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Design and experimental Validation of an H_∞ Adaptive Cruise Control for a Scaled Car ^{*}

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Abstract. Adaptive Cruise Control algorithms have been developed as a consequence of recent advances in automobile technology, such as sensors and on-board processing, which increase both comfort and safety. Through this paper, a longitudinal dynamic model is identified based on a collected experimental data. Moreover, the H_∞ concept is used to design a controller to regulate the longitudinal behavior of an autonomous scaled car while ensuring the safety distance between vehicles to avoid collision. The H_∞ control design is based on solving an optimization problem with guaranteed performances. The proposed approach is then implemented and experimentally validated on a real scaled car.

Keywords: Adaptive Cruise Control, Autonomous Vehicles, H_∞ control

1 Introduction

In the last decade, self-driving cars have become a popular topic of research. Intelligent and autonomous vehicles are at the heart of the societal concerns of future transportation. These cars, equipped with numerous sensors and actuators, will enhance road safety, streamline traffic, make transportation more accessible to people with disabilities, and participate in the development of new modes of transportation. Multi-objective speed control of automated vehicles has already been studied considering energy efficiency, fuel consumption and traveling time. One of the main studies is the design of Adaptive Cruise Control (*ACC*) strategies for automated car-following. Recent results have proposed new spacing policies and new control architecture to decrease the time gap between vehicles, while ensuring the string stability [1]-[2]. Concerning the cruise control performances, the speed control algorithm [3]-[4] has been augmented to enhance road stability and safety of the vehicle, see [5]. Moreover, the impact of the look-ahead cruise control on the traffic flow has also been analysed and a parameter-dependent model has been presented to consider traffic flow in the velocity trajectory design, see [4]. Hence, the design of a longitudinal control strategy becomes challenging.

The objective of the Cruise Control is to track the desired speed provided by the driver. *ACC* systems are an extension of conventional cruise control (*CCC*) systems that adjust vehicle velocity and provide a specified distance to the preceding vehicle by automatically controlling the throttle and/or the brake [6]. They rely on numerous number of sensors, i.e LiDAR, Camera, Radar... Their role is not only to control vehicle speed, but also to maintain a safety distance with the

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preceding vehicle, which is known as a gap distance, while ensuring the string stability in car platooning. *ACC* with the Stop&Go system offered by the Advanced Driver Assistance System (*ADAS*), makes driving easier and less stressful. Several control approaches in the topic of Adaptive Cruise Control systems have been proposed. The Model Predictive Control (*MPC*) is largely and commonly used, as in [7] where a high level controller is proposed based on *MPC* approaches, taking into consideration the driver longitudinal ride comfort, driver permissible tracking range, and rear-end safety. Carlos et al, [8] developed a Fractional-Order Control (*FOC*) approach to design a feedforward structure for *ACC* to enhance the car-following while ensuring the robustness/stability. A fuzzy longitudinal control is studied in [10] to control the throttle and the braking pedal, this control approach is using (IF...THEN) conditions based on experience and experimental results. In [9], the Cooperative Adaptive Cruise Control (*CACC*) is considered, it is the extend of the *ACC* by enabling the wireless communication between vehicles (*V2V*) to control the time gap. An H_∞ Linear Parameter Varying (*LPV*) approach is used to deal with the variations of the time headway while ensuring the convergence of the spacing errors towards zero and the attenuation of any disturbance propagating along the platoon.

This work considers the H_∞ concept to achieve stabilization with guaranteed performance. First, it is used to design the *CC* aiming to track the desired speed. Then an *ACC* H_∞ control strategy is synthesized aiming to follow the preceding vehicle by achieving the desired relative distance with the smallest time headway and standstill distance. Then, both controllers are simulated and experimentally validated on a scaled car.

This paper is organized as follows: Section II a detailed overview of the studied platform, the electronic components and the car body, Section III describes the longitudinal vehicle dynamics of the scaled car. The control structures and the H_∞ controllers are designed in Section IV for the Cruise Control and Adaptive Cruise Control respectively, in addition to the spacing policy. Sections V and VI are devoted for simulation and experimental results respectively. The conclusions with some suggestions and future works are presented in Section VII.

2 Platform Design and Hardware Parts

This section introduces a detailed overview of the studied platform concerning its hardwares and softwares. The vehicle body consists of DFRobot GPX RWD ROB0165 Smart Robot Brushless Motor Racing Car, it is a racing platform mounted with two brushless motors, a front servo-motor and a spring suspension allowing a more stable driving. Furthermore, the car has bumpers on both sides, the front and the back to protect it from damage as shown in **Fig.1**.

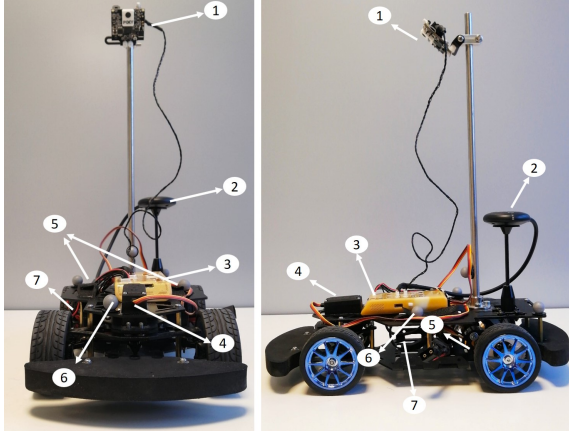


Fig. 1: Front and Side view of Car Components.

#	Part	Function
1	Pixy 2 CMUcam5	Barcodes Detection
2	GPS HolyBro Pixhawk 4	Turn on/off the rover
3	NXP RDDRONE-FMUK66	Process the data
4	MG996R Servo	For Steering
5	2122/13T BLDC	Throttle
6	8mm Qualisys markers	To track the car position
7	ACCU NI-MH 3000 mAh	Power Supply

Table 1: Represents the hardwares equipped to the platform.

The main components are briefly described below:

Pixy2 Camera : The Pixy2 camera allows the detection and reading of the "road signs" by the barcode detection capabilities using the line tracking mode, which is used later for velocity reference generation.

External Camera and Track : The platform RobotMe at Gipsa-LAB is equipped with a 8 external motion capture camera systems. Those cameras, by Qualysis, have a 3D tracking for each marker (*see Fig.1*) attached to the car offering localization for all 6 degrees of freedom (3 for position, 3 for rotation) at a rate of 100Hz. This system allows measuring the car's position and velocity at each instant, although its data is not available in real-time, so it is used for the model identification and to check the feasibility of the implemented *ACC*.

Processor Framework : For this project, a PX4 Robotic Drone FMU (fmuk66) is used to control the autonomous car. This board is designed for applications that need high memory densities with low power consumption. It guides and controls the vehicle's navigation as well as its real-time reaction to its surroundings and track. In addition to the feature that comes with the PX4, which allows to log on SD card, a new topic is created to extract the needed data that will be used in the next section to identify the car's longitudinal dynamic model.

3 Longitudinal Vehicle Dynamics

This section presents the proposed methodology to get an *LTI* model relating the longitudinal velocity with the *PWM* input to the brushless motors. It also explains the battery effects on the system dynamics.

3.1 Preprocess the Data

As discussed in **section 2**, the car motion and position can be captured by the Qualisys motion system. The longitudinal velocity is given in global coordinates and transformed to body frame

using the following relation:

$$v_B = R \cdot v_I, \quad (1)$$

where v_B is the linear velocity in body frame, R the rotation matrix and v_I the linear velocity in inertial frame.

The PWM values are extracted on a SD card with a varying sampling time that varies depending on the computation time at each instant. The information from the camera and SD are captured at different frequencies, so to overcome this problem both signals are first modified as follows:

$$x_{scaled} = \frac{x_i - \mu(x_i)}{\sigma(x_i)}, \quad (2)$$

where x_i the signal, μ the signal's mean value and σ its standard deviation.

Then, by tuning the index of the longitudinal velocity V_x extracted from the external camera and by interpolating it with the PWM signal using the variable time step from the microcontroller, the two signals are now synchronized.

For the upcoming sections, all the models are identified with a PWM ranging between $[-500]$ and $[500]$ corresponding to minimum and maximum value of $[976]$ and $[1976]$ on the real system, these intervals are the ones defining the operating conditions.

3.2 Longitudinal Dynamic Model

This subsection focuses on the modelling part of the longitudinal vehicle dynamics. Vehicle modeling is difficult due to its nonlinearities and uncertainties, as well as the fact that it must take into account several dynamic components that interact with one another (motors, tire model, frictions...). In [8], the authors have proposed a second-order transfer function to identify the longitudinal dynamics. In this section a first order system model is selected. Under the assumption of no slipping and negligible friction, the following simple linear regression allows to map the PWM to the wheel/vehicle speed :

$$V_x = p_1 \cdot PWM + p_2, \quad (3)$$

where p_1 is the slope of the estimated linear equation seen in **Fig.2** and p_2 the V_x -intercept, represents the intersection between the linear equation and the y-axis, while ensuring that $p_2 = 0$.

Now, in order to model the system dynamics, the following first order system is proposed:

$$G(s) = \frac{K}{Ts + 1}, \quad (4)$$

where T represents the time constant of the system and K the gain represents the slope of the estimated linear regression. The time constant is estimated as $T = 0.4s$ from the main dynamics using a step response of the car.

The battery voltage and state of charge have a large effect on the vehicle longitudinal dynamics. We then carried out several experimental tests with different batteries, at different voltages. We here consider a 80% battery state of charge to get the data for system identification. After synchronizing the two data (the velocity captured by the cameras and the PWM logged in the SD) and extracting the linear velocity corresponding to their PWM values and referring to **Figs.2** and **3**, the estimated linear model is validated, as the two slopes and linear estimations are very similar.

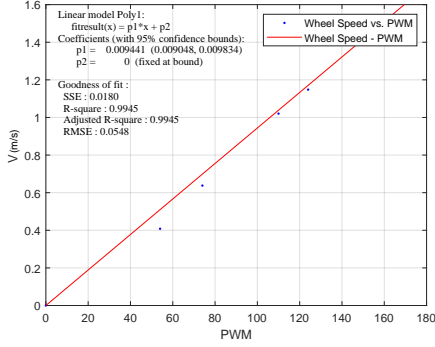


Fig. 2: Mapping Wheel Speed to PWM.

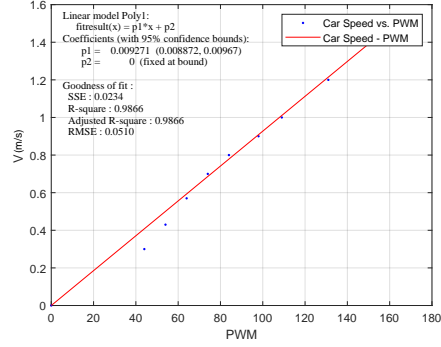


Fig. 3: Mapping Car Speed to PWM.

4 Adaptive Cruise Control in H_∞ Control Frame

Adaptive Cruise Control system is an extension of the Cruise Control. Its goal is to control the car's longitudinal motion, such as its longitudinal velocity, acceleration, or longitudinal distance from another preceding vehicle in the same lane. The considered design method here is the H_∞ control approach for which technical details can be found in [11].

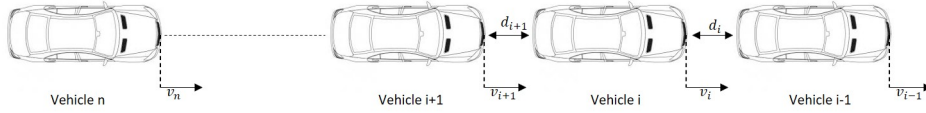


Fig. 4: Scheme of Adaptive Cruise Control.

4.1 Spacing Policy

The Adaptive Cruise Control system is based on the spacing policy. It is defined as the optimal spacing that a vehicle attempts to maintain with respect to its preceding. As shown in **Fig.4**, the relative inter-vehicle distance value is d_i , this value is based on the look ahead relative distance between both vehicles, it is also called velocity-dependent spacing policy.

In this paper, the constant time-headway policy is considered, to follow the leading vehicle (i) with a desired relative distance defined as :

$$d_{r,i} = d_{0,i} + hv_i, \quad 1 \leq i \leq n \quad (5)$$

where $d_{r,i}$ is the desired safety distance between the two vehicles, represents the desired relative distance between the rear bumper of the vehicle $x_{r,i-1}$ and the front bumper of the following vehicle $x_{f,i}$, $d_{0,i}$ the standstill distance equal to $0.1m$, h is the desired time headway equal to $0.2s$, represents

the time that the following vehicle needs to reach the same position as its preceding, and v_i the longitudinal velocity of the (i th) vehicle.

The relative distance is defined as follows:

$$d_i = x_{r,i-1} - x_{f,i} \quad (6)$$

Finally, the spacing error represents the relative difference between the relative distance and the desired relative distance between vehicles, and it is defined as follows:

$$e_i = d_{r,i} - d_i = x_{r,i-1} - x_{f,i} - d_{0,i} - hv_i \quad (7)$$

4.2 CC and ACC problems definition

The Cruise Control and Adaptive Cruise Control problems are represented as in **Figs.5** and **6** below.

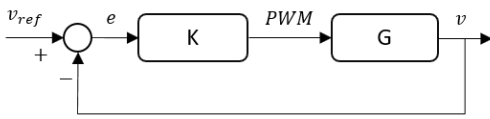


Fig. 5: Control Structure for Cruise Control.

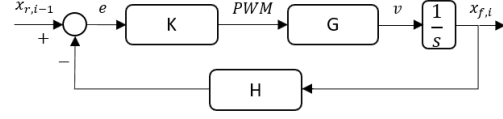


Fig. 6: Control Structure for Adaptive Cruise Control.

The lower-level controller K is responsible to regulate the throttle-accelerator to correctly maintain a desired speed chosen by the driver without any outside interference in the CC framework. However, in the ACC its objective is to follow the preceding vehicle at a desired relative distance while ensuring the inter-vehicle safety distance. In a real car, this distance is calculated using a look forward sensors i.e radar, LiDAR.

In the CC/ACC framework the aim is to ensure a good tracking with zero steady state error, fast rise time, small overshoot and above all, the comfort and maintaining the stability of the system. The aim of this controller is to ensure a convergence towards zero of the spacing error (7), which expresses the difference between the relative distance and the desired relative distance. To meet that requirement an integrator is added at the output of the longitudinal model (as the longitudinal dynamical model of the vehicle (4) relates the longitudinal velocity to the PWM input) in order to get the instant position of the vehicle, as seen in **Fig.6**.

Finally the transfer function of the velocity-dependent spacing policy is written as :

$$H_i(s) = hs + 1 \quad 1 \leq i \leq n \quad (8)$$

4.3 CC and ACC H_∞ Control Problems

To reach the objectives an H_∞ approach is used to control the longitudinal motion of the vehicle. The aim of this approach is to synthesize a controller K that minimizes the H_∞ norm of the closed loop system (between the external inputs w to the controlled outputs z), as:

$$\|T_{wz}(s)\|_\infty \leq \gamma \quad (9)$$

where γ is the best achieved H_∞ norm of the closed-loop system $T_{wz}(s)$.

The performance specifications are formulated through weighting functions on the closed-loop system. We will follow here a method similar to [12] for the *ACC* case, with slight modifications on the weighting functions. Therefore we have selected W_e for the tracking error and W_u for the actuator limitations, as given in the new control scheme as shown in **Figs.7a** and **7b** for Cruise Control and Adaptive Cruise Control respectively.

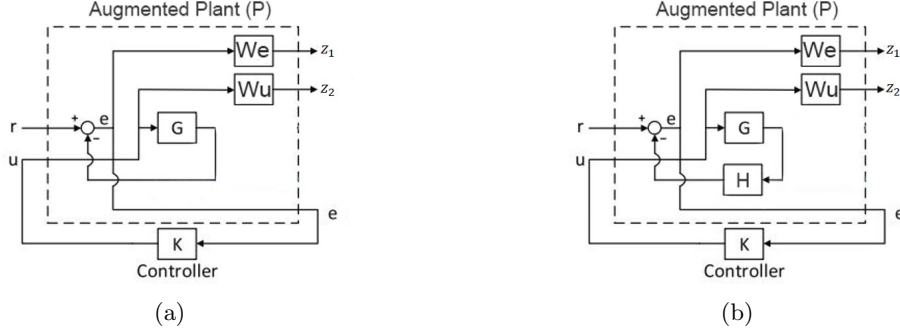


Fig. 7: Closed loop system for CC (a) and ACC (b).

The augmented plant P encompasses the model of the system to be controlled plus the performance weights, which has two inputs and three outputs as shown in **Figs.7a** and **7b**: r the exogenous input, u the control input of the plant, z_1 and z_2 the two exogenous outputs and e the controller input.

The first weighting function, W_e , is chosen to ensure a good robustness margin, small steady state error and fast tracking of the reference with respects to actuators time response, which is represented by :

$$W_e = \frac{s}{\frac{M_s}{s + \omega_b \varepsilon} + \omega_b} \quad (10)$$

where M_s , ω_b and ε parameters to be tuned to meet the requirements as follows:

- $M_s = 2$, to ensure sufficient module margin,
- $\omega_b = 8$ rads, to ensure a fast tracking of the reference with respect to the actuator bandwidth,
- $\varepsilon \leq 1e^{-4}$, to have a small steady state error.

On the other hand, the second weighting functions, W_u , are chosen in a way to minimize the actuator control effort, while ensuring a good noise rejections from the inputs and fixing the maximum allowed variations control efforts of the actuators, they are represented as follows:

$$W_u = \frac{s + \frac{\omega_{bc}}{M_u}}{\varepsilon_1 s + \omega_{bc}} \quad (11)$$

where M_u , ω_{bc} and ε_1 parameters to be tuned to meet the requirements as follows:

- M_u , represents the maximum variation of the reference with respect to the input,
- ω_{bc} is related to the actuator bandwidth,
- $\varepsilon_1 \leq 1e^{-2}$, to have a good noise rejection from the control inputs at high frequencies.

For the Cruise Control case, the parameter M_u represents the maximum variations of the input (PWM) over the maximum variations of the reference (v_{ref}), it is equal to 250. In order to meet the new requirements, as in the *ACC* the reference is the leading vehicle position, the parameter M_u is modified and it is equal to 625. The parameter ε in the error weighting function is tuned as well, to have a very low steady state error at low frequency, it is less or equal to $1e^{-5}$.

4.4 Frequency Domain Analysis for *CC* and *ACC*

The controller performances are now analysed in frequency-domain in order to determine whether the controllers satisfy the requirements or not. The input/output performances are defined by different sensitivity functions as shown in **Figs.8a** and **8b**. It can be seen that the sensitivity functions $S = \frac{e}{v_{ref}}$ and $KSr = \frac{PWM}{v_{ref}}$ globally meet the requirements since they are below the templates with $\gamma = 0.78$ for Cruise Control and, with a very small overpass of the template for KSr in Adaptive Cruise Control (where $\gamma = 1.48$). The control input analysis is carried out to study

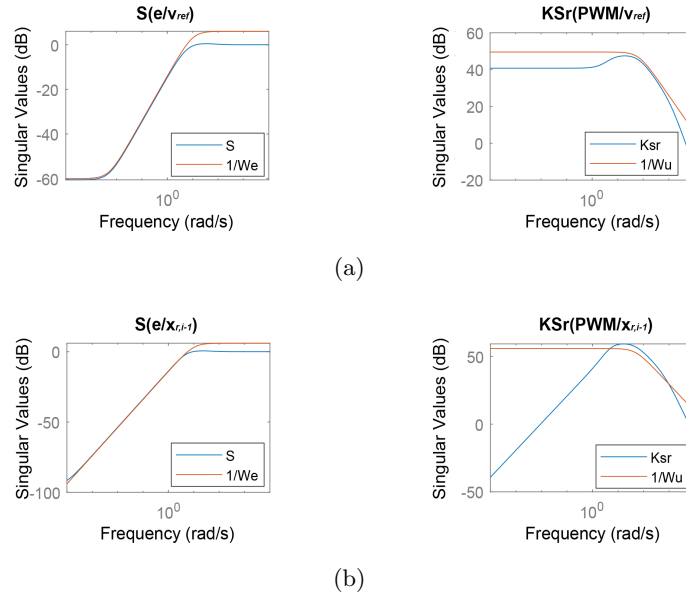


Fig. 8: Frequency domain response of the H_∞ control for the *CC* (a) and *ACC* (b).

the behavior of the controllers at low and high frequencies. Referring to KSr shown in **Fig.8a** and **8b**, there is a low risk of actuators saturation and good noise attenuation at the control input. The different sensitivity functions meet the requirements with a small steady state error, good noise and disturbance rejections while ensuring a good module margin and fast time response of the system, despite the small overpass shown in the controller sensitivity KS in *ACC* case.

5 Simulation Results

The Matlab simulations are carried out using the *LTI* first order longitudinal dynamical model (4) in discrete-time domain with a sampling time $T_s = 0.03s$.

Remark 1. The sampling time is chosen based on the mean value of the variable time step exported directly from the micro-controller.

To test the longitudinal control performance for the Stop&Go mode which includes the Cruise Control (*CC*) and the Adaptive Cruise Control (*ACC*) systems, using the *LTI* controllers calculated in section 4.3, two scenarios are considered as follows:

Scenario 1 : Test the Cruise Control system

Referring to **Fig.9**, as emphasized before in the frequency-domain analysis the *LTI* controller

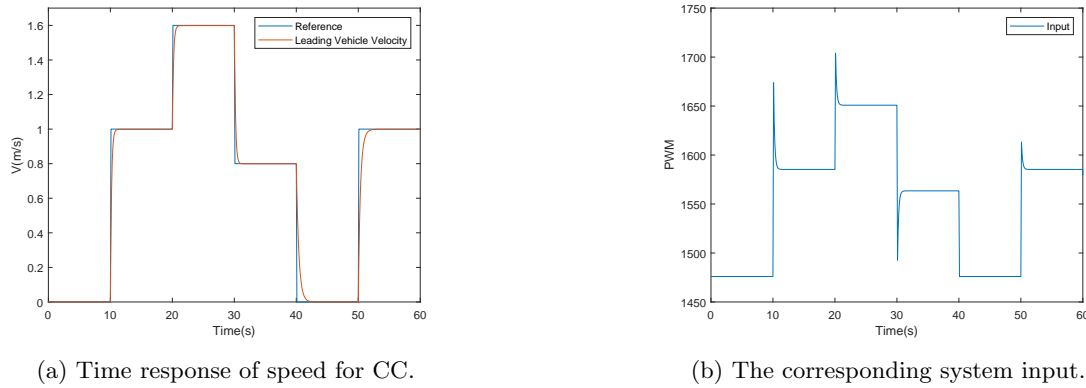


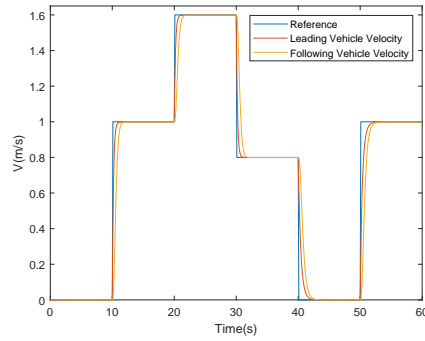
Fig. 9: Simulation of the Cruise Control system.

satisfies the requirements with a small steady error and fast time response without any overshoot. Taking into consideration the same generated reference velocity, the adaptive cruise control system is tested in the second scenario.

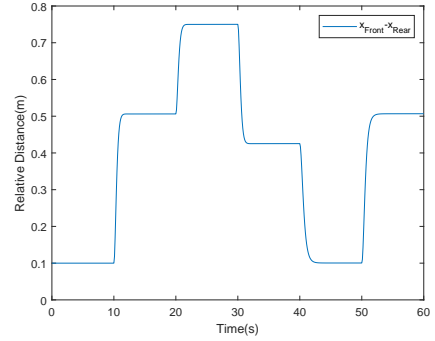
Scenario 2 : Follow the preceding vehicle starting from stationary state and with relative distance equal to $0.1m$ (*ACC*).

The leading vehicle is simulated using the *CC* system, and the following vehicle using the *ACC* system in order to follow its preceding at a inter-vehicle safety distance. Referring to **Fig.10a**, the proposed controller showed satisfactory results since there is a fast tracking to the generated reference, with a very small steady state error and no overshoot. As discussed in the subsection 4.1, the spacing policy is called velocity-dependent spacing policy as well, since its transfer function (8) depends on the following vehicle velocity. The relative safety distance is represented in **Fig.10b**, it is clear that for each vehicle speed there is a different inter-vehicle distance.

The next section will address the implementation of the developed controllers on a real scaled vehicle.



(a) Time response of speed for ACC.



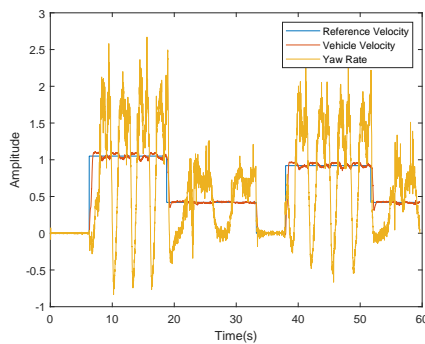
(b) The relative distance between vehicles.

Fig. 10: Simulation results for ACC with square leading vehicle velocity profile.

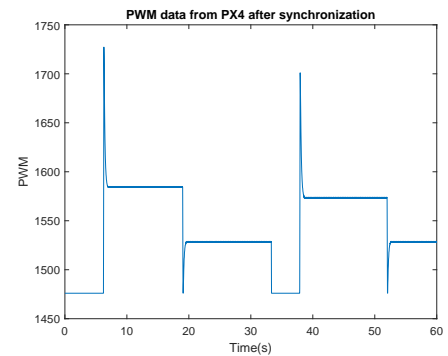
6 Experimental Results

To assess the performances of the proposed longitudinal control methods, some experimental tests have been carried out on the real scaled car.

After implementing the discrete identified model with its relevant H_∞ controller for the Stop&Go scenario on the pixhawk microcontroller board, the cruise control system with the signs detection is tested in a zero-loop test-track. This test-track is challenging due to the different existing scenarios: slowing down, speeding up, staying between the center lanes using the lateral control, which the car came equipped with.



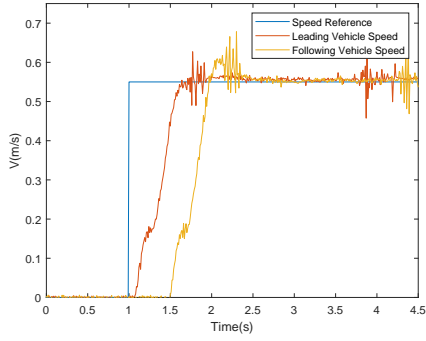
(a) Time domain response of CC.
(Yaw Rate (rad/s), Velocity(m/s))



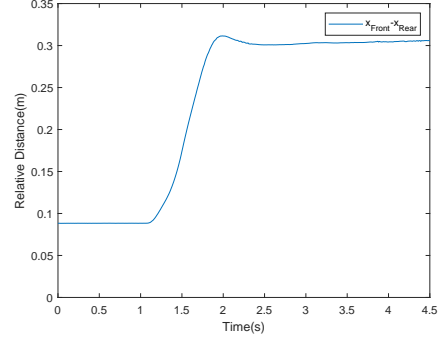
(b) The corresponding System input after synchronization.

Fig. 11: CC System's experimental results for different velocities generated by the "road signs" detection.

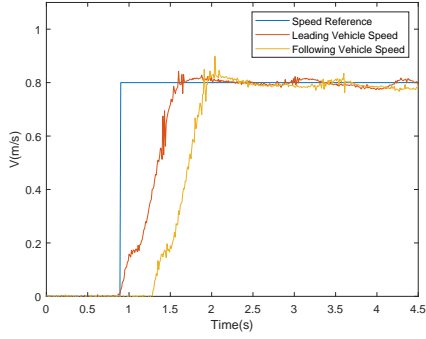
As a result, **Figs.11a** and **11b** corresponds to the first scenario (speed tracking). The proposed H_∞ controller shows satisfactory results with fast tracking performance, without any overshoot and zero steady state error. These shown oscillations are due to the two sharp turns in the track (which induces a coupling between longitudinal and lateral dynamics), and to the conversion from global frame to local frame in addition to the external camera data noises.



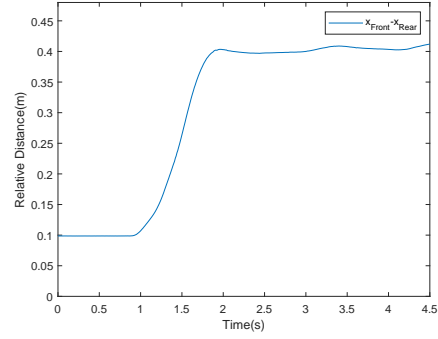
(a) Time domain response of ACC.



(b) Relative Distance between Vehicles.



(c) Time domain response of ACC.



(d) Relative Distance between Vehicles.

Fig. 12: Experimental validation of the ACC by simulating a virtual leading car using the CC.

Now, for the second scenario, corresponding to the Stop&Go mode, the *ACC* system is tested on a straight lane (to avoid any oscillation due to the lateral motion and for the sake of clarity and accuracy). Referring to **Figs.(12a,12b)** and **(12c,12d)**, for the reference velocity $v_{ref} = 0.55m/s$ and $v_{ref} = 0.8m/s$ respectively, there is a fast tracking of the preceding vehicle with a coherent relative inter-vehicle distance, despite the small overshoot in the first case. The proposed H_∞ controllers show very promising results while satisfying the requirements cited before.

7 Conclusions

In this paper, we have proposed and experimentally validated the longitudinal control of autonomous vehicles in *CC* and *ACC* using an H_∞ approach. The proposed controllers meet the physical specifications and limitations, thanks to the tuning parameters set in the frequency-domain.

The comparison revealed that the experimental controller's behavior for the *ACC* problem is consistent with theory. Both controllers presented were able to handle multiple objectives starting safety, speed regulation and fast time response.

Future works may concern the use and validation of an *LPV* control approach to handle the variations of the time-headway online set by the driver, in particular in the Cooperative Adaptive Cruise Control *CACC* case, which takes into consideration the inter-communication delay between vehicles [9].

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