control algorithm to improve the tracking performance and control precision.

To realize the target acceleration tracking control, it is popular to utilize classical control method as the controller of vehicle longitudinal control. Li et al [7] developed a PID controller for VLC. In the method, it has been tested and verified by Simulink and Carsim. Wang et al [8] developed a braking device and an electronic throttle control device with dual mode for commercial vehicle ACC. The VLC of ACC has been constructed by combining proportional-integral (PI) controller and Smith predictive compensator. Because vehicle dynamics is varying while the driving situation changing, scholars from Kingston University of UK, P. Shakouri et al [9] utilized the gain scheduling proportional integral controller (GSPI) to control the throttle opening position and brake separately. In their method, in order to obtain tuning sets of the PI gains, several linear models have been approximated around operating points to imitate the nonlinear vehicle dynamic model. Then PI controller was tested in various traffic scenarios. Behnam Ganji et al [10] used a classical controller to implement VLC and the swarm optimization is implemented for parameter self-tuning of the controller.

For mass production, the VLC always developed based on the relationship of the actuator action (the throttle opening position and brake pressure) and target acceleration, which is represented by a series of numerical look-up tables and calibrated by road tests under different conditions. Liu et al [11] designed a throttle controller and a brake controller respectively with feedforward and feedback control. To avoid troublesome system parameter identification, the empirical look-up table was calibrated based on tests. Then the vehicle control is achieved by the look-up table in his method.

Moreover, the vehicle longitudinal control based on the vehicle longitudinal dynamic model is proposed by J.C. Gerdes et al [12] and Sunan Huang et al [13,14]. Later, a throttle and brake control algorithm for ACC based on vehicle dynamics has been proposed by Kyongsu Yi et al [15]. In addition, a proportional-integral-derivative (PID) control law is used to compensate the disturbances in this method.

With simple structure and good performance, the classical controller such as PID controller relies only on the measured process variable, not on knowledge of the plant mathematics model, making it a broadly useful controller. While PID controllers are applicable to many control problems, and often perform satisfactorily. However, they perform poorly in some applications, and do not provide optimal control generally. On the one hand, PID controller is linear. Thus, the performance of PID controllers in non-linear systems is variable. On the other hand, PID controllers may show poor performance when the PID gains have to change according to the set point. Furthermore the researches of P. Shakouri et al [5] and Behnam Ganji et al [6] reveal that the PID controller is not a powerful method to manage the rapid transformation of the desire set point. The numerical look-up table based VLC relies on plenty of road tests to calibrate the relationships of the throttle opening position / brake and actual acceleration in wide situation. Because the acceleration is influence seriously by many factors, such as the vehicle mass, vehicle speed, gear position, wind, and road slope, besides throttle opening position and brake pressure. The relationships of control input and actual acceleration have to be determined by a lot of experiments. Hence, this method is costly and time consuming. Furthermore the portability of the approach is poor, because the look-up table is calibrated on a specific vehicle, and cannot be applied to other vehicles. With the help of vehicle dynamic model, the model based VLC could alleviate the calibration and match work in practical application. However, the control method relies on accurate vehicle longitudinal dynamic model, so the performance and the stability of this controller can be worsen by any uncertainties and errors of the vehicle dynamic model.

Aiming at the shortcomings of the existing control methods above, a novel VLC is proposed in the paper, which is designed based on iterative learning control (ILC). The iterative learning control is good at control system with repeat task, and can be applied to the vehicle longitudinal control, because the VLC need to perform repetitive control objectives in general condition. Due to the self-learning ability of ILC, the VLC based ILC can be achieved free of model and calibration.

In recent years, with good tracking performance and simple structure, the researches in this field of ILC have caused widely attention [16,17,18,19,20]. The ILC is a method of tracking control for systems that work in a repetitive mode, and use previous information to design a new control signal. The method can learn from experience to improve the control performance, so the method is categorized as learning-type control [21]. In other words, with the learning control schemes, the tracking errors in any phase of the time domain, either in the transient phase or in the steady state, can be made to be within the specified error bound. Moreover, the iterative learning control schemes work equally well for unknown dynamic systems with or without parameter changes. Hence based on ILC the VLC can be achieved without vehicle dynamic model. In addition, the calibration of controller parameters may be eliminated due to the self-learning ability of ILC.

A novel VLC approach is proposed in the paper, which is designed based on ILC. The advantages of the ILC based VLC to implements vehicle control are free of vehicle dynamic model and free of parameters calibration. That is to say, the ILC based VLC relies on the information of input and output of vehicle, not demands on the vehicle dynamic model. Moreover the ILC based VLC can improve tracking accuracy by learning from experience iteratively, and no need to calibrate the controller parameters.

The rest of this paper is organized as follows: The iterative learning control method is introduced in Section 2. Section 3 discusses how to design the VLC based on ILC. The proposed VLC algorithm is verified and compared with PID method and model based control method and tests results are analyzed in Section 4. Section 5 gives the conclusions.

OVERVIEW OF ILC

ILC is an approach to solve the control problem for systems or processes that operate repetitively. It can improve its control performance by learning from previous information. The architecture of ILC is shown in Figure 1. The systems model is basis to the analysis. To make a precise mathematical definition of the ILC problem consider the following continuous-time time-varying model defined over a finite time-interval $t \in [0, T]$:

$$\begin{cases} \dot{x}(t) = f[t, x(t), u(t)] \\ y(t) = g[t, x(t), u(t)] \end{cases} \quad (1)$$

where the state $x \in R^{n-1}$, output $y \in R^{m-1}$, input $u \in R^{l-1}$. The operators f , g in (1) are vector function of appropriate dimensions, which can represent unknown dynamic systems with unknown parameter. Time t in (1) is a continuous parameter. The control objective is defined in terms of a reference signal $y_d(t)$. The task is to construct $u(t)$ so that $y(t)$ tracks $y_d(t)$ as accurately as possible.

The systems model at trial k can be written as follow.

$$\begin{cases} \dot{x}_k(t) = f[t, x_k(t), u_k(t)] \\ y_k(t) = g[t, x_k(t), u_k(t)] \end{cases} \quad (2)$$

where $x_k \in R^{n-1}$, $y_k \in R^{m-1}$, $u_k \in R^{l-1}$ denotes states, outputs, inputs respectively at k th trial.

The tracking error can be defined as follow.

$$e_k(t) = y_d(t) - y_k(t) \quad (3)$$

Control systems design in ILC takes a quite specific form. If $u_k(t)$ is the input applied at trial $k \in \mathbb{N}$ and $e_k(t)$ is the resulting tracking error, the control design problem is to construct a control law (or algorithm) expressed, for generality, as a functional relationship typified by the equation as follow [22]:

$$u_k(t) = Q_{ILC}(u_{k-1}(t)) + r_k(t) \quad (4)$$

where $Q_{ILC}(u_{k-1}(t))$ is called the feedforward part of ILC; $r_k(t)$ is called the updating law for ILC; $Q_{ILC}(\cdot)$ is called the Q-filter. Specially, if $Q_{ILC}(u) = Q \times u$, where Q is a scalar within (0, 1), it is also called the forgetting factor. In much of the literature, $Q_{ILC}(u) = u$. Most linear updating laws can be written in the following form:

$$r_k(t) = L_{ILC}(e_{k-1}(t)) \quad (5)$$

where $L_{ILC}(u_{k-1}(t))$ is called the L-filter. For example, if $L_{ILC}(e) = K_{ILC} \times e$, this leads to a P-type ILC; if $L_{ILC}(e) = K_{ILC} \times (\dot{e})$, this is a D-type ILC.

It is assumed that there exists an input u^* which gives perfect tracking in the problem definition. The control law is required to have the property that $\lim_{k \rightarrow \infty} u_k = u^*$ (i.e. the control signal converges to the control signal that generates $y_d(t)$ exactly). As a consequence, if the control law is converged, the tracking error at k th trail approximates to zero ($e_k \rightarrow 0$) when the trail index approximates to positive infinite ($k \rightarrow \infty$).

The procedure to design ILC can be divided into following steps [23]:

- Step1. Choose the updating law's structure, design the Q-filter and the updating law based on Eq. (4).
- Step2. Set the initial control input $u_1(t)$ and feed it into the real plant.
- Step3. Record the output $y_k(t)$ and the corresponding tracking error $e_k(t)$ using Eq. (3).
- Step4. Determine whether if the tracking error $e_k(t)$ meets the terminal condition, if yes, finish the iteration; if no, continue.
- Step5. Determine control input of next trail $u_{k+1}(t)$ based on the updating law and run a new experiment. Set $k \rightarrow k+1$ and go to Step3.

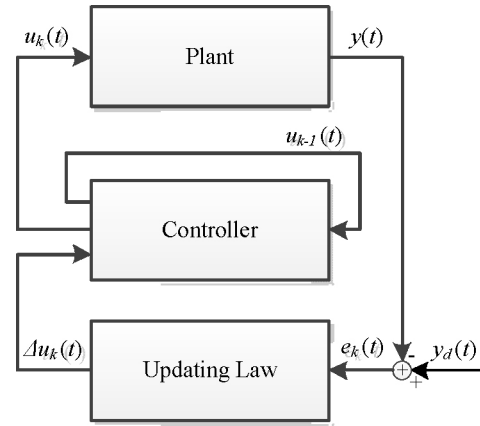


Figure 1. Iterative Learning Control architecture

VEHICLE LONGITUDINAL CONTROL ALGORITHM BASED ON ILC

The objective of VLC is to track the target acceleration accurately by intervening the vehicle throttle and brake, which is determined by the decision algorithm for ACC.

As a learning-type control method, with the updating law, ILC can make the control output track the reference trajectory as closely as possible iteratively. The structure of updating law is the key point of designing ILC. PID-type should be the most common structures of the updating law [17,19].

Considering the delay of the vehicle longitudinal dynamics, an algorithm of closed loop PD-type iterative learning control (ILC) for the vehicle longitudinal control (VLC) is proposed in this paper. Because of using the current information of the system, the closed loop ILC has good convergence and robustness, need only a small number of iterations to achieve good tracking performance. The PD-type ILC is defined as follows [24,25]:

$$u_{k+1}(t) = u_k(t) + L_p e(t) + L_d \dot{e}(t) \quad (6)$$

where L_p and L_d is the learning gain.

Convergence is naturally the most important requirement for an ILC algorithm. It is meaningful to apply ILC in practice only if the convergence of the algorithm can be approached. If the tracking error e_k approximates to zero while the iteration index k approximates positive infinite, that is, the ILC is convergent.

The structure of iterative learning control is shown in Figure 2. It is assumed that the transfer function of the plant and the control law are $P(s)$ and $L(s)$, respectively. Then

$$y_k(s) = u_k(s) \cdot P(s) \quad (7)$$

$$u_k(s) = u_{k-1}(s) + L(s) \cdot e_k(s)$$