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Distributed PI Control For Heterogeneous Nonlinear Platoon of Autonomous Connected Vehicles

Sabato Manfredi * **Alberto Petrillo** * **Stefania Santini** *

* *Department of Information Technology and Electrical Engineering (DIETI), University of Naples Federico II, Naples 80125, Italy, e-mail: (sabato.manfredi, alberto.petrillo, stefania.santini)@unina.it*

Abstract: In this paper we present a distributed PI-based control law that guarantees the platoon formation to track leader velocity with a pre-fixed inter-vehicular distance, when vehicles are heterogeneous in both parameters and nonlinear drivetrain dynamics. Moreover, differently from most of the approaches in the literature, the proposed PI protocol intrinsically compensates for the nonlinear, heterogeneous and uncertain drivetrain dynamics without requiring any feedforward control action. We formulate sufficient conditions for closed-loop heterogeneous non-linear vehicular network stability that can be used to tune the PI control parameters. Simulation results confirm the effectiveness of the proposed PI controller in both nominal and uncertain platooning scenario.

Keywords: Autonomous Vehicle Platoon; Distributed PI Controller; Heterogeneous Nonlinear Vehicle Dynamics; Parameter Uncertainties.

1. INTRODUCTION

During last years, it has been shown that the deployment of autonomous connected vehicles, moving with a desired speed and acceleration profiles, while maintaining an optimal inter-vehicular spacing policy, may lead to many benefits in terms of fuel efficiency, road safety, traffic congestion and pollution (Coelingh and Solyom, 2012). In this driving scenario, all vehicles are connected through Vehicle-to-Vehicle (V2V) wireless communication and the IEEE 802.11p is the facto vehicular networking standard (Alasmary and Zhuang, 2012). On the basis of the exchanged information, the on-board control algorithm is responsible of the safe tracking of the desired velocity and acceleration profiles, i.e. vehicles have to track the leader motion while respecting at the same time a pre-determined inter-vehicle spacing policy (Petrillo et al., 2018b). In the technical literature, different control approaches for the design of the platoon controller have been proposed (see (Jia et al., 2015) and references therein). First attempts include Cooperative Adaptive Cruise Control (CACC) strategies which adopt pre-fixed communication patterns during control design (e.g. predecessor-follower) and aim at providing robustness to the string of vehicles, focusing only on small perturbations acting on the solely leader motion that have to be de-amplified downstream (see e.g. (Rajamani, 2011)). More recently, leveraging the framework of multi-agent systems, some advanced platoon control strategies have been proposed. For instance, Model Predictive Control (MPC)(Liu et al., 2017) and sliding mode (Wu et al., 2016) control approaches have been proposed to tackle the problem of vehicular communication topology variety.
Consensus-based approaches have been also proposed in (Fiengo et al., 2018; Jia and Ngoduy, 2016; Petrillo et al., 2018b,a, 2020) to deal with both topology variety and heterogeneity in the time-varying communication delays, or in (Fiengo et al., 2019) to deal with the problem of vehicles dynamics uncertainties.

All the aforementioned works consider linear dynamical system to describe the vehicle dynamics and do not take into account for model nonlinearities. However the latter are present in a more accurate and realistic problem formulation where nonlinearities are induced by vehicle powertrain system, e.g. engine, driveline, and aereodynamic drag (Zheng et al., 2016). To face this issue, (Zheng et al., 2016) presents a distributed model predictive control (DMPC) algorithm that, exploiting for each node a local compensation action of the external drag, guarantees the platoon formation of heterogeneous non linear vehicles with unidirectional topologies and a priori unknown desired set point. More recently, as alternative solution, a distributed sliding mode controller (DSMC) has been proposed in (Wu et al., 2019) to deal with the problem of vehicular communication topology for nonlinear vehicles platoon. However, to counteract model nonlinearities effects, for each vehicle a feed forward action is added to the proposed controller.

In this paper we propose a distributed PI-based control that guarantees the platoon formation to track leader velocity with a pre-fixed inter-vehicular distance, and is characterised by the following notable features. Firstly, the proposed control can deal with the scenario of heterogeneous platoon where vehicles may be different or affected by mismatched uncertainties in both parameters and nonlinear drivetrain dynamics (e.g. aerodynamics drag, rolling resistance, gravitational force). Secondly, the

[1] Authors are in alphabetic order
[2] Corresponding Author: Alberto Petrillo

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PI-type protocol intrinsically compensates for nonlinear, heterogeneous and uncertain drivetrain dynamics without requiring any feedforward control action. This improves recent approaches in the literature (e.g. (Zheng et al., 2016; Wu et al., 2019)) based on drivetrain dynamic feedforward control, that may fail or require online measurements/estimations when vehicle parameters are uncertain or time-varying. Moreover, the PI control protocol is fully distributed and is less computational demanding than most of existing distributed or centralized approaches in the literature (i.e. see (Zheng et al., 2016) and references therein). We formulate sufficient conditions for closed-loop heterogeneous non-linear vehicular network stability that can be used to tune PI control parameters. To the best of our knowledge, this is the first application of distributed PI control to nonlinear and heterogeneous vehicles platooning, where cars may be different or affected by mismatched uncertainties in both parameters and nonlinear drivetrain dynamics. Simulations results on nominal and uncertain scenario confirm the effectiveness of the proposed control. The rest of the paper is organized as follows. In section 2 the problem statement and the proposed control strategy are presented; in Section (3) the closed-loop vehicular network is obtained and stability conditions are derived; in Section (4) the theoretical derivation is validated via numerical simulations, while in Section (5) are drawn.

2. PROBLEM STATEMENT

Consider a platoon of N heterogeneous vehicles plus a leader moving on a single lane. Each vehicle within the platoon shares their state information (e.g. the absolute position and speed) with all the other vehicles within its communication range through a V2V communication paradigm. The reference behavior for the platoon is imposed by the leader, labeled with index 0, that can be either the first vehicle of the fleet or a virtual leader. The aim is that, without any centralized action, the entire formation tracks the leading dynamic behavior, while it also preserves a pre-fixed inter-vehicular distance. In so doing the platoon moves along a string as a rigid and cohesive 1-D formation.

2.1 Nonlinear Longitudinal Platoon Dynamics

The vehicle longitudinal dynamics are inherently nonlinear, heterogeneous and mainly governed by the drivetrain dynamics, including aerodynamics drag, rolling resistance, gravitational force (Rajamani, 2011). To derive a mathematical model for control design we assume that: *i)* the vehicle is moving on flat road, and hence tire slip on the longitudinal direction is neglected; *ii)* the driving/braking torques are integrated into one high level control input. Accordingly, the i-th heterogeneous vehicle dynamics can be described by the following non linear system (Wu et al., 2019):

$$\begin{aligned} \dot{p}_i(t) &= v_i(t) \\ \dot{v}_i(t) &= \frac{1}{m_i}\left(\frac{\eta_i}{R_i}T_i(t) - C_{A,i}v_i^2(t) - gf_i\right), \end{aligned} \tag{1}$$

where $p_i(t)$ and $v_i(t)$ are the longitudinal position and velocity of the i-th vehicle respectively; $T_i(t)$ is the control

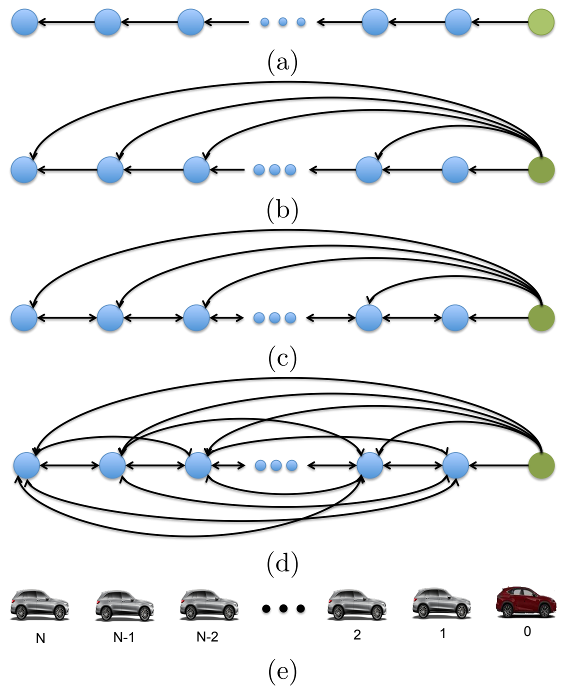


Fig. 1. Exemplar platoon communication topologies (Fiengo et al., 2019): (a) Predecessor-Following (P-F), (b): Leader-Predecessor-Following (L-P-F); (c): Bidirectional-Leader (B-D-L); (d): All-to-All (Broadcast, BR); (e): Platoon of N vehicles plus a leader.

input that represents the driving/braking force; m_i is the vehicle mass; η_i is the drivetrain mechanical efficiency; R_i is the wheel radius; $C_{A,i}$ is the aerodynamic drag coefficient; g is the gravity acceleration; f_i is the rolling resistance coefficient.

Indicating with $x_i(t) = [p_i(t), v_i(t)]^\top \in \mathbb{R}^{2\times 1}$ the i-th vehicle state vector and with $u(t) \in \mathbb{R}$ the control input, the nonlinear dynamic in (1) can be recast in the following state-space form:

$$\dot{x}_i(t) = \begin{bmatrix} v_i(t) \\ \varphi_i(v_i(t)) \end{bmatrix} + \begin{bmatrix} 0 \\ b_i \end{bmatrix} u_i(t) \tag{2}$$

where $b_i = \eta_i/(m_i R_i)$ while $\varphi_i(v_i(t)) \in \mathbb{R}$ is a continuously differentiable and bounded nonlinear vector field, defined as:

$$\varphi_i(v_i(t)) = -\frac{1}{m_i}\left(C_{A,i}v_i^2(t) + gf_i\right). \tag{3}$$

The leader dynamics are, instead, described by the following nonlinear autonomous system:

$$\dot{x}_0(t) = \begin{bmatrix} v_0(t) \\ \varphi_0(v_0(t)) \end{bmatrix}. \tag{4}$$

2.2 Network Communication

The communication structure of the V2V wireless network is represented by a graph where each vehicle is a node. A N autonomous vehicles network can be hence modeled by a N-order directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$, being $\mathcal{V} = \{1, \ldots, N\}$ the nodes set and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ the edges set. The graph structure is described by the adjacency matrix $\mathcal{A} = [\alpha_{ij}]_{N\times N}$ whose elements are such that $\alpha_{ij} = 1$ if vehicle i exchange information with vehicle j to vehicle i (but not necessarily viceversa), $\alpha_{ij} = 0$ otherwise. The degree matrix is hence defined as $D = \mathrm{diag}\{\Delta_1, \Delta_2, ..., \Delta_N\}$, with $\Delta_i = \sum_{j\in\mathcal{V}} \alpha_{ij}$. In this work, to model the platoon of N autonomous vehicle plus a leading vehicle, we exploit an augmented directed graph $\mathcal{G}_{N+1}$, where the additional agent, labeled as 0, is the leader that imposes the desired behaviour. In the resulting graph $\mathcal{G}_{N+1}$, we assume that $\alpha_{0j} = 0$ ($\forall j = 0, \ldots, N$), since the leader can only send information but does not acquire data from vehicles within the platoon. Moreover, in what follows we consider node 0 to be *globally reachable* in $\mathcal{G}_{N+1}$ and, therefore, there exists a path in $\mathcal{G}_{N+1}$ from every vehicle i in $\mathcal{G}$ to vehicle 0 (Horn and Johnson, 2012). Note that in typical network topologies for platoon applications, i.e. Predecessor-Follower (P-F), Leader-Predecessor-Follower(L-P-F), Bidirectional Leader Predecessor Follower (B-L-F), Broadcast (BR) (as depicted in Fig.1) the leader is always globally reachable (see (Li et al., 2015) and reference therein). Indeed, this is not a restrictive assumption for vehicular networks since it only implies that information can be shared through a path from the leader to any generic vehicle within the formation, but it is not always assumed them to be directly linked.

2.3 Control objective

The aim of the platoon control is to guarantee that each heterogeneous vehicle i ($\forall i = 1, \cdots, N$) tracks the leader speed while maintaining a desired spacing policy w.r.t. its neighboring vehicles j ($j = 0, \cdots, N$), i.e.

$$\begin{aligned}&\lim_{t\to\infty} \|v_i(t) - v_0(t)\| = 0\\ &\lim_{t\to\infty} \|p_i(t) - p_j(t) - d_{ij}\| = 0\end{aligned} \tag{5}$$

where d_{ij} is the desired spacing policy among vehicle i and vehicle j.

2.4 Distributed PI Control Protocol

To solve Problem (5) we propose for each heterogeneous vehicle i the following cooperative distributed PI control strategy that updates its action based on the errors among the state information shared by vehicles:

$$\begin{aligned}u_i(t) = &- K_P \sum_{j=0}^{N} a_{ij}\Big(p_i(t) - p_j(t) - d_{ij}\Big)\\ &- K_I \sum_{j=0}^{N} a_{ij} \int_0^t \Big(p_i(\tau) - p_j(\tau) - d_{ij}\Big)d\tau\\ &- K_D \sum_{j=0}^{N} a_{ij}\Big(v_i(t) - v_j(t)\Big),\end{aligned} \tag{6}$$

where K_P, K_D are the proportional gains while K_I is the integral one; a_{ij} models the network topology emerging from the presence/absence of the communication link between the $i-th$ and $j-th$ vehicle.

3. STABILITY ANALYSIS

3.1 Closed-Loop Heterogeneous Vehicular Network

By defining the error of the generic i-th vehicle with respect to leader as

$$e_i(t) = \begin{bmatrix} r_i(t) - r_0(t) - d_{i0} \\ v_i(t) - v_0(t) \end{bmatrix} = \begin{bmatrix} \bar{r}_i(t) \\ \bar{v}_i(t) \end{bmatrix} \forall i = 1, \ldots, N, \tag{7}$$

after some algebraic manipulation, the PI control protocol (6) can be recast as

$$\begin{aligned}u_i(t) = &- K_P \sum_{j=0}^{N} a_{ij}\Big(\bar{r}_i(t) - \bar{r}_j(t)\Big)\\ &- K_I \sum_{j=0}^{N} a_{ij} \int_0^t \Big(\bar{r}_i(\tau) - \bar{r}_j(\tau)\Big)d\tau\\ &- K_D \sum_{j=0}^{N} a_{ij}\Big(\bar{v}_i(t) - \bar{v}_j(t)\Big).\end{aligned} \tag{8}$$

Given (2), the closed-loop error dynamics for the generic i-th vehicle can be written as:

$$\begin{aligned}\dot{e}_i(t) = &\begin{bmatrix} \bar{v}_i(t) \\ \varphi_i(\bar{v}_i(t)) \end{bmatrix} - \begin{bmatrix} 0 \\ b_i \end{bmatrix} \Big(K_P \sum_{j=0}^{N} a_{ij}\Big(\bar{r}_i(t) - \bar{r}_j(t)\Big)\\ &+ K_I \sum_{j=0}^{N} a_{ij} \int_0^t \Big(\bar{r}_i(\tau) - \bar{r}_j(\tau)\Big)d\tau\\ &+ K_D \sum_{j=0}^{N} a_{ij}\Big(\bar{v}_i(t) - \bar{v}_j(t)\Big)\Big),\end{aligned} \tag{9}$$

being $\varphi_i(\bar{v}_i(t)) = \varphi_i(v_i(t)) - \varphi_0(v_0(t))$.

Now, by introducing the new state vector $\bar{e}_i(t) = [z_i(t), \bar{r}_i(t), \bar{v}_i(t)]^\top \in \mathbb{R}^{3\times1}$, being $z_i(t) = \int_0^t \bar{r}_i(\tau)d\tau$, the closed-loop system (9) can be recast as:

$$\begin{aligned}\dot{\bar{e}}_i(t) = &\begin{bmatrix} \bar{r}_i(t) \\ \bar{v}_i(t) \\ \varphi_i(\bar{v}_i(t)) \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ b_i \end{bmatrix} \Big(K_P \sum_{j=0}^{N} a_{ij}\Big(\bar{r}_i(t) - \bar{r}_j(t)\Big)\\ &+ K_I \sum_{j=0}^{N} a_{ij}\Big(z_i(t) - z_j(t)\Big)\\ &+ K_D \sum_{j=0}^{N} a_{ij}\Big(\bar{v}_i(t) - \bar{v}_j(t)\Big)\Big).\end{aligned} \tag{10}$$

or in a more compact notation as:

$$\dot{\bar{e}}_i(t) = \bar{\varphi}_i(\bar{v}_i(t)) + A_{ii}\bar{e}_i(t) + \sum_{j=1}^{N} A_{ij}\bar{e}_j(t), \tag{11}$$

being the vector field $\bar{\varphi}_i(\bar{v}_i(t)) \in \mathbb{R}^{3\times1}$ defined as

$$\bar{\varphi}_i(\bar{v}_i(t)) = \begin{bmatrix} 0 \\ 0 \\ \varphi_i(\bar{v}_i(t)) \end{bmatrix}, \tag{12}$$

while the matrices A_{ii}, $A_{ij} \in \mathbb{R}^{3\times3}$ assumes the following expression:

$$\begin{aligned}A_{ii} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -b_i\sum_{j=0}^{N} a_{ij}K_I & -b_i\sum_{j=0}^{N} a_{ij}K_P & -b_i\sum_{j=0}^{N} a_{ij}K_D \end{bmatrix},\\ A_{ij} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -b_ia_{ij}K_I & -b_ia_{ij}K_P & -b_ia_{ij}K_D \end{bmatrix}.\end{aligned} \tag{13}$$

Now, by defining the following vectors containing the errors components

$$\bar{x}(t) = [\bar{e}_1, \bar{e}_2, \cdots, \bar{e}_N] \in \mathbb{R}^{3N\times1}, \tag{14}$$

we can describe the closed-loop dynamics of the entire network of heterogeneous vehicles as:

$$\dot{\bar{x}}(t) = \bar{\varphi}(\bar{v}(t)) + \mathcal{A}\bar{x}(t), \tag{15}$$

where

$$\bar{\varphi}(\bar{v}(t)) = [\bar{\varphi}_1(\bar{v}_1(t)), \bar{\varphi}_2(\bar{v}_2(t)), \cdots, \bar{\varphi}_N(\bar{v}_N(t))] \in \mathbb{R}^{3N\times 1} \tag{16}$$

and $\mathcal{A} \in \mathbb{R}^{3N\times 3N}$ is defined as:

$$\mathcal{A} = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & A_{22} & \cdots & A_{2N} \\ \vdots & \cdots & \ddots & \vdots \\ A_{N1} & A_{N2} & \cdots & A_{NN} \end{bmatrix}. \tag{17}$$

Given the definition of the closed-loop system in (15), since each vector field $\bar{\varphi}_i(\bar{v}_i(t))$ is continuous, differentiable and bounded, i.e. a Lipchitz function, the following condition holds.

Condition 1. *(Manfredi, 2018) There exists constants ω_i ($\forall i = 1, \cdots, N$) such that for any vectors $x_i(t), x_0(t)$, the vector fields $\bar{\varphi}_i(.)$ satisfy the condition:*

$$\begin{aligned} &(x_i(t) - x_0(t))^\top \Big(\bar{\varphi}_i(x_i(t)) - \bar{\varphi}_0(x_0(t))\Big) \\ &\leq \omega_i (x_i(t) - x_0(t))^\top (x_i(t) - x_0(t)) \end{aligned} \tag{18}$$

3.2 Proof of Convergence and Control Gains Tuning

Theorem 1. *Consider the closed-loop heterogeneous non-linear vehicular network (15) under the action of PI control strategy (6) and assume Condition 1 holds. The platoon control objective in (5) is achieved if the leading vehicle is globally reachable and if the PI control gains, i.e. K_I, K_P and K_D, are designed such that:*

$$\begin{aligned} &K_D > \max_i \left\{ \frac{\omega_i}{b_i(\Delta_i + 1)} \right\} \\ &K_I > 0 \\ &K_P > \max_i \left\{ \frac{K_I}{b_i(\Delta_i + 1)K_D - \omega_i} \right\}, \end{aligned} \tag{19}$$

being $b_i = \eta_i/(m_i R_i)$, $\Delta_i = \sum_{j=1}^N a_{ij}$ and ω_i a positive constant ($\forall i = 1, \cdots, N$).

Proof. Consider the following Lyapunov function:

$$V(\bar{x}(t)) = \frac{1}{2}\bar{x}^\top(t)\bar{x}(t). \tag{20}$$

Differentiating $V(\bar{x}(t))$ along the trajectories of the closed loop system (15), we have:

$$\begin{aligned} \dot{V}(\bar{x}(t)) &= \bar{x}^\top(t)\dot{\bar{x}}(t) = \bar{x}^\top(t)\Big(\bar{\varphi}(\bar{v}(t)) + \mathcal{A}\bar{x}(t)\Big) \\ &= \bar{x}^\top(t)\bar{\varphi}(\bar{v}(t)) + \bar{x}^\top(t)\mathcal{A}\bar{x}(t). \end{aligned} \tag{21}$$

Considering (16) and the expression of its elements in (12), under Condition 1, the term $\bar{x}^\top(t)\bar{\varphi}(\bar{v}(t))$ can be recast as

$$\begin{aligned} \bar{x}^\top(t)\bar{\varphi}(\bar{v}(t)) &= \sum_{j=1}^N \bar{v}_i(t)\varphi_i(\bar{v}_i(t)) \\ &\leq \sum_{j=1}^N \omega_i \bar{v}_i^2(t). \end{aligned} \tag{22}$$

According to (22), the derivative of the Lyapunov function (21) can be rewritten as

$$\dot{V}(\bar{x}(t)) \leq \sum_{j=1}^N \omega_i \bar{v}_i^2(t) + \bar{x}^\top(t)\mathcal{A}\bar{x}(t) = \bar{x}^\top(t)\widehat{\mathcal{A}}\bar{x}(t). \tag{23}$$

where $\widehat{\mathcal{A}} \in \mathbb{R}^{3N\times 3N}$ is defined as

$$\widehat{\mathcal{A}} = \begin{bmatrix} \bar{A}_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & \bar{A}_{22} & \cdots & A_{2N} \\ \vdots & \cdots & \ddots & \vdots \\ A_{N1} & A_{N2} & \cdots & \bar{A}_{NN} \end{bmatrix}, \tag{24}$$

being $\bar{A}_{ii} \in \mathbb{R}^{3\times 3}$ the following matrix:

$$\bar{A}_{ii} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -b_i \sum_{j=0}^N a_{ij} K_I & -b_i \sum_{j=0}^N a_{ij} K_P & -b_i \sum_{j=0}^N a_{ij} K_D + \omega_i \end{bmatrix}. \tag{25}$$

To guarantee $\dot{V}(\bar{x}(t)) < 0$ and hence the asymptoic stability of the closed-loop system (15), it is necessary showing that $\widehat{\mathcal{A}}$ is a negative definite matrix.

If the leading vehicle is globally reachable, by construction, this matrix is a strictly diagonally dominant block matrix (Petrillo et al., 2020, 2018b), whose generic block element $\bar{A}_{ii} \in \mathbb{R}^{3\times 3}$ on the main diagonal is defined as in (25). Hence, to show that $\widehat{\mathcal{A}}$ is negative definite, it suffices to prove that each block $\bar{A}_{ii}$ is a negative definite matrix ($\forall i = 1, \ldots, N$).

Our aim is hence to find the control gains tuning rule that ensures the asymptotic stability of $\bar{A}_{ii}$. Accordingly, $\forall i$ we compute the characteristic equation of the matrix $\bar{A}_{ii}$ as follows:

$$\begin{aligned} \det\Big(\lambda \mathrm{I}_{3\times 3} - \bar{\mathrm{A}}_{\mathrm{ii}}\Big) = \lambda^3 &+ \Big(b_i(\Delta_i + 1)K_D - \omega_i\Big)\lambda^2 \\ &+ \Big(b_i(\Delta_i + 1)K_P\Big)\lambda + b_i(\Delta_i + 1)K_I \end{aligned} \tag{26}$$

being Δ_i defined in Section 2.2.

Applying Routh-Hurwitz criterion (Franklin et al., 1994) it is possible to find the value of the control gains guaranteeing that $\bar{A}_{ii}$ is Hurwitz stable, i.e.

$$\begin{aligned} &K_D > \frac{\omega_i}{b_i(\Delta_i + 1)} \\ &b_i(\Delta_i + 1)K_I > 0 \\ &K_P > \frac{K_I}{b_i(\Delta_i + 1)K_D - \omega_i}. \end{aligned} \tag{27}$$

Therefore, to guarantee that each $\bar{A}_{ii}$ ($\forall i = 1, \cdots, N$) is Hurwitz stable, hence guaranteeing $\dot{V}(\bar{x}(t)) < 0$ it suffices to select control gains as follows:

$$\begin{aligned} &K_D > \max_i \left\{ \frac{\omega_i}{b_i(\Delta_i + 1)} \right\} \\ &K_I > 0 \\ &K_P > \max_i \left\{ \frac{K_I}{b_i(\Delta_i + 1)K_D - \omega_i} \right\}. \end{aligned} \tag{28}$$

This completes the proof. □

4. NUMERICAL RESULTS

In this section, the effectiveness of the distributed PI-based consensus control strategy in (6) is validated by considering an exemplar platoon of $N = 5$ vehicles plus a leader connected through a representative Leader-Predecessor-Follower (L-P-F) topology (Zheng et al., 2014). In this case, each vehicle i can communicate with its preceding vehicle $i-1$ and with the leading vehicle 0. As consequence,

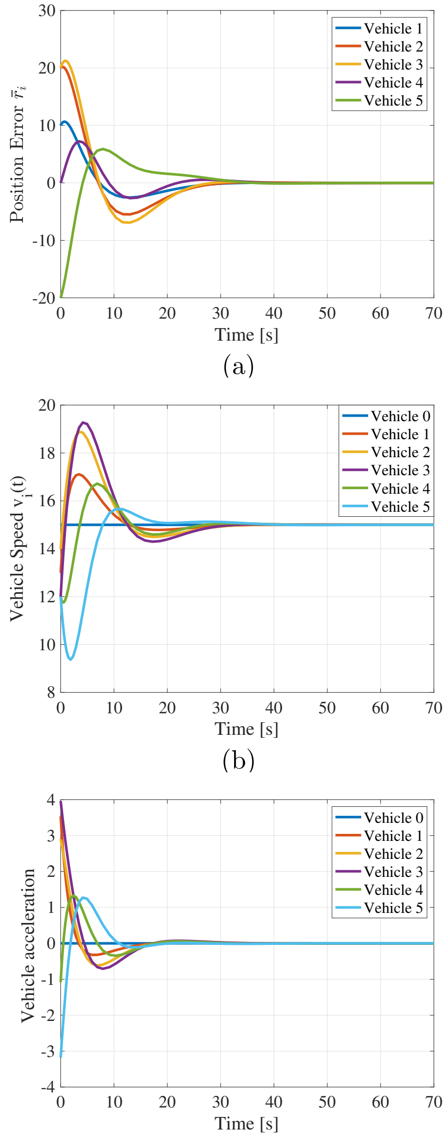
$\Delta_i = 1\ \forall i$. Note that, although many different communication topologies may arise for platooning, according to the V2V paradigm, the appraised L-P-F structure has been chosen as meaningful illustrative case study since it is very common in the technical automotive literature (see i.e. (Zheng et al., 2014; Petrillo et al., 2018b) and references therein). The numerical analysis have been performed by exploiting the MATLAB© platform and simulation parameters are reported in Table 1. Results are related to an illustrative leader tracking maneuver, where the leader moves with a constant speed of 15 $[m/s]$. With this kind of vehicles speed, Condition 1 is satisfied by selecting $\omega_i = 3$. The PI control gains are tuned as $K_I = 10$, $K_P = 100$ and $K_D = 400$, according to Theorem 1. Results in Fig.2 confirm the theoretical derivation showing the ability of the proposed distributed robust PI control in guaranteeing that each heterogeneous and nonlinear vehicle tracks the leader behavior (see Fig.2(b), Fig.2(c)) while keeping the desired inter-vehicular distance $d_{ij} = 20\ [m]$ (see Fig.2(a)). Similar results have been obtained for the other communication topologies under investigation (i.e. P-F, L-P-F, B-L-F) and, hence, they are here omitted for sake of brevity.

Table 1. Traffic Simulation Parameters

Vehicle mass $m_i\ [kg]$	$m_0 = 1500,\ m_1 = 1445$ $m_2 = 1550,\ m_3 = 1450$ $m_4 = 1400,\ m_5 = 1600$
Vehicle mechanical efficiency η_i	$\eta_0 = 0.85,\ \eta_1 = 0.80$ $\eta_2 = 0.82,\ \eta_3 = 0.87$ $\eta_4 = 0.83,\ \eta_5 = 0.81$
Vehicle aerodynamic coefficient $C_{A,i}\ [kg/m]$	$C_{A,0} = 0.43,\ C_{A,1} = 0.41$ $C_{A,2} = 0.42,\ C_{A,3} = 0.44$ $C_{A,4} = 0.47,\ C_{A,5} = 0.46$
Vehicle wheel radius $R_i\ [m]$	$R_0 = 0.28,\ R_1 = 0.285$ $R_2 = 0.29,\ R_3 = 0.275$ $R_4 = 0.281,\ R_5 = 0.278$
Vehicle rolling resistance $f_i\ [m]$	$f_0 = 0.02,\ f_1 = 0.022$ $f_2 = 0.019,\ f_3 = 0.021$ $f_4 = 0.023,\ f_5 = 0.024$
Vehicles max acceleration $[ms^{-2}]$	4
Vehicles max deceleration $[ms^{-2}]$	-5
Desired spacing policy d_{ij}	$20\ [m]$
Initial position $[p_0(0), \cdots, p_5(0)]^\top\ [m]$	$[280, 250, 220, 190, 170, 140]^\top$
Initial speed $[v_0(0), \cdots, v_5(0)]^\top\ [m/s]$	$[15, 13, 14, 12, 11, 13]^\top$

4.1 Robustness w.r.t. Parameters Uncertainties

Here we test the effectiveness of the proposed controller in counteracting mismatched uncertainties in vehicle model parameters by considering variations of 10% of m_i, $C_{A,i}$, f_i, η_i $(\forall i)$ w.r.t. nominal parameters reported in Table 1. In this uncertain scenario, we aim at comparing the performances of our controller with the ones achievable with a typical consensus-based strategy that also leverages a feed forward compensation of vehicle model nonlinerities (Li et al., 2015). Comparison results are disclosed in Figure 3, where it possible to observe how the proposed PI control (Figure 3(b)) outperforms the typical consensus-based control with feed-forward action (Figure 3(a)) still guaranteeing zero position error in the presence of unknown parameters uncertainties. Notice that the proposed PI deals with platoon uncertainties and nonlinear dynamics without requiring any compensation or parameter/variable measurement/estimation.

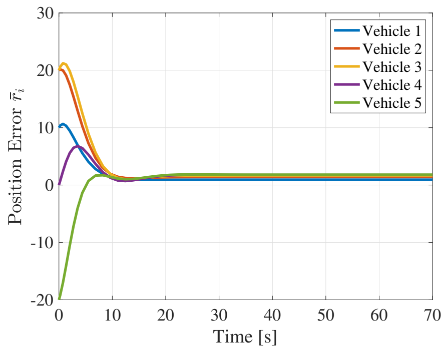


(c)

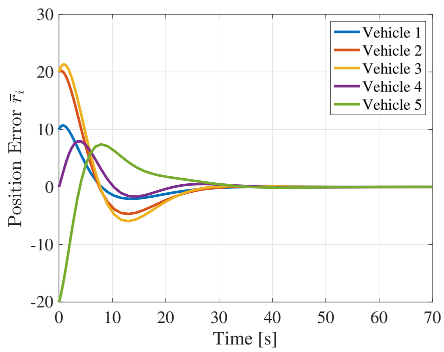
Fig. 2. Leader tracking performance under the distributed PI control in (6). Time history of: a) inter-vehicle distances $p_i(t) - p_0(t) - d_{i0}$ $(i = 1, 2, 3, 4, 5)$; b) vehicles speed $v_i(t)$ $(i = 0, 1, 2, 3, 4, 5)$; c) vehicles acceleration $a_i(t)$ $(i = 0, 1, 2, 3, 4, 5)$.

5. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a fully-distributed PI-based control protocol to automatically drive a platoon of vehicles tracking the leader velocity, while maintaining a pre-fixed spacing policy. The proposed approach allows to deal with realistic road scenarios where platoons are heterogeneous, i.e. the vehicles are different and/or affected by mismatched uncertainties in both parameters and nonlinear drivetrain dynamics. Indeed, the distributed PI protocol intrinsically compensates for these nonlinear and heterogeneous drivetrain dynamics without requiring



(a)



(b)

Fig. 3. Comparison among the proposed distributed PI control in (6) and the consensus-based control strategy with feed forward compensation action. Time history of: a) $\bar{r}_i(t)$ $(i = 1, 2, 3, 4, 5)$ under consensus-based strategy; b) $\bar{r}_i(t)$ $(i = 1, 2, 3, 4, 5)$ under the proposed PI control strategy.

any feed-forward control action, as instead proposed in the recent technical literature. Sufficient conditions for the closed-loop heterogeneous nonlinear vehicular network stability and for tuning PI control gains are provided. Simulation results confirm the effectiveness of the control design in both nominal and uncertain platooning scenario. Ongoing work is devoted to extend our analysis by also considering external disturbances acting on the vehicle dynamics and/or the presence of communication impairments among connected vesicles, such as time-varying communication delays.

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