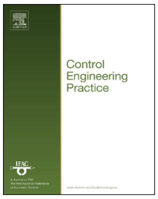
Control Engineering Practice 26 (2014) 160–177

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac



Nonlinear Model Predictive Control approach in design of Adaptive Cruise Control with automated switching to cruise control

Payman Shakouri *, Andrzej Ordys

School of Mechanical and Automotive Engineering, Kingston University London, Friars Avenue, Roehampton Vale, London SW15 3DW, UK

ARTICLE INFO

Article history:
Received 15 July 2011
Accepted 17 January 2014
Available online 17 February 2014

Keywords:
Vehicle dynamic
Adaptive Cruise Control
Model Predictive Control
Nonlinear Model Predictive Control
State-dependent linear model

ABSTRACT

In this paper the Nonlinear Model Predictive Control (NMPC) is used in designing of Adaptive Cruise Control (ACC) and Cruise Control (CC) systems. An algorithm is proposed to carry out automatic switching between ACC and CC, depending on the situation in front of the vehicle. Also, an algorithm based on MPC equation is devised to obtain the prediction of future reference trajectories corresponding to desired speed and distance. NMPC equation used in this paper is developed based on state-dependent representation of linear models corresponding to the modes of the operation: accelerating-throttle is active and braking-brake is active. The developed automated ACC system is tested in simulation against different scenarios proving good performance of the system. Furthermore, the results of proposed control algorithm based on NMPC methods are compared with a different ACC structure.

1. Introduction

Adaptive Cruise Control (ACC) is an extension of the Cruise Control (CC) system which is capable of adjusting the velocity of the vehicle depending on the behaviour of other vehicles moving in front, by applying the brake and modulating the throttle to produce the necessary power (Xiao & Gao, 2010). This system uses the radar or other sensory devices to measure the distance between vehicles (Moon, Moon, & Yi, 2009; Winner, Winter, & Lucas, 2003). The extended version of the ACC is so-called ACC stop & go. Unlike the conventional ACC, which is unable to operate at speed below 30 km/h, the stop & go function, in combination with automatic transmission can operate at low speed and maintain the safe gap to the vehicle in front all the way down to standstill.

Along with the CC and ACC systems another version of the velocity controlling system has been introduced, so-called Look Ahead Cruise Controller (Hellström, Ivarsson, Åslund, & Nielsen, 2009; Kozica, 2005; Keulen et al., 2009). It uses the information about the road ahead of the vehicle to reduce the fuel consumption. For that purpose some “derivative velocity controlling system” is introduced, for instance; Predictive Cruise Control (PCC) (Lattemann, Neiss, Terwen, & Connolly, 2004), Expert Cruise Control (ECC) (Wingren, 2005) or Model Predictive control (MPC), (Axehill & Sjöberg, 2003).

It is known that ACC is capable of managing the traffic flow. By making platoons of vehicles it improves highway capacity. In ACC mode many vehicles can move at highway speed with small inter-distance which can increase density of the vehicles on the highway. It also has the positive effect on the optimisation of fuel consumption especially for heavy vehicles. This is due to significant effect of the aerodynamic drag dependent on the cross section front area for such vehicles (Vahidi & Eskandarian, 2003). On this matter, Cooperative Adaptive Cruise Control (CACC) has been proposed as an advance in the area of Intelligent Transportation Systems (ITS) – to increase traffic efficiency and to improve passenger comfort and safety (Desjardins & Chaib-draa, 2011; Shladover et al., 2009; ven Arem, ven Driel, & Visser, 2006; Ploeg, Serrarens, & Heijenk, 2011). CACC requires that the distances between vehicles are controlled to a high precision and this in turn implies the use of direct communication – exchange of information between the vehicles in the platoon. This may be accomplished in two ways; Inter-Vehicle Communication (IVC) and Roadside-to-Vehicle Communication. IVC is conducted by exchanging information about congestion, incidents or emergency between the follower and leader vehicles through wireless communication. Other automotive safety system such as collision avoidance has also been incorporated in the vehicle to further assist the driver in enhancing safety and preventing accident with a sequence of warnings and active intervention (Isermann, Mannale, & Schmitt, 2012; Moon et al., 2009). Furthermore, since many automotive safety systems such as ACC, collision avoidance or emergency lane assist require accurate information about both road shape and object position, researches have been carried out on advancing the technologies applied for capturing those

---

* Corresponding author.
E-mail address: p.shakouri@kingston.ac.uk (P. Shakouri).

0967-0661/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2014.01.016

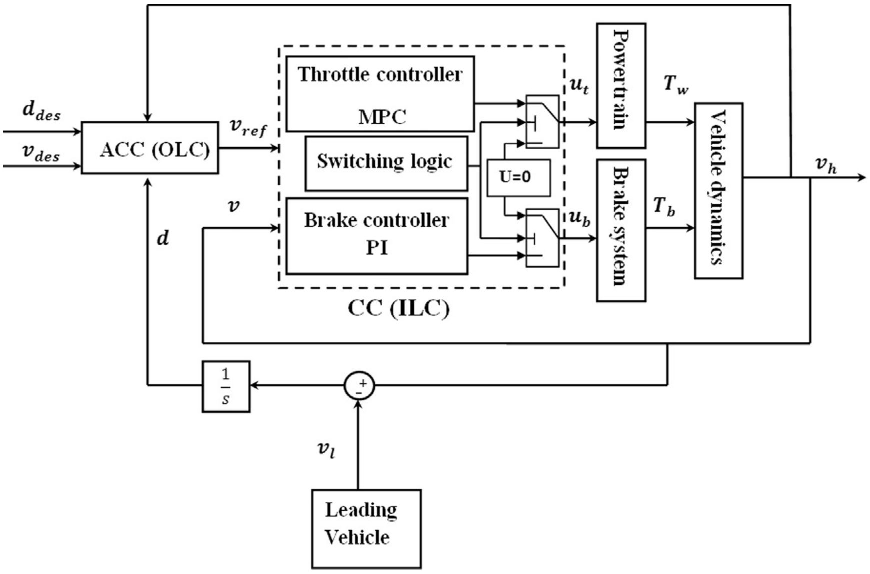


Fig. 1. The ACC structure based on two separate control loops; Outer-Loop Controller (OLC) and Inner-Loop Controller (ILC).

information (Park, Hwang, & Kang, 2010; Eidehall, Pohl, & Gustafsson, 2007; Mattews, An, & Harris, 1996).

The above approach relies on the availability of the IVC system. In this paper the assumption of such system availability is not made. However, improvements in control quality reported in this paper may have significance to situations being matter of interest for CACC approach – without the communication being available.

In literature, various control algorithms have been suggested considering the stop & go function. To design an ACC system being able to perform at the stop & go situation, (Martinez & Canudas-de-Wit, 2007) proposed a nonlinear reference model-based control approach with a compensator which uses a feedback loop so as to take the unmodeled and external disturbances into account. The considerable amount of work has been carried out in design of an ACC system through the model-based control design methods. An ACC structure is mainly developed consisting of two controller loops; outer loop controller and inner loop controller (see Fig. 1). The reason for introducing two levels of controller is to distinguish the vehicle dynamic control (brake and throttle control) design from highway control. Therefore, the outer loop controller can control the distance between vehicles regardless of the design of inner loop (which may be specific for a make/type of the vehicle). From this prospective, (Gerdes & Hedrick, 1997) designed a controller to accomplish the speed and distance tracking by utilising the multi-surface sliding controller consisting of three control levels. An additional level was introduced beside of two others mentioned levels, i.e. outer-loop and inner-loop, in order to perform switching between the brake and throttle controllers. The inner-loop controller containing the brake and throttle controllers is also called the servo control. Servo control tracks the reference value computed by outer loop controller, i.e. the reference value can be either the desired acceleration or the desired speed. In some cases the desired vehicle acceleration is applied to derive the required engine and brake torques. This is mainly because all engine management systems are torque-based which means that the air flow, ignition, fuel injection timing etc. are all set in the optimum position to deliver the required torque. In Shakouri, Ordys, Laila, and Askari (2011) and Riis (2007) the outer loop controller uses a conventional Proportional (P) control to derive a required speed, i.e. outer loop controller adapts the functionality of cruise control system through calculating the required vehicle speed to maintain the distance preset by the driver. The outer loop controller also contains switching function to implement switching between the driver's preset speed, i.e. cruise control speed, and the ACC control calculated reference speed. Eventually, the inner loop controller regulates the brake pedal and throttle opening position to achieve the reference speed calculated by outer-loop controller in order to guarantee a flawless distance tracking from other vehicles as traffic speeds up and slows down. Following this approach, (Shakouri et al., 2011) has proposed various control methods including Gain Scheduling PI (GSPI) control, Gain Scheduling Linear Quadratic (GSLQ) control and Model Predictive Control (MPC) in design of inner loop controller (Fig. 1). Following this principle, inner loop controller is decoupled into the throttle controller and the brake controller by itself and their operation need to be coordinated by use of a proper switching logic.

A Model Predictive Controller (MPC) was employed by van den Bleek (2007) for designing an ACC system by using a linear model in which the states are distance between the following and the leading vehicles, the relative velocity and the following vehicle velocity and the states related to the dynamics of the vehicle were disregarded. Similar approach was followed by Jonsson (2003), there the desired acceleration is calculated by the outer-loop controller or master control loop. Furthermore, van den Bleek (2007) introduced two separate MPCs corresponding to throttle and brake controllers. Each MPC controller computes the desired acceleration for the throttle and the brake controllers. Subsequently, the calculated accelerations are converted to the throttle and the brake controlling signals through inner loop controller or slave control loop. Riis (2007) studied the optimisation of the fuel consumption through an ACC system for which the Nonlinear Model Predictive Controller (NMPC) was utilised.

A proper logical algorithm needs to be devised in order to provide smooth switching between the brake and throttle controllers. The subject of coordinated switching between the brake and the throttle for the ACC application has been researched in the literature (Gerdes & Hedrick, 1997). Coordinated operation between the brake and throttle is crucial due to the following reasons:

- Frequent switching between the brake and the throttle or chattering has negative impact on the longitudinal dynamic of the vehicle as it causes the variation of vehicle's acceleration which provides an un-comfortable environment for passengers. Also, this behaviour causes rapid damage in vehicle's components.
- The frequent and rapid switching between throttle and brake causes loss of the energy, and therefore increases the fuel consumption.
- Inappropriate switching can be a source of instability and disturbance in the system which makes the control design task