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Adaptive Feedforward Compensator Based on Approximated Causal Transfer Function for CACC with Communication Delay ⋆

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Abstract: In this paper, we propose an adaptive feedforward compensator using parameter estimation to compensate for the communication time delay in cooperative adaptive cruise control (CACC). When CACC uses a feedforward controller to improve tracking performance and satisfy the string stability, it should take into account the communication delay between vehicles. Padé approximation of the time delay can be used for the design of feedforward compensator, but there is a limitation since the approximated system becomes the non-minimum system. To cope with this inherent non-causality problem, we propose an approximated causal transfer function for the feedforward compensator. Then, we apply extended Kalman filter as one of parameter estimation methods with a nonlinear model from the state augmented by a parameter of the approximated causal transfer function. Numerical simulation results show that the proposed system not only mitigates spacing error in time-varying communication delay but also satisfies string stability in a platoon.

Keywords: Cooperative adaptive cruise control, Parameter estimation, Extended Kalman filter, Heterogeneous vehicles, vehicle-to-vehicle (V2V) communication, Communication delay

1. INTRODUCTION

Adaptive cruise control (ACC), one of the vehicle's longitudinal motion control technologies, automates vehicle acceleration and deceleration without driver intervention, thereby it enhances driver convenience and road availability Shladover et al. (1991); Wang and Rajamani (2002); Xiao and Gao (2010). However, the ACC cannot decrease traffic by allowing smaller headway between vehicles and moving vehicles safely in a platoon at a harmonized speed. To resolve the problem, cooperative adaptive cruise control (CACC), which uses the information of the acceleration of the front vehicle through wireless vehicle-to-vehicle (V2V) communication between vehicles, has been widely researched Dey et al. (2016); Ploeg et al. (2011); Naus et al. (2010); Darbha et al. (2001). The advantage of CACC is that vehicles can reduce the length of the platoon by reducing inter-vehicle spaces since the CACC can reduce headway time compared to the ACC van Arem et al. (2006); Öncü et al. (2014); Bian et al. (2019). Therefore, the CACC technology can more improve traffic flow efficiency and reduce driver stress than the ACC.

However, imperfections induced by wireless communication, such as delays, sampling intervals, packet loss, and communication constraints, can affect string stability Heemels and van de Wouw (2010). To resolve these problems, Naus et al. (2010) presented theoretical analysis and experimental results that the effect of communication delay degrades the string stability performance. Further, Zhang and Orosz (2016); di Bernardo et al. (2015); Ge and Orosz (2014) analyzed the effect of linkage structure, achieving consensus in a network, and researched information of delay on the heterogeneous vehicles. Recently, Harfouch et al. (2018) designed adaptive switched control strategy and handled inevitable communication losses for the heterogeneous vehicles. Xing et al. (2016) also researched using Padé approximation of the time delay including vehicle actuator delay. They applied the Padé approximation to arrive at a finite-dimensional model, which allows for many standard control methods. Further, the Padé approximation can be used for the design of an feedforward compensator considering the communication

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delay. However, there is a limitation that the approximated system has the non-minimum system.

In this paper, we present an adaptive feedforward compensator using parameter estimation to compensate for the communication delay in CACC adequately. Although the CACC uses the feedforward controller, which has been designed to improve tracking performance and satisfy the string stability, the communication delay between vehicles impedes the string stability. To cope with this problem, we propose an approximated causal transfer function considering the communication delay as well as the vehicle dynamics. Then, we apply extended Kalman filter (EKF) as one of parameter estimation methods with a nonlinear model from the state augmented by a parameter of the approximated causal transfer function. The proposed method was validated through numerical simulations for the unknown but bounded time-varying communication delay. The results show that the feedforward compensator not only reduces the spacing error but also satisfies string stability in the platoon.

2. CACC CONTROLLER DESIGN

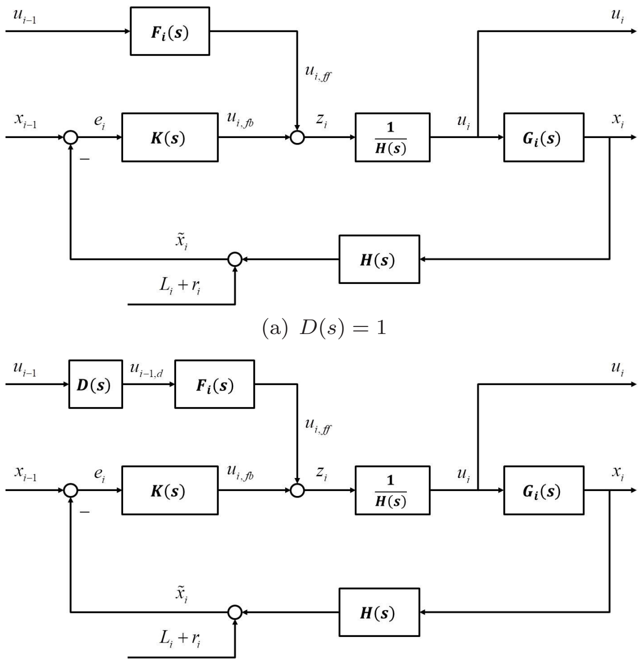
One of the longitudinal control objectives is to keep a desired distance with its preceding vehicle. Control strategies for heterogeneous vehicles, including this purpose, were described in Ploeg et al. (2011). Wang and Nijmeijer (2015) has studied the causes of heterogeneous vehicles, which appear through communication topology and information, spacing policy, controllers, error signals to be controlled, communication delay time, actuator delay time, vehicle lag and constraints and analyzed their effects on string stability. They have also presented control methods, including the feedforward controller, to improve tracking performance and string stability performance for the heterogeneous vehicles. This section describes how to design the feedforward controller among heterogeneous vehicles when the communication time delay is present.

A description of controller design for the heterogeneous platoon helps take the concept to compensate for the communication delay. Figure 1 shows overall control architectures of CACC. For the feedforward controller used to improve the vehicle following and string stability performances in Fig. 1, (a) is shown without communication delay, and (b) is presented with communication delay. As CACC uses the feedforward controller, Wang and Nijmeijer (2015) researched that using the desired acceleration u_{i-1} is better than using the measured acceleration a_{i-1} for the communication information since the response time of the vehicle is shorter. Then, the control structure of the CACC system depicted in Fig. 1 can be designed based on the heterogeneous platoon presented in Wang and Nijmeijer (2015).

2.1 Feedback Controller

The spacing error e_i between the relative distance d_i and the desired distance $d_{r,i}$ of two adjacent vehicles is controlled for its minimization. The spacing error is given by

$$e_i(t) = d_i(t) - d_{r,i}(t). \tag{1}$$



(a) $D(s) = 1$

(b) $D(s) \neq 1$

Fig. 1. Control system structures of CACC with feedforward controller: (a) without communication delay and (b) with communication delay

The desired distance and the relative distance are defined as follows:

$$\begin{aligned} d_{r,i} &= r_i + hv_i(t) \\ d_i &= x_{i-1}(t) - (x_i(t) + L_i) \end{aligned} \tag{2}$$

where r_i is the constant representing the distance between successive vehicles in the standstill state, h is the headway time, $v_i(t)$ is the velocity of the host vehicle i, $x_{i-1}(t)$ and $x_i(t)$ are the positions of the host vehicle i and the preceding vehicle $i-1$, and L_i is the length of vehicle i.

Let us consider the transfer function model from control input $U_i(s)$ to vehicle position $X_i(s)$ of vehicle i given by

$$G_i(s) = \frac{X_i(s)}{U_i(s)} = \frac{1}{s^2(1+\tau_i s)} e^{-\phi_i s} \tag{3}$$

where $U_i(s)$ and $X_i(t)$ are the Laplace transformations of the signal $u_i(t)$ and $x_i(t)$ respectively, τ_i is the time constant representing the vehicle dynamics, and ϕ_i is the vehicle time delay which represents the actuator and internal communication delay time. This paper neglects the time delay since its influence in string stability is smaller than that of the communication delay. And the transfer function of the headway time policy is as follows:

$$H(s) = 1 + hs. \tag{4}$$

The purpose of (4) is to cancel the influence of changing the headway time in the feedback loop on stability. The feedback controller then uses the PD controller such as

$$K_i(s) = k_p + k_d s. \tag{5}$$

In this paper, the PD gain is considered as $k_p = k_d^2$ for the desired bandwidth and phase margin in Naus et al. (2010).

2.2 Feedforward Controller

The feedforward controller is designed to improve tracking performance and to satisfy string stability of the system.

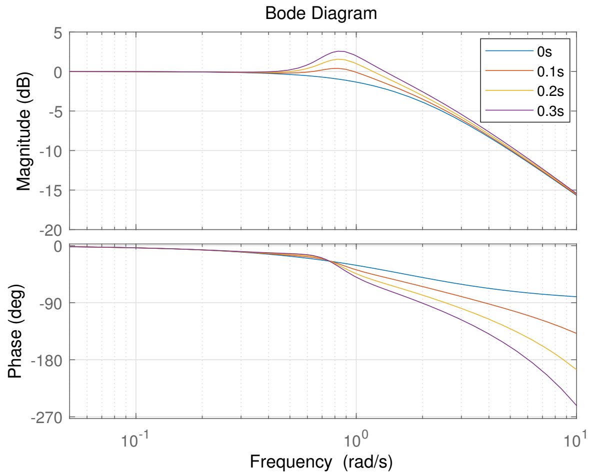


Fig. 2. The string stability bode diagrams of the CACC system with respect to communication delay θ with $k_p = k_d^2 = 0.7$, $h = 0.6s$, and $\tau = 0.5s$

It is added into the system with the feedback controller. According to the control structure in Fig. 1 (a), the Laplace transformation of the spacing error is given by

$$E_i(s) = \frac{1 - F_i(s)\left(\frac{G_i(s)}{G_{i-1}(s)}\right)}{1 + G_i(s)K(s)} X_{i-1}(s). \quad (6)$$

The nominal feedforward controller can be commonly designed without communication delay ($D(s) = 1$) to consider the error to zero as follows:

$$\begin{aligned} F_i(s) &= \frac{G_{i-1}(s)}{G_i(s)} \\ &= \frac{\tau_i s+1}{\tau_{i-1}s+1}. \end{aligned} \quad (7)$$

Equation (7) can be designed with the time constant τ_{i-1} considering the vehicle dynamics of the preceding vehicle with one of the host vehicle.

However, if the communication delay exists ($D(s) \neq 1$), the error cannot be made to zero with the feedforward controller. To consider communication delay, its Laplace transformation is given by

$$D(s) = e^{-\theta_i s} \quad (8)$$

where θ_i is the communication time delay between a vehicle i and a preceding vehicle $i-1$. Then, (6) can be rewritten considering (8) as follows:

$$E_i(s) = \frac{1 - D(s)F_i(s)\left(\frac{G_i(s)}{G_{i-1}(s)}\right)}{1 + G_i(s)K(s)} X_{i-1}(s). \quad (9)$$

Equation (9) shows that the feedforward controller can reduce the error as it could compensate for the communication delay as well as the dynamics of heterogeneous vehicles.

Consequently, the control input $Z_i(s)$ for the CACC is composed as follows:

$$\begin{aligned} Z_i(s) &= U_{i,fb}(s) + U_{i,ff}(s) \\ &= K(s)E_i(s) + F_i(s)D(s)U_{i-1}(s). \end{aligned} \quad (10)$$

2.3 String Stability Analysis

It is well known that the CACC, including the ACC, should be verified for string stability of the entire platoon as well as individual vehicle stability. When multiple vehicles run on a platoon, all disturbance from the preceding vehicle must be attenuated as the following vehicles move. The string stability is defined as the amplification of the signal transmitted from the preceding vehicle to the following vehicle. For a homogeneous platoon, $X_i(s)/X_{i-1}(s)$, $A_i(s)/A_{i-1}(s)$, $U_i(s)/U_{i-1}(s)$, and $E_i(s)/E_{i-1}(s)$ are the same according to the control structure in Fig. 1. However, for a heterogeneous platoon, they are not the same. The string stability of the heterogeneous platoon is rather complicated since the weak string stabilities ($A_i(s)/A_r(s)$, $U_i(s)/U_r(s)$, and $E_i(s)/E_r(s)$, where $A_r(s)$, $U_r(s)$, and $E_r(s)$ are the Laplace transformations of the acceleration, the control input and the control error of the reference vehicle or the first vehicle in a platoon in Öncü (2014)) as well as the above string stabilities are satisfied.

The string stability considering the communication delay was proven for the heterogeneous platoon in Wang and Nijmeijer (2015). They also presented feedback controller conditions, $k_p > 0$, $k_d > 0$, and $k_d > k_p\tau_i$, for stability using Routh stability criterion, which is also a necessary condition for a vehicle using CACC. For the string stability of CACC with the communication delay, the homogeneous platoon is assumed first. Then, since $X_i(s)/X_{i-1}(s)$, $A_i(s)/A_{i-1}(s)$, $U_i(s)/U_{i-1}(s)$, and $E_i(s)/E_{i-1}(s)$ can be the same, the output string stability function $SS(s)$ can be defined as follows:

$$SS(s) = \frac{X_i(s)}{X_{i-1}(s)}, \text{ for } i > 1. \quad (11)$$

String stability is satisfied when following the necessary condition given by

$$\|SS(s)\|_\infty = \left\| \frac{X_i(s)}{X_{i-1}(s)} \right\|_\infty \leq 1, \text{ for } i > 1. \quad (12)$$

From the CACC structure with the communication delay in the homogeneous platoon in Fig. 1 (b), (11) can be expressed as follows:

$$\begin{aligned} SS(s) &= \frac{X_i(s)}{X_{i-1}(s)} \\ &= T(s) \cdot \frac{1}{H(s)} \end{aligned} \quad (13)$$

where

$$T(s) = \frac{D(s)F(s) + G_i(s)K(s)}{1 + G_i(s)K(s)}.$$

If there are no communication delay ($D(s) = 1$) and unit feedforward controller ($F(s) = 1$), the string stability is guaranteed. However, if the communication delay exists ($D(s) \neq 1$), string stability can not be guaranteed such as a numerical simulation result shown in Fig. 2 with the CACC controller using $k_p = k_d^2 = 0.7$, headway time $h = 0.6s$, and time constant $\tau = 0.5s$ representing vehicle dynamics, the string stability is not satisfied for the three cases having communication delay.

3. COMPENSATION OF COMMUNICATION TIME DELAY USING FEEDFORWARD COMPENSATOR

In this section, we describe how to compensate for the communication time delay in the viewpoint of the time-domain. In the control system of the host vehicle, we can measure a time-delayed control input but a preceding vehicle position without time delay since the radar system of the host vehicle directly measures the distance and

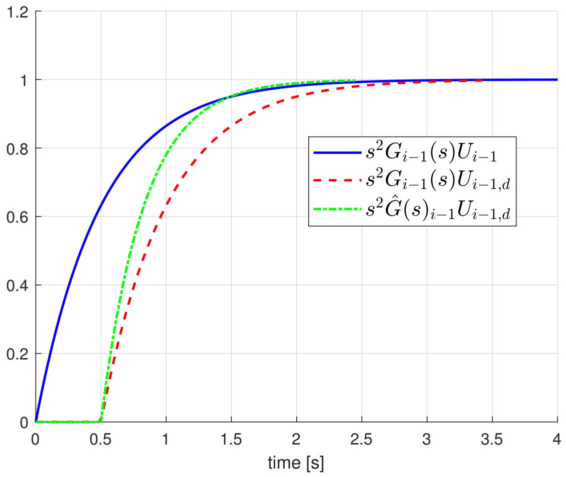


Fig. 3. Comparison of step responses: Blue solid line is step response of $s^2G_{i-1}(s)$ for u_{i-1}. Red dashed line is step response of $s^2G_{i-1}(s)$ for $u_{i-1,d}$. Green one-dot chain line is step response of $s^2\hat{G}_{i-1,d}(s)$ for $u_{i-1,d}$. ($u_{i-1,d}$ with time delay, 0.5[sec]).

velocity of the preceding vehicle. In the platoon, even if the host vehicle can receive the vehicle dynamics information of the preceding vehicle, the error of (9) cannot be reduced because we cannot know the communication delay transmitted to the rear vehicle in advance. For example, as time-delayed control input $U_{i-1,d}(s)$ is given by

$$U_{i-1,d}(s) = D(s)U_{i-1}(s), \tag{14}$$

the transfer function model from time-delayed control input $U_{i-1,d}(s)$ to vehicle position $X_{i-1}(s)$ is presented as follows:

$$G_{i-1,d}(s) = \frac{X_{i-1}(s)}{U_{i-1,d}(s)} = \frac{1}{s^2(1+\tau_{i-1}s)}e^{\theta_i s}. \tag{15}$$

Notice that Equation (15) is the transfer function of the non-causal system in view of the preceding vehicle since the future information is needed. Since we measure $u_{i-1,d}$ and x_{i-1}, (15) becomes the non-causal transfer function. Thus, using a parameter μ_{i-1} to take into account the time constant τ_{i-1} and the communication delay θ_i, we would like to find the transfer function $\hat{G}_{i-1,d}(s)$ as the approximated causal transfer function from $U_{i-1,d}(s)$ to $X_{i-1}(s)$ such as

$$\frac{X_{i-1}(s)}{U_{i-1,d}(s)} \simeq \hat{G}_{i-1,d}(s) = \frac{1}{s^2(1+\mu_{i-1}s)}. \tag{16}$$

Figure 3 illustrates examples of the time responses of the three systems, $s^2G_{i-1}(s)u_{i-1}$, $s^2G_{i-1}(s)u_{i-1,d}$, and $s^2\hat{G}_{i-1,d}(s)u_{i-1,d}$. Letting $\mu_{i-1} = \tau_{i-1} - \Delta$ with a variable Δ to adjust the time constant τ_{i-1} in view point of the time-domain reflecting the communication delay θ_i, we want to get the approximated causal transfer function $\hat{G}_{i-1,d}(s)$. If the approximated causal transfer function is designed, then the feedforward compensator is designed by

$$\begin{aligned} \hat{F}_i(s) &= \frac{\hat{G}_{i-1,d}(s)}{G_i(s)} \\ &= \frac{\tau_i s+1}{\mu_{i-1}s+1}. \end{aligned} \tag{17}$$

Remark 1. Notice that the feedforward compensator is in the form of a phase lead compensator, which compensates the phase lag due to time delay in communication.

4. PARAMETER ESTIMATION WITH EXTENDED KALMAN FILTER

In this section, we will explain how to obtain the approximated causal linear system using EKF with parameter estimation of μ for the feedforward compensator (17). Let us define the state $\mathbf{x} = [v_{i-1},\ a_{i-1}]^T$, the input $\mathbf{u} = u_{i-1,d}$, and the measurement $\mathbf{y} = v_{i-1}$ where v_{i-1}, a_{i-1}, and $u_{i-1,d}$ are velocity, acceleration, and delayed acceleration command of the preceding vehicle, respectively. Considering velocity and acceleration, the state-space representation of (16) can be put in the form of

$$\begin{cases} \dot{\mathbf{x}}(t) &= A\mathbf{x}(t) + B\mathbf{u}(t) \\ \mathbf{y}(t) &= C\mathbf{x}(t) \end{cases} \tag{18}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{\mu_{i-1}} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{\mu_{i-1}} \end{bmatrix}$$
$$C = [1\ 0].$$

With the sampling time $T_s = 10$ms of the electronic control unit (ECU) of the vehicle, the discretization of (18) using the zero-order-hold (ZOH) equivalence sampling rate of $1/T_s$ leads to the discrete-time model. We augment μ_{i-1} to the state in order to estimate the parameter μ_{i-1} in the system. In this paper, we assume that μ_{i-1} is bounded and slowly time-varying. Then, with the augmented state $\mathbf{x}_a = [x_1,\ x_2,\ x_3]^T = [v_{i-1},\ a_{i-1},\ \mu_{i-1}]^T$, the nonlinear model can be presented as follows:

$$\begin{cases} \mathbf{x}_a(k+1) &= f_a(\mathbf{x}_a(k),\ u_{i-1,d}(k)) \\ \mathbf{y}_a(k) &= C_a\mathbf{x}_a(k) \end{cases} \tag{19}$$

where

$$f_a(\mathbf{x}_a,\ u_{i-1,d}) = \begin{bmatrix} x_1 + T_s x_2 \\ \left(1 - \frac{T_s}{x_3}\right)x_2 + \left(\frac{T_s}{x_3}\right)u_{i-1,d} \\ x_3 \end{bmatrix}$$
$$C_a = [1\ 0\ 0].$$

To estimate the state of the nonlinear model, this paper apply EKF. Using Jacobian for linearization at the current state estimation, the EKF algorithm can be summarized as follows Corigliano and Mariani (2004)

- *Prediction* :

$$\begin{aligned} \bar{\mathbf{x}}_a(k+1) &= f_s(\hat{\mathbf{x}}_a(k),\ u_{i-1,d}(k)) \\ \bar{\Sigma}(k+1) &= (\Phi(k))\,\hat{\Sigma}(k)\,(\Phi(k))^T + Q \end{aligned} \tag{20}$$

where

$$\Phi[k] = \left.\frac{\partial f_s(\mathbf{x}_a(k),\ u_{i-1,d}(k))}{\partial \mathbf{x}_a}\right|_{\hat{\mathbf{x}}_a(k)}$$

- *Correction* :

$$\begin{aligned} \hat{\mathbf{x}}_a(k) &= \bar{\mathbf{x}}_a(k) + L(y_a(k) - C_a\bar{\mathbf{x}}_a(k)) \\ \hat{\Sigma}(k) &= (I - LC_a)\bar{\Sigma}(k) \end{aligned} \tag{21}$$

where

$$L = \bar{\Sigma}(k){C_a}^T(C_a\bar{\Sigma}(k){C_a}^T + R)^{-1}.$$

5. NUMERICAL SIMULATION

For a case study with the proposed method, this paper considers a platoon consisting of 4 homogeneous vehicles, 1 leading and 3 following vehicles, for analysis of string stability considering the communication delay. We assume that all vehicles have the same time constant $\tau = 0.5s$

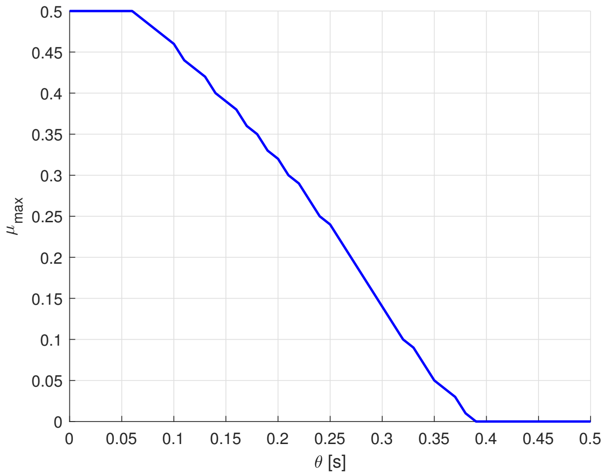


Fig. 4. Maximum allowable μ with respect to the communication time delay when headway time $h = 0.6$s

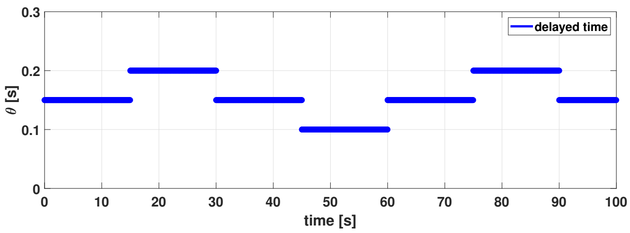
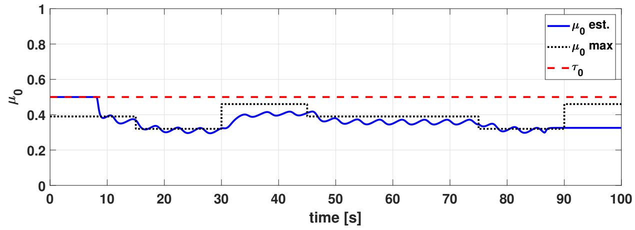
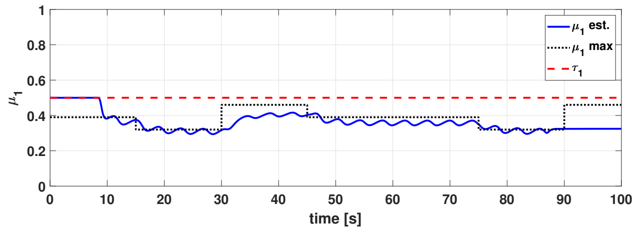


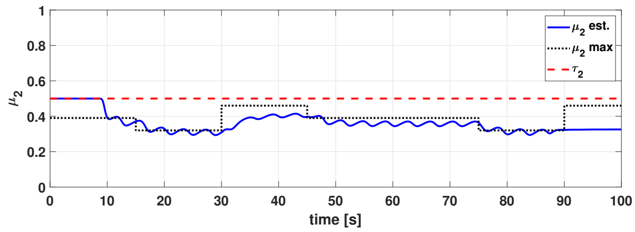
Fig. 5. Common communication delay of all vehicles



(a) μ_0 estimated in *vehicle#1*



(b) μ_1 estimated in *vehicle#2*



(c) μ_2 estimated in *vehicle#3*

Fig. 6. Parameter estimation performance of each following vehicle: blue solid lines are the estimated μ by the proposed EKF, black one-dot chain lines are the available maximum μ, and red dashed lines are the time constant τ_{i-1} of the predecing vehicle.

representing the vehicle dynamics and the same communication delay $\theta \in [0.1, 0.2]$s, respectively. We also consider that vehicle i receives only data of preceding vehicle $i-1$. And for parameter estimation, covariance matrixes Q and R of the EKF have set $diag(0.001, 1, 5)$ and $diag(1)$, respectively. Then, the initial errors are assumed to be zero, and a sinusoidal input $u_0 = \sin(\omega(t - 2\pi))$ where $\omega = 0.8$ rad/s, which is imposed on the leading vehicle during the time period $2\pi \leq t \leq 22\pi$. If the time delay is not compensated for, the string stability has the maximum peak greater than 1 at the frequency $\omega = 0.8$ rad/s.

Figure 4 shows an area where the approximated causal transfer function can be designed. The plot was calculated iteratively by taking a fixed value for $h = 0.6s$ and $\theta \in [0, 0.5]$ and searching for the maximum value of μ such that string stability is satisfied. From the curve, for $\theta = 0.2s$ the string stability is satisfied for $\mu \leq 0.32$. However, it is not recommended to use unnecessarily small μ to avoid to make the system sensitive to noises.

Figure 6 shows that the proposed EKF estimates the parameter μ for the approximated causal transfer function in the presence of uncertain but bounded communication delay, as shown in Fig. 5. In parameter estimation performance of each vehicle as shown in Fig. 6, blue solid lines track the estimated μ by the proposed EKF, black one-dot chain lines represent the allowable maximum μ to satisfy string stability as the curve shown in Fig. 4, and red dashed lines present the time constant τ_{i-1} of the preceding vehicle.

With the estimation performances of the proposed EKF, we also compared simulation results of the CACC systems using the unit feedforward controller ($F_i = 1$) and the proposed feedforward compensator ($F_i = (\tau_i)/(\mu_{i-1})$) in time-domain. Using the unit feedforward controller without parameter estimation, as shown in Fig. 7, the spacing error of each vehicle is amplified as the communication progresses to the following vehicles because the CACC system is string unstable due to the communication delay. On the other hand, using the proposed adaptive feedforward compensator with parameter estimation, Fig. 8 shows that the spacing error is mitigated under the same situation since the system is string stable due to compensating for the communication delay adequately. Since the platoon considers homogeneous vehicles as the case study, the velocity and acceleration also take similar results.

Notice that from 15s to 20s, from 45s to 50s and from 75s to 80s in Fig. 6 and 8 we observed that the parameter estimation of the EKF goes beyond the maximum bound of μ required for string stability. In that case, we see that the spacing error slightly increases during the period. We presume that it is due to the convergence of parameter estimation with the EKF. We expect that it can be resolved by imposing CACC standardization to the participating vehicles.

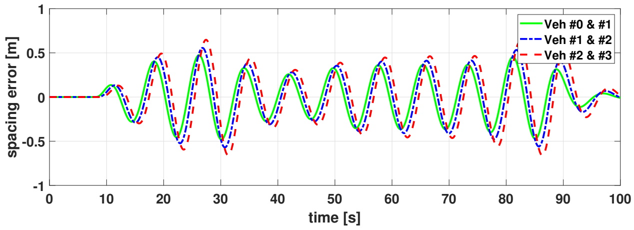


Fig. 7. Time responses of the spacing error with the unit feedforward controller

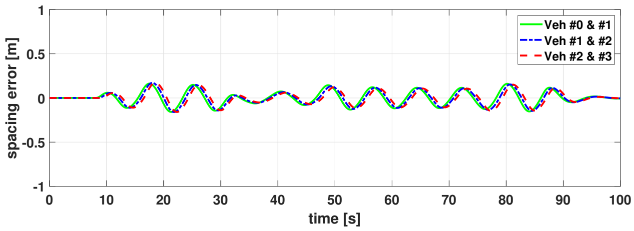


Fig. 8. Time responses of the spacing error with the proposed feedforward compensator

6. CONCLUSION

This paper proposed the adaptive feedforward compensator using parameter estimation to compensate for the communication time delay. Although the CACC uses the feedforward controller, which has been designed to improve tracking performance and to satisfy the string stability, the communication delay between vehicles impedes the string stability. To cope with this problem, we introduced the approximated causal transfer function. Then feedforward compensator was designed based on the approximated causal transfer function. Further, we applied EKF as one of the parameter estimation methods with the nonlinear model from the state augmented by the parameter of the approximated causal transfer function. Simulation results showed the effectiveness of the proposed method applied to CACC resolving communication time delay. Based on this application, we look forward to improving the performance of the ADAS beyond the CACC with the proposed method.

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