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# Design of Passivity-Based Controllers for Lateral Dynamics of Intelligent Vehicles

Gilles Tagne, Reine Talj and Ali Charara

**Abstract**—This paper deals with the lateral control of intelligent vehicles. It is based on the passivity results presented recently in [1]. It shows how the intrinsic properties of the lateral dynamics can be used to design robust controllers for tracking of a reference trajectory. The additional passivity properties proved in this paper allow to theoretically explain some previous results in the literature. Then a PI controller based on the state feedback of passive outputs is proposed. Simulation validation was performed using real data representing common driving situations. Data acquisition has been made using the vehicle DYNA of Heudiasyc laboratory. This validation serves to highlight the improvement provided by the proposed approach.

## I. INTRODUCTION

Several contests such as the DARPA (Defense Advanced Research Projects Agency) Challenges in the USA [2]; the Korean Autonomous Vehicle Competitions (AVC) and many others have been organized worldwide to favor the development of autonomous intelligent vehicles. The establishment of these vehicles would give rise to various advantages which will diminish road accidents. An autonomous system is indeed more reliable and speedy to react than human drivers. It is important to notice that the driver's mistakes contribute entirely or partially to nearly 90% of road accidents. As result, various research laboratories and firms are progressively stimulated by the development of autonomous driving applications. Some examples can be seen in [3] and [4]. This research field is in expansion and one of the current major defiance is to warrant a high speed autonomous driving.

An autonomous navigation can be completed in three mandatory steps: the perception and localization, the path planning and the control. The vehicle control can be divided into two tasks: longitudinal control and lateral control. The objective of this paper is the lateral control of intelligent vehicles, which is a very active research field that has been studied since the 1950s.

Lateral control consists on automatically handling the vehicle using the steering wheel to track the reference trajectory. Considering the high nonlinearity of the vehicle on one hand, and the uncertainties and disturbances in automotive applications on the other hand, robustness can be considered

as a key issue in control design. The controller should be able to dismiss disturbances and handle parameter's uncertainties and variations.

Lately, significant research has been carried out to provide lateral guidance of autonomous vehicles. In literature, several control strategies have been developed. [5] and [6] have proposed a simple PID controller. We also have a nested one in [7]. Furthermore, other classical approaches have been used such as: state feedback [8];  $H_\infty$  [9]; Lyapunov stability based control [10]; fuzzy logic [11]; fuzzy Takagi-Sugeno LQ [12]; linear quadratic approach [13]; backstepping based approach [14] and many others. Model Predictive Control (MPC) seems to be well suited to the trajectory tracking [15]. Nonetheless, the computation time of non linear MPC is the main drawback of this approach. In [16], Sliding Mode Control (SMC) has been applied. This control strategy is known for its robustness against uncertainties and its capacity to reject noises. However, its main drawback is the chattering.

Some comparisons between existing controllers can be found in the literature. In [17], a comparison is made between proportional, adaptive,  $H_\infty$  and fuzzy controllers. More recently, in [18], the authors have compared two emergency trajectory tracking controllers. In [19], continuous-time and discrete-time switched  $H_\infty$  are compared. Also, the Immersion and Invariance  $I&I$  and the SMC controllers have been compared in [20]. From all this, we can notice that it is difficult to make an objective classification, but it is clear that different results pointed out the adaptive controller's class as a very promising approach for such uncertain and nonlinear application.

Passivity is a concept that expresses a very interesting stability property of some physical systems. Indeed, passive systems are dynamical systems in which the energy exchanged is the point of interest. So, a passive system is not able to store more energy than it's been supplied; this reflects a strong stability proof. Passivity theory is a groundwork for evaluating physical systems and designing controllers using a characterization of the input-output relationship based on energy considerations. Passivity is been studied to analyze the frequency behavior to determine the passive outputs in order to control the system more easily. Therefore, passivity is found to be a way to impose robust stability by developing passivity-based controllers. This is particularly relevant in this application given the parametric variations and uncertainties (speed, curvature, road friction coefficient, etc...).

In this paper, the passivity of several input-output maps of the system has initially been proved. Then, the design of

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The authors are working at Heudiasyc Laboratory, UMR CNRS 7253, Université de Technologie de Compiègne, BP 20529, 60205 Compiègne, France  
gilles.tagne@hds.utc.fr, reine.talj@hds.utc.fr,  
ali.charara@hds.utc.fr

a control law based on the state feedback Passivity-Based Control (PBC) has been presented.

To design the controller, we assume that the vehicle is fitted with sensors and/or observers to measure yaw rate, lateral error and its derivative. To validate the control strategy, simulation was performed using real experimental data describing common driving situations. Data recovery has been performed using the vehicle DYNA of Heudiasyc laboratory.

This paper is structured as follows. Section II presents the dynamic models of the vehicle, used for control design and validation. In Section III, the controller design is developed. Section IV presents results. Finally, we conclude in Section V, with some remarks and future work directions.

## II. DYNAMIC VEHICLE MODELS

Two vehicle models are used in this work. The bicycle model for the control design is used because of its simplicity. The second one is the 4-wheels vehicle model used to validate the proposed controller in closed-loop with real data.

The controller is based on a simple and widely used dynamic bicycle model [8] (see Fig. 1). This model is used

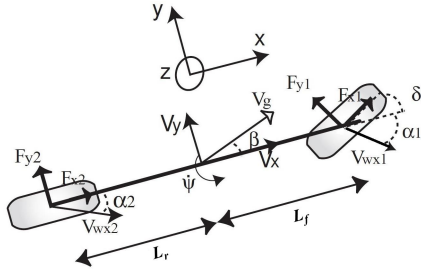


Fig. 1. Bicycle model

to represent the lateral vehicle behavior (lateral acceleration  $\dot{y}$ , yaw rate  $\dot{\psi}$ , sideslip angle  $\beta$ ). It assumes that the vehicle is symmetrical and that tire sideslip angles on the same axle are equal. The roll and pitch dynamics are neglected and angles (steering  $\delta$ , sideslip  $\beta$ , yaw  $\psi$ ) are assumed to be small. With a linear tire force model we obtain a linear parameter varying (LPV) model, where the longitudinal velocity  $V_x$  is considered as a varying parameter. Dynamic equations in terms of sideslip angle and yaw rate of the bicycle model are given by:

$$\begin{cases} \dot{\beta} = -\frac{\mu(C_f+C_r)}{mV_x}\beta - \left(1 + \frac{\mu(L_f C_f - L_r C_r)}{mV_x^2}\right)\dot{\psi} + \frac{\mu C_f}{mV_x}\delta \\ \dot{\psi} = -\frac{\mu(L_f C_f - L_r C_r)}{I_z}\beta - \frac{\mu(L_f^2 C_f + L_r^2 C_r)}{I_z V_x}\dot{\psi} + \frac{\mu L_f C_f}{I_z}\delta \end{cases} \quad (1)$$

where  $\beta$ ,  $\psi$  and  $\delta$  represent respectively the sideslip angle, the yaw angle of the vehicle and the steering wheel angle (control input). Table I presents the vehicle's parameters and nomenclature.

For simulation with real data, we used a more representative model, namely the 4-wheels model to represent the behavior of the vehicle and Dugoff's tire model for longitudinal and lateral tire forces.

TABLE I  
VEHICLE PARAMETERS AND TERMINOLOGY (BICYCLE MODEL)

Symbol	Parameter	Value	Unit
$V_x$	Longitudinal velocity	-	[m/s]
$\beta$	Sideslip angle	-	[rad]
$\dot{\psi}$	Yaw rate	-	[rad/s]
$\delta$	Steering wheel angle	-	[rad]
$\mu$	Road friction coefficient	1	-
$m$	Mass	1421	[kg]
$I_z$	Yaw moment of inertia	2570	[kgm <sup>2</sup> ]
$L_f$	Front axle-COG distance	1.195	[m]
$L_r$	Rear axle-COG distance	1.513	[m]
$C_f$	Cornering stiffness of the front tire	170550	[N/rad]
$C_r$	Cornering stiffness of the rear tire	137844	[N/rad]

## III. PBC CONTROLLER DESIGN

### A. Passivity-Based Control method

The Passivity-Based Control (PBC) was introduced in 1989 to define a control methodology that aims to make the closed-loop system (system + controller) passive [21]. These passivity properties guarantee the stability and robustness of the closed-loop system. Two approaches are used in the literature to design PBC controllers:

- Controller design, choosing an appropriate energy function which will guarantee the passivity of the closed-loop system (so that the closed-loop system is made passive by the command) [21];
- Controller design, based on the passivity properties of the system as well as the interconnection of passive systems [22].

Typically, a resistor is a passive system. A negative feedback interconnection of a resistor with all positive gains will be stable and robust against resistor variations or uncertainties. We can therefore seek the passivity as a way to impose robust stability and robustness against parameter variations and uncertainties. This is particularly relevant in applications of intelligent vehicles to ensure robust stability for high speed driving and robustness against parameter variations or uncertainties.

### B. Interconnection of passive systems

The interconnection of passive systems has been studied in the literature, particularly the re-looping and cascading.

The following corollary (corollary 4.1 in [22]) reminds a very useful property of stability of two systems on feedback interconnections.

*Corollary 1:* Considering the diagram of Fig. 2, this feedback system with finite gains is stable if either of the following statements is true:

- $S_1$  is Passive (P) and  $S_2$  is Strictly Passive (SP);
- $S_1$  is Strictly Passive (SP) and  $S_2$  is Passive.

*Corollary 2:* Considering the diagram of Fig. 3, the system resulting from this cascade interconnection is passive if one of the following statements is true (satisfied):

- $S_1$  is Passive (P) and  $S_2$  is Strictly Passive (SP);
- $S_1$  is Strictly Passive (SP) and  $S_2$  is Passive.

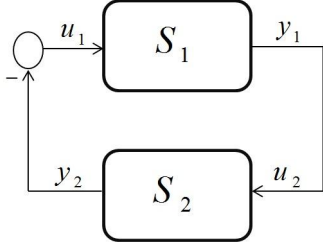


Fig. 2. Feedback interconnection of passive systems scheme

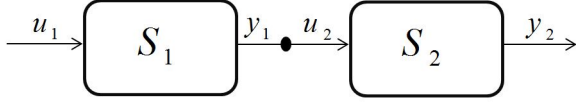


Fig. 3. Cascade interconnection of two passive systems

### C. PBC-PI controller Design

Probably the main property used in PBC for passive systems is the fact that the feedback interconnection of passive systems is passive. So passivity is invariant under negative feedback interconnection. Therefore, some passive systems can be decomposed into passive sub-systems. Thus, in this methodology, the controller can be designed as a passive system. However, it will be also useful to know that interconnections not only preserve the passivity properties of the subsystems but, in certain cases, passivity can be strengthened.

In [1], we have shown that the passivity maps of the lateral dynamics for all road coefficient of friction  $\mu = 1$  can be resumed in the Fig. 4.

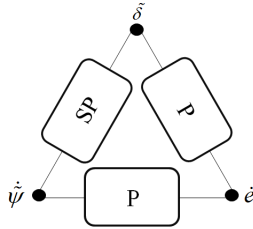


Fig. 4. Passivity maps of the lateral dynamics for  $\mu = 1$

- the yaw rate error  $\dot{\psi}$  is a strictly passive output (SP) for a steering input  $\tilde{\delta}$ ;
- the derivative of the lateral error  $\dot{e}$  is a passive output (P) for a steering input  $\tilde{\delta}$ ;
- the derivative of the lateral error  $\dot{e}$  is a passive output (P) for a yaw rate error input  $\dot{\psi}$ ;
- the sideslip angle  $\tilde{\beta}$  error is not a passive output (at high-speed) to a steering input  $\tilde{\delta}$ .

The aim of the lateral control of autonomous intelligent vehicles is to minimize the lateral displacement  $e$  and/or the yaw rate error  $\dot{\psi}$  of the vehicle with respect to a given reference path.

*Proposition 1:* Consider an output defined by:

$$z_1 = \dot{e} + \lambda_1 e \quad (2)$$

**The map  $\tilde{\delta} \rightarrow z_1$  is Passive.**

*Proof:* The proof of the passivity of  $z_1$  is established by showing that it is a cascade interconnection of two systems respectively passive  $S_1$  and strictly passive  $S_2$  (see the Corollary 2).

Consider  $H_1(s)$  the transfer function between  $\tilde{\delta}$  and  $\dot{e}$ . Hence, the transfer function  $H_{z_1}(s)$  between  $\tilde{\delta}$  and  $z_1$  can be given by the Fig. 5.

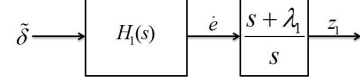


Fig. 5. Transfer function  $H_{z_1}(s)$  of the output  $z_1$

We have shown that  $S_1 = H_1$  is passive (see [1] Section 4, Proposition 2).

$$S_2(s) = \frac{s + \lambda_1}{s}$$

$S_2$  defines a Strictly Passive (SP) map; it is easy to show that [22]:

$$\Re[S_2(j\omega)] \geq \varepsilon > 0, \forall \omega \in (-\infty, +\infty)$$

So the map  $\tilde{\delta} \rightarrow z_1$  is stable and passive, what yields to the desired result. ■

This result partially explains the stability result obtained previously in the literature [23]. Indeed, we have previously developed different control approaches based on the variable  $z_1$ , and the stability obtained was robust. In fact,  $z_1$  was chosen as the sliding variable for the SMC in [16], and as the off-the-manifold variable for the *I&I* controller in [23]. Now, this passivity result explains and allows to extend our results by using this intrinsic property in Passivity-Based robust controllers for example.

*Proposition 2:* Consider an output defined by:

$$z_2 = z_1 + \lambda_2 \dot{\psi} \quad (3)$$

**The map  $\tilde{\delta} \rightarrow z_2$  is Passive.**

*Proof:* The proof of the passivity of  $z_2$  is established by showing that it is an addition of two systems respectively passive  $H_{z_1}(s)$  and strictly passive  $H_3(s)$  (the transfer function of the map  $\tilde{\delta} \rightarrow \dot{\psi}$  [1]). ■

Now, considering the Fig. 6, we can design the lateral controller with the purpose to control the lateral error  $e$  using the variable  $z_1$ , or the lateral error  $e$  and the yaw rate error  $\dot{\psi}$  simultaneously, using the variable  $z_2$ . The controller is designed to cancel the passive output  $z_1$  or  $z_2$  with respect to the reference trajectory curvature  $\rho$ . The control input is the steering angle  $\tilde{\delta}$ .

*Proposition 3:* Consider the diagram in Fig. 6, where the control is achieved by a linear PI controller, the closed-loop system is stable and passive. Indeed, the closed-loop system preserves its passivity properties necessary for high speed driving while having good performance.

*Proof:* The proof is relatively simple, the Corollary 1 allows to show it.

The map  $\tilde{\delta} \rightarrow z_1$ , respectively  $\tilde{\delta} \rightarrow z_2$ , is passive (P). So any Strictly Passive (SP) controller guarantees stability and passivity of the closed-loop system. ■

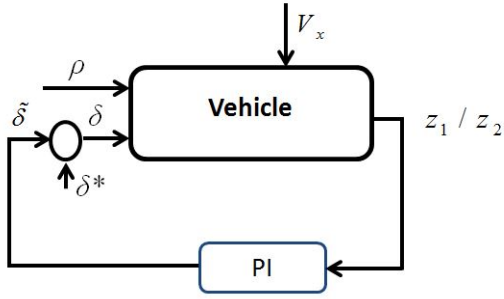


Fig. 6. PBC control strategy

In this paper, we choose a linear PI. The control input given by the PBC-PI controller is as follows:

$$\tilde{\delta}_i = -K_{I_i} \int z_i dt - K_{P_i} z_i ; i = 1, 2. \quad (4)$$

where  $K_{I_i}$  and  $K_{P_i}$  are positive gains.

Finally, the control input applied to the system is:

$$\delta_i = \tilde{\delta}_i + \delta^* = -K_{I_i} \int z_i dt - K_{P_i} z_i + (L_f + L_r) \rho + \frac{mV_x^2(L_r C_r - L_f C_f)}{\mu C_f C_r (L_f + L_r)} \rho \quad (5)$$

Given the passivity of the output  $z_1$ , respectively  $z_2$ , the closed-loop system with a strictly passive controller is stable and passive. Note that any strictly passive controller, a simple proportional for example, would achieve the same result. The addition of integral action, well known to reject constant disturbances also has the advantage of compensating the parameter uncertainties of the model in  $\delta^*$  (which depends on the uncertain model parameters). In the near future, we will develop a non-linear PI controller based on the passive output  $z_i$  to improve the performance with adaptive gains.

#### IV. SIMULATION RESULTS

Simulation validation was performed using real data representing common driving situations. For control laws, we used the following values of the gains:  $\lambda_1 = 8$ ,  $\lambda_2 = 1$ ,  $K_P = 0.2$  and  $K_I = 0.05$  for the controllers.

For the simulation, we have used the 4-wheels model to represent the behavior of the vehicle and Dugoff's tire model for longitudinal and lateral tire forces. Simulations have been performed using experimental data acquired by the DYNA vehicle (a Peugeot 308) belonging to the Heudiasyc laboratory (Fig. 7).

The experimental vehicle is equipped with several sensors: an Inertial Measurement Unit (IMU) measuring accelerations ( $x, y, z$ ) and the yaw rate, CORREVIT for measuring the sideslip angle and longitudinal velocity, torque hubs for measuring tire-road efforts and vertical loads on each tire, four laser sensors to measure the height of the chassis, GPS and a CCD camera. Data provided via the CAN bus of the vehicle were also used, including data on the steering angle and the rotational speed of the wheels.

Fig. 8 shows the scheme of validation in simulation using real data:

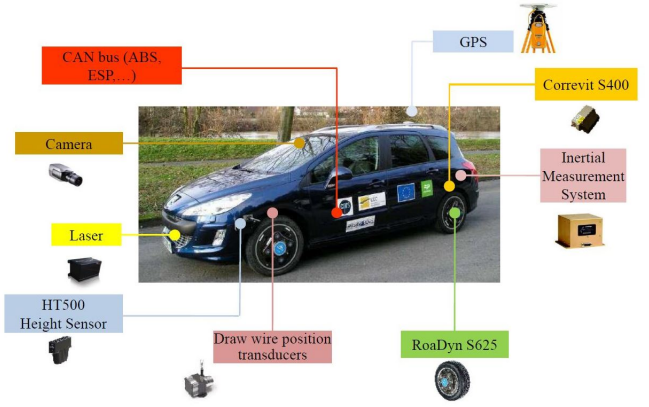


Fig. 7. Experimental vehicle (DYNA)

- The first step consists in acquiring the data. A human driver drives the experimental vehicle according to well-defined scenarios. During this step, the dynamic variables of the vehicle are stored. These actual data are used to develop the reference trajectory. Measurements of the yaw rate and lateral acceleration are used as references for computing the errors.
- The second step is to test the closed-loop controller with the full vehicle model, to follow the reference trajectory.

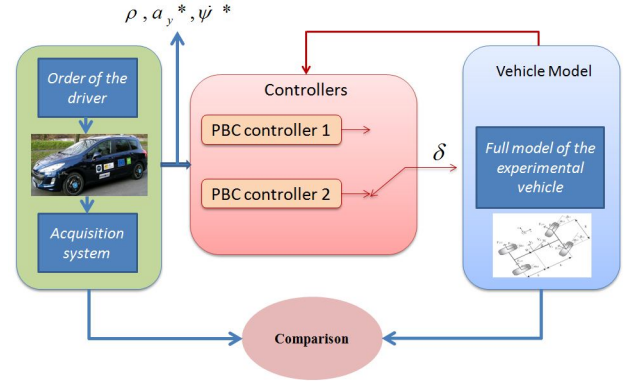


Fig. 8. Validation scheme

The experimental data used here were acquired on the CERAM<sup>1</sup> test circuits (Fig. 9).



Fig. 9. CERAM test circuit

In the test shown in Fig. 10, lateral acceleration is less than  $4m/s^2$ . Longitudinal velocity is almost constant ( $13.5m/s$ ).

<sup>1</sup>CERAM - "Centre d'Essais et de Recherche Automobile de Morte-fontaine" is an automobile testing and research center located in France.

Fig. 10-(a) shows the reference path and the paths followed by the controlled vehicle with both controllers. Fig. 10-(b) presents the longitudinal speed and errors; the lateral error and the yaw rate error.

Fig. 10-(c) presents the vehicle's dynamic variables; the steering angle, the yaw rate and the lateral acceleration. We compare real data with data given by the simulated closed-loop system. Dynamic variables are very close to measured ones. To assess the robustness of controllers with respect to

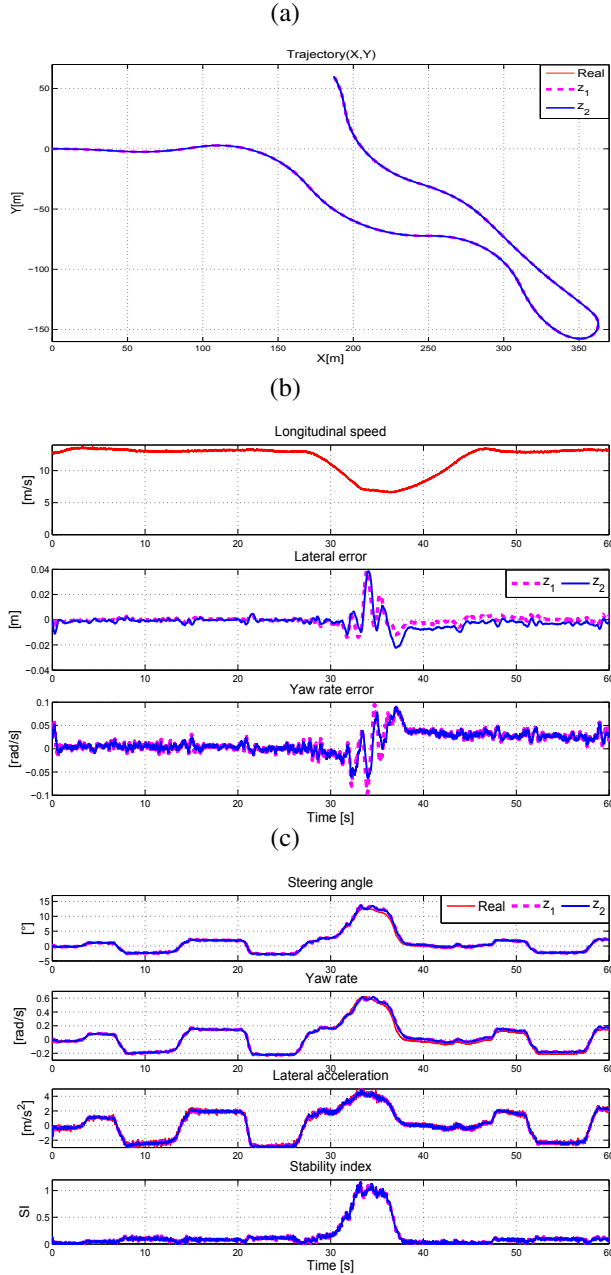


Fig. 10. Test 1: (a) Paths, (b) Longitudinal speed and errors, (c) Dynamics variables

strong nonlinearities we computed the stability index given by [24]:

$$SI = \left| \frac{1}{24} \dot{\beta} + \frac{4}{24} \beta \right| \quad (6)$$

When  $SI < 1$  the vehicle is in a stable region.

The controllers have comparable maximum errors, and ensure that the path (with variable curvature) is followed.

The test shown in Fig. 11 was carried out with the goal of verifying the robustness of the controller during normal driving at high and varying speed. We have a tight turn to test the performance of controllers for large variations in curvature and strong nonlinearities (see the stability index). Longitudinal speed varies between  $5m/s$  and  $25m/s$ . Note that the maximal lateral acceleration is  $5m/s^2$ .

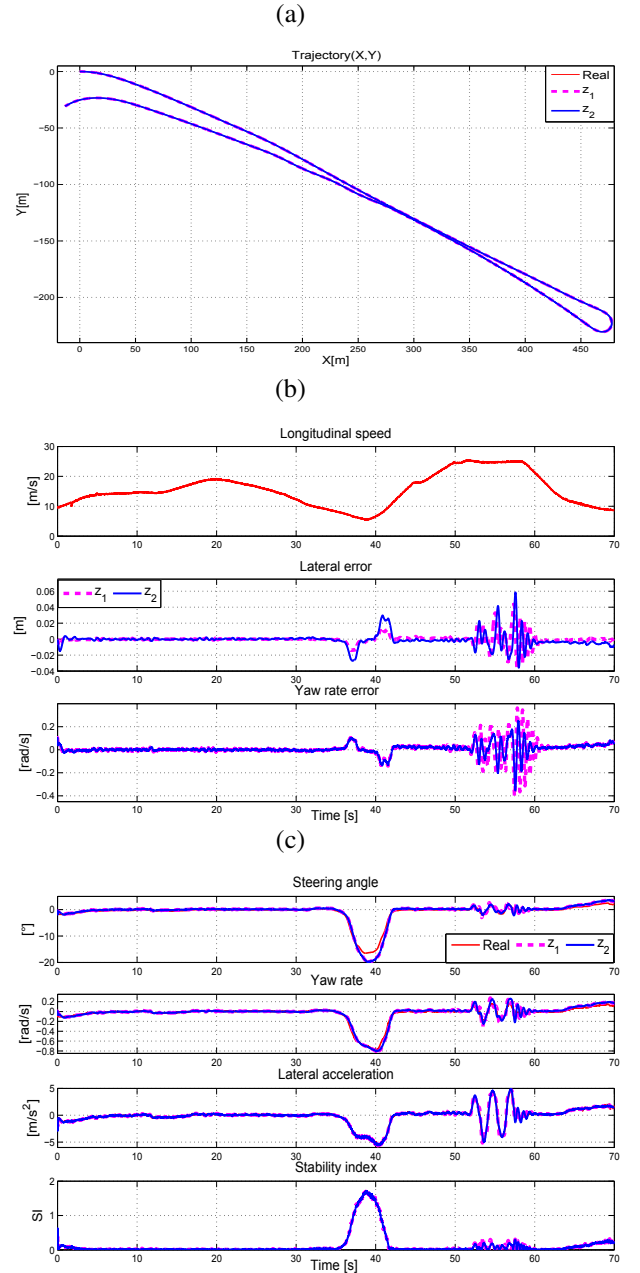


Fig. 11. Test 2: (a) Paths, (b) Longitudinal speed and errors, (c) Dynamics variables

In these two scenarios, the assumption of small angles is not respected (the steering angle is greater than 15 degrees during a bend). The controllers are nevertheless able to

follow the path with small errors. It is more difficult to control both the lateral and yaw error (under-actuated system). Indeed, the error of the PI controller using the output  $z_2$  is higher than the one using the output  $z_1$ . Both controllers are robust to variations in speed. It is important to note that during the validation the assumptions were not always respected (low angles, nonlinear forces and varying speed). Indeed, several tests soliciting the vehicle in nonlinear zones have been done ( $SI > 1$ ). However, the controller provides a robust trajectory tracking.

It is well-known that PI controllers, if suitably tuned, provide a good solution to many practical applications without requiring a detailed description of the system dynamics (when their use does not destabilize the system). In the presence of strong non-linearities, their performances can be deteriorated and it is therefore necessary to re-tune the controller or to use adaptive gains. Based on the principle presented in this paper, we will develop an adaptive version of the controller (nonlinear PI) using the passive output  $z_1$  to control the system easily.

## V. CONCLUSION

This paper has dealt with the lateral control of intelligent vehicles. Based on the passivity results presented recently in [1], we have additionally proved passivity properties of two outputs of the system commonly used in lateral control applications. In addition, we have shown how the intrinsic properties of the lateral dynamics can be used to design robust controllers for tracking of a reference trajectory. Then a PI controller based on the feedback of the passive outputs  $z_1$  and  $z_2$  is proposed. The design of the controller was presented. The controller guarantees robust stability (not depending on the value of the system parameters) and passivity of the closed-loop system.

Simulation validation was performed using real experimental data representing common driving situations. Data acquisition has been made using the vehicle DYNA of Heudiasyc laboratory. The validation has shown robustness and good performance of the proposed PBC-PI controller.

As outlook, an adaptive version of the PBC-PI controller is under study; a nonlinear PI controller will be used to improve the robustness and performance, using adaptive gains. We are also studying the properties of passivity of the lateral dynamics using a nonlinear model of tire contact forces in order to extend these results to vehicle stabilization applications.

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