To appear in: Proceedings of the 26th International Conference on Intelligent Transportation Systems (ITSC 2023), Bilbao, Bizkaia, Spain, 2023

Observer Based Cooperative Adaptive Cruise Control for Heterogeneous Vehicle Platoons with Actuator Delay

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***Abstract*— Cooperative Adaptive Cruise Control (CACC) has the potential to increase road throughput and safety. By utilizing vehicle-to-vehicle (V2V) communication, string stability can be achieved at short inter-vehicle distances. This paper presents a decentralized control approach suitable for heterogeneous platoons with drivetrain delays. By approximating the plant with delay during the controller design, a controller is obtained that ensures string stable behavior and has a nominal performance similar to an approach where the delay is compensated by a Smith predictor. The controller presented in this paper has the added benefit that the feedback action can be determined directly by measured signals and the error converges to zero in steady state situations. By combining the controller with an acceleration observer and error observer, undesired effects of measurement noise are mitigated.**

I. INTRODUCTION

The increasing number of vehicles on the roads contributes to the rising numbers of traffic accidents and congestion on highways [1]. Mitigating these negative effects, motivates the research toward vehicle automation.

A well known technique for longitudinal automation of vehicles is Adaptive Cruise Control (ACC). By using on-board forward looking sensors, ACC aims to control the distance to the preceding vehicle [2]. Extending ACC by adding a wireless communication link between vehicles results in the technique commonly referred to as Cooperative Adaptive Cruise Control (CACC) [3]. Adopting longitudinal automation such as (C)ACC, enables vehicles to drive in closely packed formations with short inter vehicle distances, so called platoons. The formation of platoons has various benefits, e.g., the road throughput can be increased [4] and reduced aerodynamic drag results in fuel savings [5].

The common control objective for a platooning vehicle is to control the distance of the ego vehicle with respect to the preceding vehicle to a desired distance defined according to a spacing policy. An additional requirement is the attenuation of disturbances throughout the vehicle string, so called string stability [6]. Numerous control approaches have been presented to fulfill these objectives. For example, sliding mode control [7], model predictive control [8], or PD-controllers with a communicated feedforward [3] have shown to be effective.

Most of these controllers have in common that they only consider homogeneous platoons where each vehicle in the platoon is considered to have identical characteristics as the ego vehicle. In practice however, platoons likely consist of different types of vehicles. Even when the vehicles are identical, it is possible that the characteristics differ when they carry for instance a different load. Therefore, it is desirable to employ a control method that is not limited to a single type of vehicle in the platoon.

To deal with heterogeneous platoons, robust control approaches have been adopted, where the heterogeneity in driveline dynamics is modeled as an uncertainty [9]. Also adaptive control approaches [10], or model predictive control strategies [11] have been used. In [12] a class of controllers is presented that is suitable for heterogeneous platoons, which only requires the current acceleration of the directly preceding vehicle as a feedforward to achieve string stable following behavior. Although this approach works well for vehicles with longitudinal behavior according to a first-order model, the performance deteriorates when the ego vehicle has a delay in the drivetrain. By extending the control approach with a Smith predictor to compensate for the delay, the performance is restored [13]. However, in this paper we show that the controller with Smith predictor does not achieve the desired performance and control objectives when measured signals are considered. Therefore, we propose an alternative controller design, extended with two observers, that is able to achieve the objectives in a more realistic setting that includes measurement noise and disturbances.

The outline of the paper is as follows. In Sec. II preliminary knowledge on the controller design for heterogeneous platoons and the extension to deal with driveline delay are presented. The problem definition in Sec. III shows the difficulties these approaches have when measured signals are considered. In Sec. IV an alternative controller is presented, which is combined with the observer design from Sec. V to deal with negative effects that are introduced by measured signals. The simulations in Sec. VI show the results of the alternative control approach in the presented framework.

II. PRELIMINARIES

Consider the platoon from Fig. 1 where the longitudinal dynamics of individual vehicle $i \in S_n$ are described by

$$\dot{q}_i(t) = v_i(t) \tag{1a}$$
$$\dot{v}_i(t) = a_i(t) \tag{1b}$$
$$\dot{a}_i(t) = -\frac{1}{\tau_i}a_i(t) + \frac{1}{\tau_i}u_i(t-\phi_i). \tag{1c}$$

Here, q_i, v_i and a_i (all $\in \mathbb{R}$) denote the rear bumper position, velocity and acceleration of vehicle i respectively, $\tau_i > 0$ is a constant associated with the vehicle's driveline and $\phi_i \geq 0$ is a pure driveline delay. The control input $u_i \in \mathbb{R}$ can be

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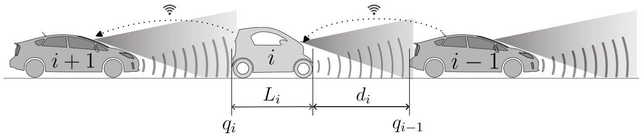

Fig. 1: Heterogeneous string of vehicles equipped with Cooperative Adaptive Cruise Control.

considered to be the desired acceleration of vehicle i. The set $S_n = \{ i \in \mathbb{N}^+ \mid 1 \leq i \leq n\}$ denotes all vehicles in the platoon of length n that is heterogeneous with respect to the driveline as we do not require τ_i and ϕ_i to be identical for each vehicle. The model (1) is the result of feedback linearization of a complex model [14], extended with a delay ϕ_i that is shown to be necessary to accurately describe the dynamics of the vehicles [15].

A. Platoon Control

The objective of each following vehicle (i.e., $i > 1$) in the platoon, is to control its distance d_i with respect to the predecessor to a desired distance $d_{\mathrm{des},i}$ defined according to a constant headway spacing policy as

$$d_{\mathrm{des},i}(t) = h_i v_i(t) + r_i, \tag{2}$$

where $h_i > 0$ denotes the desired headway time in seconds of vehicle i with respect to its predecessor, and r_i is a constant describing the desired spacing at standstill.

The desired following behavior is captured in the error definition for vehicle i as

$$e_i(t) = [q_{i-1}(t) - q_i(t) - L_i] - [h_i v_i(t) + r_i], \tag{3}$$

where L_i is the length of vehicle i.

For heterogeneous platoons without drivetrain delay ($\phi_i = 0$), an input-output linearization approach can be used to obtain a controller that asymptotically stabilizes the error dynamics [12]. They show that a change of input as

$$u_i(t) = \frac{\tau_i}{h_i} a_{i-1}(t) + (1 - \frac{\tau_i}{h_i}) a_i(t) + \frac{\tau_i}{h_i} \xi_i(t), \tag{4}$$

results in error dynamics according to

$$\begin{bmatrix} \dot{e}_i \\ \ddot{e}_i \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_i \\ \dot{e}_i \end{bmatrix} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} \xi_i \tag{5}$$

such that for $\xi_i(t)$ any controller that stabilizes the error dynamics can be taken. For instance, the PD controller as adopted in [12] according to

$$\xi_i(t) = k_p e_i + k_d \dot{e}_i. \tag{6}$$

No driveline information of the preceding vehicle is required, which enables heterogeneous platoons with respect to the driveline dynamics.

B. String Stability

Next to individual vehicle stability, the collective behavior of the platoon of vehicles should be considered in the controller design. Therefore, string stability is an important aspect associated with control of vehicle platoons. String stability indicates whether disturbances are attenuated through the vehicle string. When the decentralized control approach as presented in Sec. II is used, the string stability of the system can be assessed by analyzing two consecutive vehicles and determining the String Stability Complementary Sensitivity (SSCS), defined as $\Gamma_i(s) = \frac{a_i(s)}{a_{i-1}(s)}$. This transfer function relates the acceleration a_{i-1} of the preceding vehicle, to the acceleration a_i of the ego vehicle. The system (of two) consecutive vehicles is $\mathscr{L}_2$ string stable if

$$\|\Gamma_i(s)\|_{\mathscr{H}_\infty} \leq 1, \tag{7}$$

where $\|\cdot\|_{\mathscr{H}_\infty}$ denotes the $\mathscr{H}_\infty$ norm [6].

For the controller (4) with (6) and delay free (i.e., $\phi_i = 0$) plant (1), the resulting SSCS is given by

$$\Gamma_i(s) = \frac{1}{h_i s + 1}, \tag{8}$$

such that $\|\Gamma_i(s)\|_{\mathscr{H}_\infty} = \sup_{\omega \in \mathbb{R}} \left| \frac{1}{h_i j\omega + 1} \right| = 1$, that is, the system is string stable for any headway $h_i \geq 0$.

When there is a drivetrain delay present in the ego vehicle, i.e., $\phi_i > 0$, the SSCS is given by

$$\Gamma_i(s) = \frac{1}{(h_i s + 1) + (1 - e^{-\phi_i s}) \frac{h_i s^2 (1 + \tau_i s)}{\left(k_p + k_d s + s^2\right) \tau_i e^{-\phi_i s}}}, \tag{9}$$

which shows a minimum headway $h_i \geq h_i^*(\phi_i)$ is required to achieve string stability for a given delay.

C. Drivetrain delay in platoons

The SSCS (9) shows the performance of the controller (4) deteriorates when there is a drivetrain delay present in the ego vehicle. The loss in performance is to such an extent, that close vehicle following is no longer possible [13].

Since there is a pure in-/output delay in the plant, where the acceleration dynamics (1c) can be described by $P_i(s) = D_i(s) G_i(s)$, with delay-free dynamics $G_i(s) = \frac{1}{\tau_i s + 1}$ and delay $D_i(s) = \mathrm{e}^{-\phi_i s}$, a delay compensation technique like a Smith predictor [16] can be used. Adopting the Smith predictor control scheme from [13] as depicted in Fig. 2, by including a model of the delay-free plant $\hat{G}_i(s)$ and a model of the delay $\hat{D}_i(s)$ in the control loop, the string stability properties of the controller are restored. With perfect knowledge of plant and delay, i.e, $\hat{G}_i(s) = G_i(s)$ and $\hat{D}_i(s) = D_i(s)$, the controller from (6) as $C_i(s) = k_p + k_d s$, and spacing policy transfer function as $H_i(s) = h_i s + 1$, the SSCS from block diagram Fig. 2 reduces to

$$\Gamma_i(s) = \frac{a_i(s)}{a_{i-1}(s)} = \frac{1}{h_i s + 1} \mathrm{e}^{-\phi_i s}, \tag{10}$$

which indicates string stability again for any headway $h_i \geq 0$.

Alternatively, the Smith predictor control scheme can be expressed using the model of the plant as

$$\dot{\bar{a}}_i(t) = -\frac{1}{\tau_{i,sp}} \bar{a}_i(t) + \frac{1}{\tau_{i,sp}} u_i(t), \tag{11a}$$

where $\bar{a}_i$ is the delay free estimate of vehicle i's acceleration, and $\tau_{i,sp} > 0$ is the time constant used by the Smith predictor. Subsequently, the output of the Smith predictor is given by

$$\hat{a}_i(t) = \bar{a}_i(t) + a_i(t) - \bar{a}_i(t - \phi_i) \tag{11b}$$

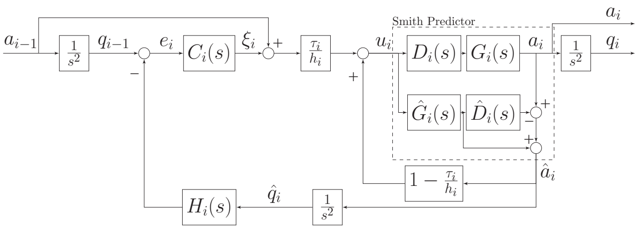

Fig. 2: Block diagram of CACC with a Smith predictor.

such that the error that is used by the controller is

$$e_{i,sp}(t) = q_{i-1}(t) - \hat{q}_i(t) - h_{i,sp}\hat{v}_i(t) - r_i - L_i \tag{12a}$$
$$\dot{e}_{i,sp}(t) = v_{i-1}(t) - \hat{v}_i(t) - h_{i,sp}\hat{a}_i(t), \tag{12b}$$

where $\dot{\hat{q}}_i(t) = \hat{v}_i(t)$ and $\dot{\hat{v}}_i(t) = \hat{a}_i(t)$. Consequently the control action is given by

$$\xi_{i,sp}(t) = k_p e_{i,sp}(t) + k_d \dot{e}_{i,sp}(t), \tag{13}$$

resulting in the input to the system as

$$u_i(t) = \frac{\tau_i}{h_i} a_{i-1}(t) + (1 - \frac{\tau_i}{h_i})\hat{a}_i(t) + \frac{\tau_i}{h_i}\xi_{i,sp}(t). \tag{14}$$

With the proper choice of initial conditions for $\hat{q}_i$, $\hat{v}_i$, $\hat{a}_i$, the Smith predictor states will be the time shifted version of the real vehicle states, i.e., $\hat{a}_i(t) = a_i(t+\phi_i)$, $\hat{v}_i(t) = v_i(t + \phi_i)$, $\hat{q}_i(t) = q_i(t+\phi_i)$. The result is a difference in controlled error (12) with respect to the original control objective (3). This effect can be mitigated by the choice of an alternative timegap [13] defined as

$$h_{\mathrm{sp},i} = h_i - \phi_i, \tag{15}$$

resulting in (3) being zero, when a_{i-1} is zero.

III. PROBLEM STATEMENT

The control system as described in Sec. II has the benefit that no driveline knowledge of the preceding vehicle is required. Extending the controller with a Smith predictor control scheme as described in Sec. II-C gives the controller (14) that enables close vehicle following for platoons that are both heterogeneous with respect to the driveline constant τ_i and delay ϕ_i. However, the control approach will encounter several problems when moving to an experimental application. In this section, we show that using measured accelerations compromises passenger comfort, and disturbances severely impair the performance.

A. Measured acceleration

To implement the control action (4) or (14), the acceleration of the preceding vehicle a_{i-1}, and ego vehicle a_i is required. As the acceleration of the preceding vehicle $i-1$ cannot be directly measured by the follower vehicle i, it has to be measured and communicated by the preceding vehicle using V2V. In practice, an acceleration signal that is measured with an IMU can contain a slowly varying sensor bias and is corrupted with measurement noise [17]. Adding a bias b_i and measurement noise η_i to the acceleration, gives the measured acceleration as

$$a_{\mathrm{meas},i}(t) = a_i(t) + b_i(t) + \eta_i(t). \tag{16}$$

TABLE I: Vehicle and control parameters, noise characteristics (obtained from [18], [13]) as used in simulations.

Description	Symbol	Value
Time constant leader	τ_{i-1}	0.1 s
Driveline delay leader	ϕ_{i-1}	0 s
Time constant vehicle i	τ_i	0.0687 s
Driveline delay vehicle i	ϕ_i	0.15 s
Variance measured d_i	$\sigma^2_{d_i}$	0.0144 m^2
Variance measured $\dot{d}_i$	$\sigma^2_{\dot{d}_i}$	0.0121 $(\mathrm{m/s})^2$
Variance measured v_i	$\sigma^2_{v_i}$	0.01 $(\mathrm{m/s})^2$
Variance measured a_i	$\sigma^2_{a_i}$	0.01 $(\mathrm{m/s}^2)^2$
Measurement sample time	t_s	0.01 s
Headway time	h_i	0.5 s
Standstill distance	r_0	1 m
Proportional gain	k_p	0.2
Derivative gain	k_d	$0.7 - k_p\tau_i$

Substituting the expression for the measured acceleration (16) in (14), shows that both the measurement noise $\eta_i(t)$ and $\eta_{i-1}(t)$ directly appear in the control action $u_i(t)$ of vehicle i. As a result, (as follows from (1c)) two noisy signals are directly present in the jerk of the vehicle which negatively affects passenger comfort.

Additionally, the bias acts as a static disturbance on the system, which is a problem for the Smith predictor (11). Due to the double integrator in the Smith predictor, its states can diverge from the real vehicle states. Therefore, the assumption that $\hat{v}_i(t) = v_i(t+\phi)$ and $\hat{q}_i(t) = q_i(t+\phi)$, on which the controller design in [13] is based, does no longer hold in a setting dealing with measured signals.

To illustrate the undesired effects that are introduced by using the measured acceleration (16), simulations are performed with a platoon consisting of two vehicles. The parameters as listed in TABLE I are used to compare the nominal case (i.e., without noise and bias) to the response when the measured acceleration (16) is used. The measured accelerations contain a constant bias according to $b_{i-1} = -0.08$ m/s^2, $b_i = 0.11$ m/s^2, and white noise (with the characteristics as listed in TABLE I). Note that the particular choice of bias in this simulations is arbitrary, and only used to show the effect of the drift in the error.

The leader vehicle $i-1$ receives a step input on u_{i-1} that is defined as

$$u_{i-1}(t) = \begin{cases} 1 \ \mathrm{m/s}^2, & 2 \le t < 12 \\ 0 \ \mathrm{m/s}^2, & \text{otherwise.} \end{cases} \tag{17}$$

The follower vehicle employs the Smith predictor control scheme from Fig. 2 that results in input (14) with controller (13), where the headway $h_{i,sp}$ is chosen according to (15). The initial conditions are chosen such that the spacing error perceived by the controller (12) is zero. Fig. 3 shows the acceleration response, and original error (3) over the simulation window. In the nominal case, indicated with the dotted line, the maximum error is reached during acceleration. Additionally, the error converges to zero when $a_{i-1} = 0$ m/s^2. In the case with noise and bias on the acceleration signals, the Smith predictor states $\hat{v}_i$ (and subsequently $\hat{q}_i$) do not converge to the real vehicle states (in steady state situations). In the particular simulation, the effect is a lower velocity $\hat{v}_i(t-\phi) < v_i(t)$ that causes the error grow.

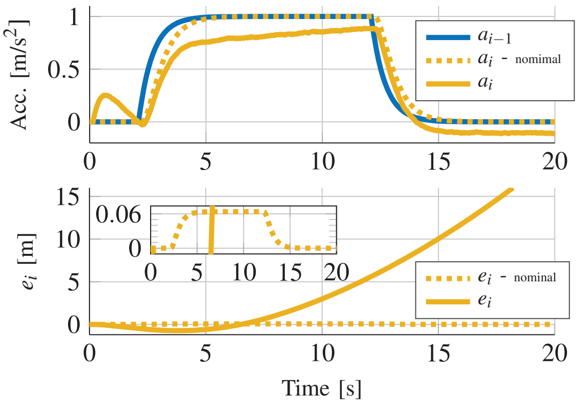

Fig. 3: Response of the Smith predictor control scheme (14) when measured accelerations (16) are used, compared to nominal performance where groundtruth acceleration is used.

Summarizing, the problems that are introduced by using measured accelerations are twofold. First, the measured signals result in two noisy signals that are directly present in the jerk of the vehicle, thereby compromising passenger comfort. Second, disturbances (such as the bias) in the acceleration measurements, result in a mismatch between the Smith predictor- and real vehicle states with the consequence that the original objective ($e_i \to 0$) is not fulfilled. In this paper, we aim to solve these problems by introducing a control approach for the system with delay, that directly uses measured signals. To mitigate the effects of measurement noise, we design two observers such that the resulting control action for the follower vehicle only contains filtered signals.

IV. CONTROLLER DESIGN

In this section we present a controller that is able to fulfill the control objective (i.e., control (3) to zero) when the ego vehicle has a delay in the driveline. Subseqently the string stability characteristics are given, and the nominal performance is evaluated.

A. Approximation of plant dynamics

Taking the Laplace transform of (1c), the transfer function from input u_i to output acceleration a_i for vehicle i is obtained as

$$\frac{u_i(s)}{a_i(s)} = \frac{\mathrm{e}^{-\phi_i s}}{\tau_i s + 1}. \tag{18}$$

Instead of compensating the drivetrain delay ϕ_i that is present in vehicle i, we approximate the first order plant with delay from (18) by a first order plant without delay that we use to design our controller according to the approach presented in Sec. II-A.

Taking the $[0/1]$ Padé approximant of (18), results in

$$\frac{u_i(s)}{a_i(s)} = \frac{\mathrm{e}^{-\phi_i s}}{\tau_i s + 1} \approx \frac{1}{(\tau_i + \phi_i)s + 1}. \tag{19}$$

Adopting the controller design from Sec. II-A [12] gives

$$u_i(t) = \tfrac{\tau_i + \phi_i}{h_i} a_{i-1}(t) + (1 - \tfrac{\tau_i+\phi_i}{h_i}) a_i(t) + \tfrac{\tau_i+\phi_i}{h_i} \xi_i(t), \tag{20}$$

to asymptotically stabilize the error dynamics of the approximated plant (19).

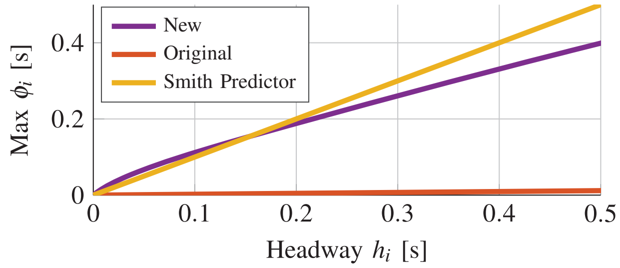

Fig. 4: Numerically determined maximum allowable drivetrain delay ϕ_i for a given headway h_i for which string stable behavior is preserved, for new approach (20), original controller (4) and Smith predictor (14).

B. String stability

When using the controller derived for the approximated plant, on the real plant with delay (1), the SSCS is obtained as

$$\Gamma_i(s) = \frac{(k_p + k_d s + s^2)}{(1 + h_i s)(k_p + k_d s) + \frac{s^2(\tau_i + \phi_i + h_i(\mathrm{e}^{-\phi_i s}(1+\tau_i s) - 1)}{\tau_i + \phi_i}} \tag{21}$$

Using (21) and the original SSCS from (9) to numerically determine the maximum allowable drivetrain delay ϕ_i for which the system is string stable (i.e., $\|\Gamma_i\|_{\mathscr{H}_\infty} \leq 1$), given a headway time h_i, we obtain Fig. 4. The maximum allowable drivetrain delay for the Smith predictor control scheme follows from (15), as $h_{i,sp} \geq 0$ is required for stability of the system. Fig. 4 indicates the new approach (given the parameters from TABLE I) can achieve a shorter headway time for small delays ($\phi_i < 0.16$ seconds). For larger delays, the Smith predictor scheme can achieve a shorter headway time. Both yield a significant improvement with respect to the original approach.

C. Nominal performance

To evaluate the nominal performance of the proposed controller, simulations are performed with the parameters as presented in Sec. III. The original controller (4), Smith-predictor based controller (14) and proposed new controller (20), are used with the controller tuning as listed in TABLE I. Ideal accelerations are used, i.e., no noise and bias is considered, to characterize the nominal (best case) performance of the controllers. Fig. 5 shows the acceleration response and errors (3) of the three controllers. Although the Smith predictor reaches zero error faster when $a_{i-1} = 0$, the new controller achieves smaller maximum (absolute) errors, and is able to converge to zero error for steady state situations where $a_{i-1} \neq 0$. Contrary to the Smith predictor control scheme, the new controller determines its feedback action on signals that can be directly measured with on-board sensors. Therefore, the problem of the drifting error as described in Sec. III will not arise in the proposed scheme.

Summarizing, the proposed controller yields comparable string stability properties to the Smith predictor control scheme (as shown in Sec. IV-B while having better performance with respect to absolute errors as shown in Sec. IV-C.

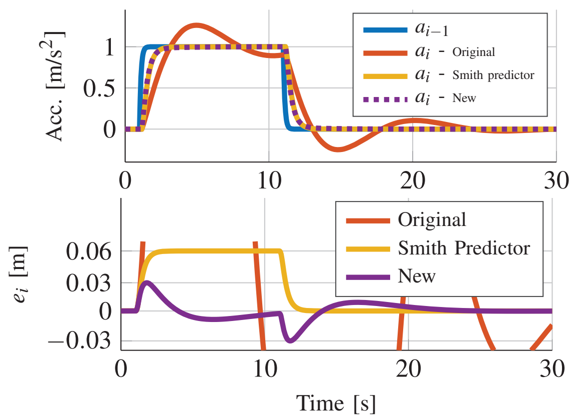

Fig. 5: Response of the new controller (20), compared to the original (4) and Smith predictor (14) controller.

V. OBSERVER BASED CACC FRAMEWORK

To mitigate the negative effects of measurement noise and sensor bias, we require each vehicle in the platoon to employ locally an acceleration observer to obtain a bias-free estimate of their respective longitudinal acceleration. Since the error that is used in the controller to determine $\xi_i(t)$ consists of measured signals, an additional observer is designed to obtain an input u_i to the vehicle that only contains filtered signals.

A. Acceleration observer

To design the acceleration observer, we are adopting the dynamics from (1), with the assumption that the measured acceleration contains a bias b_i that is constant, i.e., $\dot{b}_i = 0$. Subsequently, the state space representation of the acceleration dynamics for the observer design is given by

$$\dot{x}(t) = A_a x(t) + B_a u(t-\phi) \tag{22a}$$

$$y_a(t) = C_a x(t) + \eta_a(t), \tag{22b}$$

where $x_i(t) = \begin{bmatrix} a_i(t) & b_i(t) \end{bmatrix}^\top$, η_a denotes the measurement noise, and

$$A_a = \begin{bmatrix} -\frac{1}{\tau_i} & 0 \\ 0 & 0 \end{bmatrix}, \qquad B_a = \begin{bmatrix} \frac{1}{\tau_i} \\ 0 \end{bmatrix}, \qquad C_a = \begin{bmatrix} 1 & 1 \end{bmatrix}.$$

The observer estimating $\hat{x}(t) = \begin{bmatrix} \hat{a}_{o,i}(t) & \hat{b}_{o,i}(t) \end{bmatrix}^\top$ is given by

$$\dot{\hat{x}}(t) = A_a \hat{x}(t) + B_a u_i(t-\phi) + L_a(y_{a,i}(t) - C_a \hat{x}(t)), \tag{23}$$

where the observer gain $L_a = \begin{bmatrix} l_{a_1}, l_{a_2} \end{bmatrix}^\top$ can be obtained by pole placement of the matrix $(A_a - L_a C_a)$.

B. Error observer

To obtain a control action that only uses filtered signals, we reconstruct the error and its derivative based on the outputs of an observer. To that end, we consider the dynamics of two consecutive vehicles. By defining the states $x_e^\top(t) = \begin{bmatrix} d_i & \Delta v_i & v_i & a_i \end{bmatrix}$ and the input $u_e^\top(t) = [a_{i-1}(t)\ u_i(t-\phi_i)]$, the dynamics of two consecutive vehicles are given by

$$\dot{x}_e(t) = A_e x_e(t) + B_e u_e(t) \tag{24a}$$

$$y_e(t) = C_e x_e(t) + \eta_e(t), \tag{24b}$$

where

$$A_e = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \frac{-1}{\tau_i} \end{bmatrix}, B_e = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & \frac{1}{\tau_i} \end{bmatrix}, C_e = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$\Delta v_i = v_{i-1} - v_i$ and $\eta_e(t)$ is the measurement noise vector. The output $y_e(t)$ consists of four individual measurements. Specifically, the inter vehicle distance d_i and relative velocity $\Delta v = v_{i-1} - v_i$ are direct measurements of a radar sensor. Additionally, the ego vehicle velocity v_i and acceleration a_i are measured by a speedometer and IMU on-board of the vehicle respectively. The observer that estimates $\hat{x}_e(t)$ is subsequently given by

$$\dot{\hat{x}}_e(t) = A_e \hat{x}_e(t) + B_e u_e(t) + L_e(y_e(t) - C_e \hat{x}_e(t)). \tag{25}$$

Based on the estimated states $\hat{x}_e(t)$ of the two consecutive vehicles, the error and its derivative can be reconstructed by

$$\begin{bmatrix} \hat{e}_i(t) \\ \dot{\hat{e}}_i(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 & -h_i & 0 \\ 0 & 1 & 0 & -h_i \end{bmatrix} \hat{x}_e(t) + \begin{bmatrix} -r_0 \\ 0 \end{bmatrix}. \tag{26}$$

C. Observer based CACC

Adopting the acceleration observer (23) locally on vehicle $i-1$ and vehicle i to obtain bias free estimates of the accelerations $\hat{a}_{o,i-1}(t)$ and $\hat{a}_{o,i}(t)$, in combination with the observer (25) to reconstruct the error $\hat{e}_i(t)$ and its derivative $\dot{\hat{e}}(t)$ according to (26), the controller (20) can be implemented using only observer outputs according to

$$u_i(t) = \tfrac{\tau_i + \phi_i}{h_i} \hat{a}_{o,i-1}(t) + (1 - \tfrac{\tau_i + \phi_i}{h_i}) \hat{a}_{o,i}(t) + \tfrac{\tau_i + \phi_i}{h_i} \hat{\xi}_i(t), \tag{27}$$

where $\hat{\xi}_i(t)$ is obtained by combining the PD-controller (6) with (26) according to

$$\hat{\xi}_i(t) = k_p \hat{e}_i(t) + k_d \dot{\hat{e}}_i(t). \tag{28}$$

VI. SIMULATION RESULTS

To evaluate the performance of the proposed controller (27) in combination with the observer framework, a simulation is performed with the same settings as used in the problem setting from Sec. III. The observer gains L_a for the acceleration observers (23) are obtained through pole placement, to locate all eigenvalues of $(A_a - L_a C_a)$ at -4. The same procedure is performed to obtain the observer gain L_e for the error observer (25), to place all eigenvalues of $(A_e - L_e C_e)$ at -4. Vehicle parameters, noise characteristics and controller tuning are according to TABLE I. The initial conditions of the observer are chosen to have zero error with respect to the ground truth, since we want to illustrate the behavior of the system once the observers have converged.

The simulation results of a platoon of two vehicles, adopting controller (27) are shown in Fig. 6. The acceleration response, where for completeness also the measured accelerations are depicted, does not show any overshoot (indicating string stability), and the acceleration a_i converges to the acceleration a_{i-1} in steady state situations. The error response shows the controller is able to reach the control objective ($e_i \to 0$) in steady state situations. Additionally, the performance of the controller (27) with respect to the

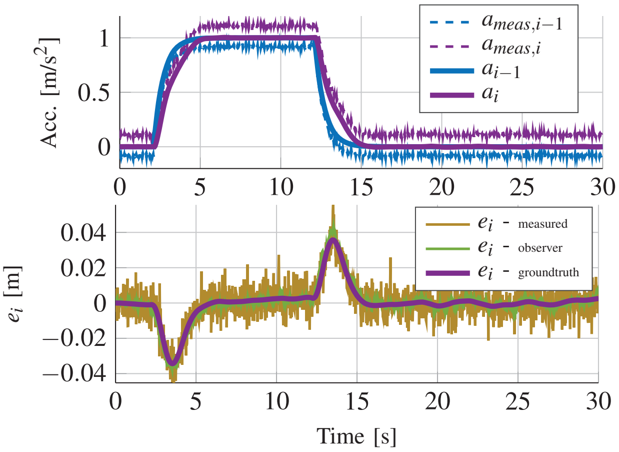

Fig. 6: Response of the platoon, adopting controller (23) with simulation settings according to TABLE I.

maximum absolute (groundtruth) error, is in the simulation with noise, better than the nominal performance of the Smith predictor (14) in the noise-free setting. The maximum absolute error during the simulated maneuver with noisy conditions is smaller than 4 cm, where the Smith predictor reaches an error of 6 cm during the same maneuver under perfect conditions.

Summarizing, the simulation shows the potential of the proposed controller (27) in combination with the acceleration observer (23) and error observer (25). The tuning of the controller in combination with the observers is planned for future research, as well as a thorough mathematical stability analysis and experiments.

VII. Conclusion

The presented controller design in combination with the acceleration and error observer enables a decentralized control approach for heterogeneous vehicle platoons with actuator delays. No driveline information of the preceding vehicle is required, as only the (estimated) acceleration of the preceding vehicle is used by the controller. The string stability properties of the controller are for low actuator delays better than an approach that uses a Smith predictor to compensate for the delay. The performance of the controller is validated by simulations where measurements are corrupted by noise and a bias. Under the simulated circumstances, the controller is able to successfully fulfill the control objective, confirming the potential of the presented solution. Future work entails the analysis of stability of the closed loop system with (uncertainties in) the delays and validating the framework in an experimental setting. Additionally, the effects of a communication delay, as well as the influence of observer tuning on the string stability properties should be characterized. Next to assessing the performance of the proposed framework in the cooperative setting (i.e., when the filtered accelerations are communicated), the loss of performance in fall-back scenarios can be determined, e.g., when the V2V communication fails. Based on these analyses, tuning guidelines for the controller and observers can be derived, such that (string) stability is guaranteed. The controller greatly depends on the identification of the driveline of the ego vehicle. Robustness of the proposed control scheme with respect to inaccuracies in the driveline parameters should be addressed.

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