Decentralized Longitudinal Tracking Control for Cooperative Adaptive Cruise Control Systems in a Platoon

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***Abstract*—This paper presents a longitudinal tracking control law for Cooperative Adaptive Cruise Control (CACC) systems in a platoon that can comprehensively enable tracking capability of various spacing policies, designed expected velocity, and designed expected acceleration. Taking into account heterogeneous traffic, i.e., a platoon of vehicles with possibly different characteristics, the longitudinal control problem is formulated as an output tracking control problem with a quadratic function so that the contradictions among the different tracking requirements are realized, which include inter-vehicle spacing, velocity and acceleration. Then, the decentralized longitudinal tracking control law is proposed by using a limited communication structure and maximum principle (in this case, a wireless communication link with the nearest preceding vehicle and designed platoon leader only), in which the feedback items are composed of the states of host vehicles, and additional information of the nearest preceding vehicle and designed platoon leader are used as feedforward items. In addition, the concepts of "expected velocity" and "expected acceleration" are introduced to design the desired velocity and acceleration, realize additional objectives, and improve the predictive abilities. Numerous simulation results show that the proposed tracking controller provides a reliable tool for a systematic and efficient design of a platoon controller within CACC systems.**

***Index Terms*—longitudinal control; distributed control; Cooperative Adaptive Cruise Control (CACC) systems; optimal tracking control ; platoon**

I. Introduction

A considerable amount of theoretical and experimental research effort has been aimed at improving cruise control technology, including traditional cruise control (CC) [1], adaptive cruise control (ACC) [2], [3], and cooperative adaptive cruise control (CACC) [4], [5], in the last few decades. As is known, CC systems are simple, and have been used often in conventional vehicles. Nevertheless, CC systems have limitations in providing both intelligence driving and good ride performance. In comparison, ACC systems can improve driver convenience, reduce driver workload and have the potential to improve vehicle safety. Nowadays, ACC is widespread and available in numerous commercially available vehicles. However, the string unstable driving behaviors (e.g., lead to the traffic jams and rear-front collision) may result by using ACC [6]. With the improvements in sensing, communicating, and computing technologies, the proposed cooperation in CACC means that vehicles could extend the standard ACC functionality by using the inter-vehicle wireless communication.

The key technology of CACC system is the inter-vehicle wireless communication. With vehicle-to-vehicle (V2V) communication, a "virtual" network is formed by using a group of equipped vehicles so that the vehicles are linked together by wireless communication in a platoon. Examples of communication structures include a centralized controller design and communication between all vehicles in a platoon [7], bidirectional communication with the nearest vehicles [8], [9], or communication with both the nearest vehicles and a designed platoon leader [10], [11]. Using such communication structures will enable vehicles to gather related information about their surroundings, e.g., position, velocity, acceleration, heading, and even related to the driving intentions of other vehicles. The communication aspect of CACC has particularly been studied by [12]. Safety inter-vehicle distance is commonly defined as the minimum inter-vehicle distance that ensures avoid of vehicles rear-front collision no matter how the driver of the leading vehicle behaves [13]. Decreasing the inter-vehicle distance to a small value of only a few meters is expected to yield an increase in traffic throughput. A variety of spacing policies have been proposed [9], [10], [14]. From the traffic capacity point of view, a constant spacing headway of about 1 meter was suggested by Shladover [15]. However, in [16] it shown that the vehicle controller needs information about the leading vehicle of the platoon to ensure platoon stability. At present, the most common spacing policy used by researchers and vehicle manufactures is described as the constant time-gap (CTG) spacing policy [2]. Unlike the constant spacing policy, the tracking requirement in CTG policy can be easily obtained without any inter-vehicle communication. It should be noted that the specific spacing policy is adapted to the different real-time traffic condition, a genetic framework for the design of a CACC system with varieties of spacing policies does not exist.

978-1-4799-0652-9/13 $31.00 © 2013 IEEE
DOI 10.1109/SMC.2013.345

Most of the projects on CACC have relied on the classic control theory to develop autonomous controllers. To our knowledge, [17] gives an overview on how such a CACC system could be designed. [18] researches on a setup for CACC where the feasibility of the actual implementation. [19] is the first researcher to suggest using RL for steering control. By using a frequency-domain approach, a string stable CACC design and experimental validation are researched [6]. A reinforcement learning approach is designed for CACC system [20]. Considering the tracking capability, fuel economy, and driver desired response, a model predictive multi-objective vehicular adaptive cruise controller is designed in [21]. Finally, [4] studies the impact of CACC on traffic-flow characteristics. In this paper, a CACC design that specifically focuses on the feasibility of implementation is proposed.

The contribution of this paper involves, first, by introducing the concepts of "expected velocity" and "expected acceleration", the decentralized longitudinal problem is formulated as a tracking problem can comprehensively enable tracking capability of various spacing policies, designed expected velocity, designed expected acceleration, and improve the predictive ability. Second, the control law is proposed by using a limited communication structure and maximum principle to make the vehicles' behaviors more intelligent, in which the feedback items are composed of the states of host vehicles, and additional information of the nearest preceding vehicle and designed platoon leader are used as feedforward items.

The paper is organized as follows. In Section II, the problem formulation is presented. The decentralized longitudinal tracking control problem and the proposed control law are given in Section III. In Section IV, simulation results are presented. This paper is closed with conclusions.

II. PROBLEM DESCRIPTION

A. Platoon Configuration and Vehicle Dynamic Modeling

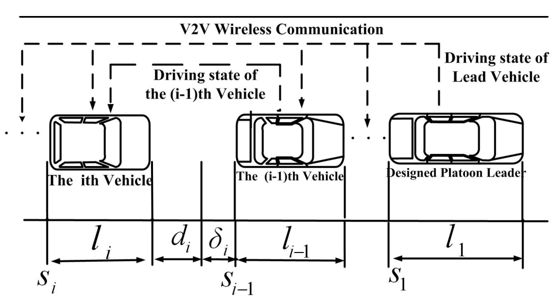

Fig. 1. Platoon structure

Fig. 1 describes a typical heterogeneous platoon of vehicles equipped with the CACC functionality. The driving states of ith vehicle include the velocity and the acceleration of the ith vehicle, respectively. In contrast to homogeneous platoons where the vehicles can be of the same kind, heterogeneous platoon described in Fig. 1 is discussed in this paper, where vehicles can be of different kind from small passenger cars to transportation trucks. The position of the lead vehicle's rear bumper with respect to the same fixed reference point is denoted by s_i . The safety spacing of the ith vehicle in the platoon is denoted by d_i. From the platoon configuration, the spacing error δ_i may be written as:

$$\delta_i(k) = s_{i-1}(k) - s_i(k) - d_i - l_i \tag{1}$$

The key technology of platoon in CACC is a wireless communication of conveying the information to the chain of vehicles so that each vehicle could receive information from a number of vehicles in front of it. There are three types of communication: leader-predecessor-follower strategy, predecessor-follower strategy, and communication in whole platoon. In this paper, host vehicle can receive the information about the nearest vehicle and designed platoon leader. Based on those information, some predictive nature is incorporated into the controller so that one can make vehicle's behaviors more intelligent. It is assumed that the designed platoon leader is fixed within a certain period of time in this paper.

Various models for vehicle dynamics have been used in the study of longitudinal control of platoons. For a vehicle traveling with a constant direction and velocity, it will be assumed in this paper that ith vehicle in a close formation platoon consisting of n vehicles can be represented by the following three-state space linear model:

$$\begin{aligned} &\dot{x}_i(t) = \Phi_i x_i(t) + \textstyle\prod_i u_i(t), \\ &\Phi_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau_i \end{bmatrix}, \ \textstyle\prod_i = \begin{bmatrix} 0 \\ 0 \\ 1/\tau_i \end{bmatrix} \\ &x_i(t) = \begin{bmatrix} s_i(t) & v_i(t) & a_i(t) \end{bmatrix}^T, \end{aligned} \tag{2}$$

where v_i and a_i are the ith vehicle's velocity and acceleration, respectably; $u_i \in R^1$ represents the control input; $x_i \in R^3$ represents the system state of the ith vehicle; τ_i is the time constant caused by the vehicle propulsion system which represents the characteristics of different vehicles. Considering the fact that the vehicle is usually designed and implemented in the discrete-time domain, the continuous-time (2) is converted into a discrete-time model by zero-order hold discretization, yielding:

$$x_i(k+1) = A_i x_i(k) + B_i u_i(k) \tag{3}$$

where k represent the kth sampling point, A_i and B_i are system matrices, mathematically expressed as:

$$A_i = \sum_{k=0}^{\infty} \frac{\Phi^k T_s^k}{k!}, \ B_i = \sum_{k=0}^{\infty} \frac{\Phi^{k-1} T_s^k}{k!} \prod \tag{4}$$

where T_s is sampling time. For a typical CACC system, all of the states in (3) are measurable.

B. Objective

CACC system can effectively improve the tracking capability, fuel economy, safety and good driver desired response. By using the wireless communication in a platoon, host vehicle receive the information about related vehicle so that the predictable performance is improved. Based on the requirements in the existing approaches to the platoon control, the following main platoon objectives derived from specific requirements within CACC systems:

(1) Based on the features of the host vehicle, road surface, and the real-time traffic situation, the appropriate inter-vehicle strategy should be selected by driver.

(2) The steady-state spacing error δ_i should be equal to zero for all the vehicles in the platoon so that the tracking capability can be ensured.

(3) When the lead vehicle accelerates, the host vehicle should accelerate before detecting the nearest preceding vehicle's acceleration to avoid frequent preceding vehicles' cut-in from adjacent lanes;

(4) When the lead vehicle decelerates, the host vehicle should decelerate before detecting the nearest preceding vehicles' decelerate to avoid rear-end collision.

The objectives (2), (3), (4) could be viewed as the tracking capability of the host vehicle. In order to satisfy the objectives (3) and (4), the desired velocity and acceleration of the host vehicle should be designed based on the driving states about the designed platoon leader and the nearest preceding vehicle. Realizing objectives (3) and (4) should avoid unnecessary acceleration or deceleration, improve fuel economy and ride comfort, and make the host vehicles' behaviors more intelligent. By tracking the appropriate inter-vehicle strategy related to the features of the host vehicle, road surface, and the real-time traffic situation, decentralized control law should be designed to satisfy the driver desired response and heterogeneous platoon. However, the above objectives (2)-(4) are contradictory. It is necessary to design a framework to realize the contradictions among the different requirements.

III. FORMULATION OF THE TRACKING PROBLEM

In this section, based on the objective in section II, a tracking problem for CACC systems is formulated, and decentralized longitudinal control law is designed.

A. The Tracking Error Variable

The tracking capability is usually specified in terms of distance error, velocity error, and acceleration error. In order to quantitatively describe (2), (3), and (4), the spacing tracking error, velocity tracking error, and acceleration tracking error are described as follows.

The safety spacing policy is defined as the distances for the following vehicle that can avoid rear-end collision throughout all possible maneuvers of the preceding vehicle. Focusing on the feasibility of implementation rather than on the definition of a new spacing policy, the desired inter-vehicle distance of ith vehicle is expressed as:

$$d_i(k) = l_i + \gamma_i d_{i_{\min}} + h_i v_i(k) \tag{5}$$

where γ_i is the safety coefficient that could be selected by the driver; $d_{i_{\min}}$ is the minimal constant inter-distance; h_i is the time delay for recognizing a hard brake in controller and hardware. Considering the heterogeneous platoon, l_i , h_i, and $d_{i_{\min}}$ are set based on the ith vehicles' feature. γ_i is relevant to the road condition, for example, driver should select a bigger value of γ_i if the road surface is wet. Therefore, $d_{i_{con}} = l_i + \gamma_i d_{i_{\min}}$ could be viewed as the constant component of spacing policy; $h_i v_i(k)$ is the velocity-dependent part. Then, based on the (4) and (5), the spacing tracking error is given by:

$$\delta_i(k) = x_{i-1}(k) - x_i(k) - (l_i + \gamma_i d_{i_{\min}} + h_i v_i(k)) \tag{6}$$

The actual distance should not too be large or small to avoid frequent preceding vehicles' cut-in from adjacent lanes or rear-end collision. Therefore, the spacing tracking error $\delta_i(k)$ should be as small as possible, even at zero.

In actual situation, the host vehicle is influenced by the designed platoon leader and the nearest preceding vehicle. For example, the acceleration or deceleration of designed platoon leader will affect the driving state of the other vehicles in a platoon. What's more, the influence from designed platoon leader for the host vehicle is related to the relative position in a platoon. Therefore, the expected velocity and acceleration of the host vehicle are depended on the driving states of designed platoon leader and the nearest preceding vehicle. The greater the distance between host vehicle and designed platoon leader, the less influence from the designed platoon leader. Therefore, in order to improve the vehicle's behaviors more intelligent and make the vehicle platoon converge to steady-state as soon as possible, the expected velocity and acceleration are designed as:

$$\begin{aligned} v_{ir}(k) &= (1 - p_i)v_{i-1}(k) + p_i v_l(k), \\ a_{ir}(k) &= (1 - p_i)a_{i-1}(k) + p_i a_l(k), \end{aligned} \tag{7}$$

where p_i is denoted the influence weight from designed platoon leader, which is related to the relative position in the platoon. Then, the tracking error for velocity and acceleration can be described as:

$$\begin{aligned} \Delta v_{ie}(k) &= v_i(k) - v_{ir}(k), \\ \Delta a_{ie}(k) &= a_i(k) - a_{ir}(k), \end{aligned} \tag{8}$$

By introducing the expected velocity $v_{ir}(k)$ and expected acceleration $a_{ir}(k)$ for the ith vehicle, some predictive nature is incorporated into the CACC systems. Then, the objectives (3) and (4) could be quantitatively described to maintain the tracking error for velocity and acceleration below a predetermined level or, if possible, at zero.

B. Formulation of the Tracking Problem

In this subsection, the decentralized longitudinal control problem is formulated as a tracking problem with a quadratic function so that the contradictions among the different tracking requirements are realized, which include inter-vehicle spacing, velocity and acceleration.

By using V2V wireless communication, the driving information of host vehicle(e.g., relative position, velocity, and acceleration) should be sent to the other vehicles in a platoon. Then, the output of (2) is expressed as:

$$\begin{aligned} z_i(k+1) &= A_i z_i(k) + B_i u_i(k), \\ y_i(k) &= C_i z(k), \end{aligned} \tag{9}$$

where

$C_i = \begin{pmatrix} -1 & -h_i & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$. The expected inter-vehicle spacing (5), expected velocity and acceleration (7) could be viewed as the tracking objectives in decentralized longitudinal problem. In order to express it more clearly, the tracking error variables can be formulated as:

$$e_i(k) = y_i(k) + H_i w_i(k), \tag{10}$$

where

$$w_i(k) = \begin{bmatrix} x_{i-1}(k) - d_{i_{con}} \\ v_{i-1}(k) \\ a_{i-1}(k) \\ v_l(k) \\ a_l(k) \end{bmatrix},$$

$$H_i = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1-p_i & 0 & p_i & 0 \\ 0 & 0 & 1-p_i & 0 & p_i \end{pmatrix}.$$

It should be noted that the host vehicle could receive the information about the velocities and accelerations of the designed platoon leader and the nearest preceding vehicle by using V2V wireless communication. Therefore, $w(k)$ is physical realizable in (9).

However, fuel consumption and tracking capability are in opposition to each other. The good tracking capability will result in unnecessary acceleration or deceleration. Therefore, a quadratic function is introduced to realize the contradictions between the fuel consumption and tracking requirements, given by:

$$J = \lim_{N\to\infty} \frac{1}{N} \sum_{k=0}^{N} \left[e_i^T(k) Q_i e_i(k) + u_i^T(k) R_i u_i(k) \right] \tag{11}$$

where Q_i and R_i are the constant diagonal matrices, given by

$$Q_i = \begin{bmatrix} q_{i1} & 0 & 0 \\ 0 & q_{i2} & 0 \\ 0 & 0 & q_{i3} \end{bmatrix}, R_i = cont_i.$$

Then, the tracking problem to be solved is the following:

Given the system (2) and the quadratic function (11), determine the such that the cost functional (11) is minimized for any initial deviations $x(0)$.

C. The Solution of the Tracking Problem

Consider the discrete-time model of the ith vehicle given by (9), the tracking variable $w_i(k)$ with respect to the quadratic performance index (11), the decentralized longitudinal control law u_i for ith vehicle is given by:

$$\begin{array}{l} u_i{}^*(k) = -R_i{}^{-1} B_i{}^T A_i{}^{-T} \times \\ \left[(P_{i1} - C_i{}^T Q_i C_i) z_i(k) + (P_{i2} + C_i{}^T Q_i) w_i(k) \right] \end{array} \tag{12}$$

where P_{i1} is the solution of the following Riccati equation:

$$P_{i1} = C_i{}^T Q_i C_i + A_i{}^T P_{i1} [I + B_i R_i{}^{-1} B_i{}^T P_{i1}]^{-1} A_i \tag{13}$$

P_{i2} is the solution of the following Stein equation:

$$\begin{array}{l} P_{i2} = A_i{}^T P_{i2} - C_i{}^T Q_i H_i \\ -A_i{}^T P_{i1} [I + B_i R_i{}^{-1} B_i{}^T P_{i1}]^{-1} B_i R_i{}^{-1} B_i{}^T P_{i2} \end{array} \tag{14}$$

Vehicle No.	1	2	3	4
l_i	4m	4.5m	5m	6m
$d_{i_{\min}}$	4.5m	3m	3.5m	5m
γ_i	1.0	1.1	1.1	1.2
τ_i	0.45	0.3	0.4	0.5
h_i	0.4	0.3	0.35	0.45
p_i	0	0.25	0.5	0.75

TABLE I

THE COEFFICIENTS OF VEHICLES IN A PLATOON

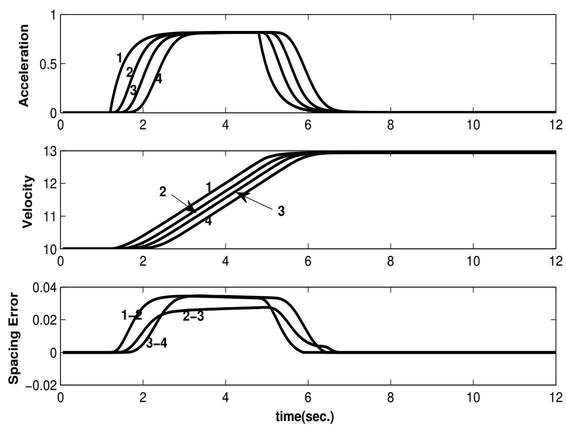

Fig. 2. Response to Abrupt Acceleration by the Designed Platoon Leader Vehicle

In decentralized longitudinal control law (12), the feedback items are composed of the states of host vehicles, and additional information of the nearest preceding vehicle and designed platoon leader are used as feedforward items. Therefore, the tracking control law (12) is physical realizable.

IV. SIMULATION

As shown in Table I, a four-vehicle platoon is chosen and used in the simulation because it must retain the essential characteristics of a platoon. Individual vehicles are assumed to be identical, and the characteristics of individual vehicles are shown in Table 1. The spacing error is set at zero for ease of presenting the simulation results. Then, the control objective is that every vehicle line up with the designed platoon leader.

A. Response to Abrupt Acceleration by the Designed Platoon Leader

In this scenario, all the vehicles are moving with the same velocity as that of the designed platoon leader, and there are initial spacing errors, as shown in Fig. 2. The designed platoon leader accelerate at 0.8182 m/s^2 for 2.4s to speed up by 12.6654 m/s. In the early state, the spacing error between the designed platoon leader and the first vehicle is the large. This is because of the delay in propulsion or engine dynamics. Although the first vehicle notices the acceleration of the designed platoon leader earlier, the difference in acceleration and velocity are still great, producing a large spacing error. But the spacing error between the next two vehicles gets smaller

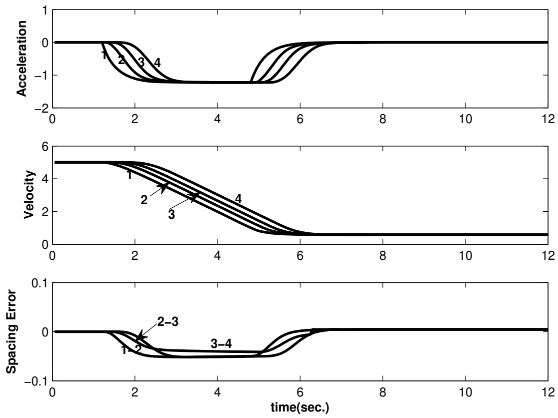

Fig. 3. Response to Abrupt Deceleration by the the Designed Platoon Leader vehicle

because the difference in acceleration and velocity have not yet built up enough to yield noticeable errors and the expected velocity and acceleration for the following vehicle are adjusted. However, as time goes by, the first vehicle catches up with leader vehicle faster than any of the other vehicle, and spacing error disappear after about 6 s. The range of spacing error is at $[0, 0.04]$m, the safety and tracking capability are realized.

It should be noted that the proposed control law in this paper shows exceptional performance in the sense that all vehicles move together and achieve almost identical acceleration and velocity. In this case, the follower vehicle predicts what its front vehicle will do and takes the same control action. Therefore, the spacing errors remain virtually unchanged.

B. Response to Abrupt Deceleration by the the Designed Platoon Leader

In this scenario, all the vehicles are moving with the same velocity as that of the designed platoon leader, and there are initial spacing errors, as shown in Fig. 3. The platoon leader vehicle accelerate at $-1.1m/s^2$ for 2s to speed down by $0.6m/s$. As the time goes by, the following vehicle catches up with the nearest preceding vehicle, and the spacing error, velocity error, and the acceleration error disappear after 6s. It should be noted that the range of spacing error is at $[-0.05, 0]$m, the safety and capability are realized.

To line up with the lead vehicle, it would be best that the following vehicle decelerate before detecting the deceleration of the nearest preceding vehicle. In this case, the following vehicle predicts what its front vehicle will do and takes the same control action to avoid unnecessary acceleration or deceleration. Therefore, the spacing errors remain virtually unchanged and the control law could have the effect of saving energy.

V. Conclusion

In this paper we have designed a new intelligent decentralized longitudinal tracking control law for CACC systems in a platoon. The prominent contribution of this paper is that the proposed control law considers various spacing policies, safety, and vehicle intelligent behavior together. By using the wireless communication among the vehicles, the feedback items of the proposed control law have been composed of the information about the related vehicle. The concepts of "expected velocity" and "expected acceleration" have been introduced to make the vehicles' behaviors more intelligent. Simulation results for a string of four vehicles indicate that the suggested design method yields an excellent control system. However, additional research is required to establish additional properties for a string composed of a large number of vehicles, such as time delay, nonlinear items and so on.

Acknowledgment

This work was partially supported by the National Natural Science Foundation of China under Grant (61074092, 61070130, 61203105), the Natural Science Foundation of Shandong Province under Grant (ZR2010FM019, ZR2011FZ003, ZR2012FQ016), the framework of the IT4 Innovations Centre of Excellence project, reg. no. CZ.1.05/1.1.00/02.0070 by operational programme Research and Development for Innovations funded by the Structural Funds of the European Union and state budget of the Czech Republic, EU, and the Doctoral Foundation of University of Jinan under Grant (XBS1318).

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