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Nonlinear cascade strategy for longitudinal control in automated vehicle guidance

Rachid Attia [1], Rodolfo Orjuela *, Michel Basset

Modelling Intelligence Process and Systems (MIPS) Laboratory, EA2332 Université de Haute-Alsace, 12 rue des frères Lumière, F-68093 Mulhouse Cedex, France

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A B S T R A C T

This paper deals with automatic control design for automotive driving with a special focus on the longitudinal control. The automotive vehicle is a complex system characterised by highly nonlinear longitudinal and lateral coupled dynamics. Consequently, the control design for automated driving should deal with both of these dynamic couplings. Indeed, the longitudinal control plays an important role in the automated guidance to ensure safety and comfort of automotive passengers. In this work, a nonlinear cascade longitudinal control based on inner and outer-loops design is proposed. The lateral control is handled following a model predictive approach ensuring the automated steering of the vehicle. Finally, the nonlinear longitudinal control is integrated with the lateral control in a whole architecture to perform a coupled longitudinal and lateral control. The effectiveness of the automated driving strategy is highlighted through simulation results.

1. Introduction

During last years, the field of automotive vehicle is experiencing an important evolution due to an increasing use of individual vehicles in everyday life. This increasing use poses new challenges such as safety and comfort of car passengers, traffic management, reduction of fuel consumption and pollutant emissions. To cope with these challenges, several automatic systems for driver assistance, chassis stabilisation and engine control have been developed by automotive manufacturers and academicians. An interesting way to investigate the bring of automatic control systems can be the automated driving framework. The automated driving offers an appropriate framework to develop and test new guidance architectures that may equip the vehicles in the future.

In this work, the proposed automated driving architecture is depicted in Fig. 1 and can be synthesised into three main layers. The outer layer percepts, using exteroceptive sensors (GPS, camera, …), the environment in which the vehicle evolves and provides the relevant information to the reference generation layer. The reference generation provides two kinds of reference profiles, geometric path and reference speed, required for control. The reference signals are computed from the information provided by the perception layer (see Attia, Daniel, Lauffenburger, Orjuela, & Basset, 2012 and references therein). The control layer ensures the automated vehicle driving along the desired path at desired speed. This task is accomplished by providing the appropriate control signals, i.e. action on throttle, brake and steering wheel. This paper deals with the control design for automated driving.

The control law design for automated vehicle guidance is a nontrivial problem due to the strong longitudinal and lateral couplings arising in the vehicle dynamics, for instance:

- Kinematic and dynamic coupling of the longitudinal and lateral motions due to the yaw motion caused by the steering of the front wheels.
- The load transfer phenomenon due to the longitudinal and lateral accelerations. These accelerations affect the tyre normal forces and so the longitudinal and lateral tyre forces.
- Tyre–road coupling forces constrained by the so-called friction circle/ellipse. In fact, the maximal available tyre–road friction is distributed between lateral and longitudinal forces.

Hence, the design of longitudinal, lateral and longitudinal/lateral control strategies becomes particularly arduous due to the strongly nonlinear models necessary to capture these couplings in a wide operational range (Lu & Hedrick, 2004). Some authors attempt to consider simultaneously longitudinal and lateral

* Corresponding author.
E-mail addresses: rachid.attia@uha.fr (R. Attia), rodolfo.orjuela@uha.fr (R. Orjuela).
[1] Fax : +33 3 89 42 32 82.

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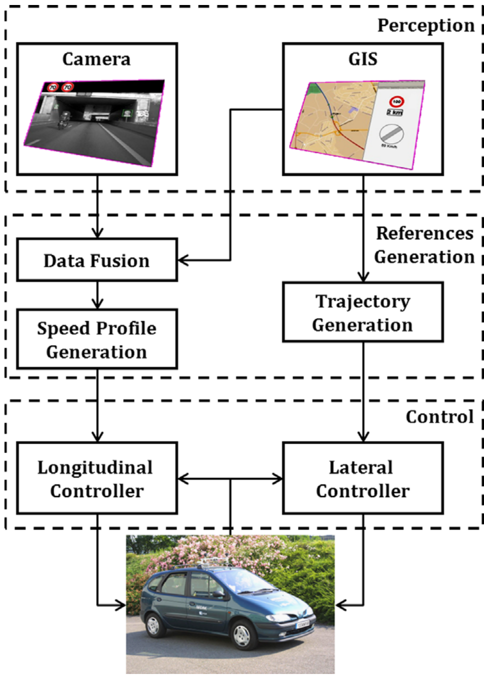

Fig. 1. Automated vehicle guidance architecture.

couplings to obtain an only one controller ensuring coupled control goals. A sliding mode technique for coupled longitudinal and lateral control is proposed in Lim (1998) and recently a solution based on flatness control theory is presented in Menhour, d'Andréa Novel, Boussard, Fliess, and Mounier (2011) and Nehaoua and Nouvelière (2012). It can be emphasised that the main handled couplings are the dynamics coupling of the chassis motion. However, other dynamics should be considered (e.g. powertain dynamics), therefore increasing the control law design complexity. This complexity can be partially overcame following a decoupled lateral and longitudinal control synthesis under some assumptions as proposed in Attia, Orjuela, and Basset (2012a).

The lateral control can be investigated using different techniques. A fuzzy control approach is adopted in Maalouf, Saad, and Saliah (2006) to deal with this problem. The fuzzy controller is compared to a classic Lyapunov controller and shows effective performance. A neural network controller designed using genetic algorithms is employed in Onieva et al. (2010). However, the stability proof and the performance analysis for artificial intelligence control are hard to be established. Recently, Model Predictive Control (MPC) has been explored to cope with this problem, see Besselmann (2010), Falcone, Borrelli, Asgari, Tseng, and Hrovat (2007), Keviczky, Falcone, Borrelli, Asgari, and Hrovat (2006) and references therein. In fact, the automatic steering of the vehicle is a complex constrained problem and MPC is a powerful tool which allows an intuitive handling of the constraints on both state and control inputs. The previously quoted papers have shown a successful implementation and have brought out the relevance of the MPC to cope with the lateral control.

The longitudinal control mainly deals with the development of new Active Cruise Control (ACC) which improves the classic Cruise Control (CC). The latter controller is designed for speed tracking, particularly in highway driving. However, some advanced applications such as autonomous vehicle guidance require high longitudinal vehicle capacities to track time varying speeds (Rajamani & Shladover, 2001). In fact, the reference speed is adapted according to the driving situations (highway, urban,…) thanks to perception and reference generation levels, see Fig. 1. In Nouvelière and Mammar (2007), an advanced longitudinal control design using sliding mode technique is proposed and experimentally validated. An ACC based on a gain-scheduling control technique is recently proposed in Shakouri, Ordys, Askari, and Laila (2010a). In the quoted papers, the authors attempt to consider the powertrain dynamics but the tyre–road interaction is neglected. Recently, a complex nonlinear model for longitudinal vehicle dynamics considering the tyre–road interaction to enhance the longitudinal control performance is proposed in El Majdoub, Giri, Ouadi, Dugard, and Chaoui (2012). A similar approach is proposed here considering also the powertrain dynamics.

The main purpose of this paper is to propose a global control strategy for automated vehicle guidance. A first issue of an integrated longitudinal and lateral guidance strategy taking into account safety aspects has been recently proposed by the authors in Attia et al. (2012a). In that paper, the lateral control is based on a Nonlinear Model Predictive Controller (NMPC), the longitudinal control is ensured by a PI controller and the powertrain dynamics is not considered. The proposed PI longitudinal control is improved in Attia, Orjuela, and Basset (2012b) using a direct Lyapunov control method considering the powertrain dynamics but neglecting the tyre–road interaction. In this paper, the powertrain dynamics as well as the tyre–road interaction are handled. The whole longitudinal controller proposed here is based on a cascade control architecture for speed tracking (outer-loop) and torque control (inner-loop). The previously proposed NMPC for lateral control is replaced here by a linear MPC to reduce the computational effort. Finally, the longitudinal and lateral controllers are integrated in an interconnected architecture to perform automated driving.

The outline of this paper is as follows. The proposed nonlinear control design for longitudinal control is exposed in Section 2. Section 3 presents the linear MPC design and details the proposed coupled longitudinal and lateral control architecture. Simulation results are presented in Section 4. Section 5 wraps up the paper by a discussion on the role of longitudinal control in reducing fuel consumption.

2. Longitudinal control strategy

The goal of the longitudinal control is to ensure the tracking of time-varying reference speed. The whole longitudinal dynamics of the vehicle is characterised by a set of nested complex systems. An external system characterises the relationship between the vehicle speed and the applied torque on the wheels. Its dynamics is governed by the longitudinal motion resulting from tyre–road contact forces. An internal system describes the interaction between the throttle and brake actions and the produced torque. This last implies complex elements such as engine, gearbox and driveline.

The longitudinal control problem is tackled through a cascade control architecture depicted in Fig. 2. The use of a cascade control has been motivated by the structure of the longitudinal dynamics. In this control architecture an outer-loop ensures the reference speed tracking and calculates the torque to be applied on the wheels. An inner-loop provides the throttle opening and the brake pressure to generate the required control torque. In the forthcoming subsections both outer and inner-loops are designed and the whole control architecture is analysed.

2.1. Outer-loop design for reference speed tracking

Consider a one-wheel vehicle model, the longitudinal motion of the vehicle is governed by Nouvelière and Mammar (2007):

$$m\dot{v} = F_l - C_a v^2 - C_r mg\ \cos(\theta) - mg\ \sin(\theta) \tag{1}$$