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Game theoretic approach for predictive lane-changing and car-following control

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ABSTRACT

This contribution puts forward a receding horizon control approach for automated driving systems, where tactical-level lane change decisions and control-level accelerations are jointly evaluated under a central mathematical framework. The key idea is that controlled vehicles predictively determine discrete desired lane sequences and continuous accelerations to minimise a cost function reflecting undesirable future situations. The interactions between controlled vehicles and surrounding vehicles are captured in the cost function. The approach is flexible in terms of application to controller design for both non-cooperative control systems where controlled vehicles only optimise their own cost and cooperative control systems where controlled vehicles coordinate their decisions to optimise the collective cost. To determine the controller behaviour, the problem is formulated as a differential game where controlled vehicles make decisions based on the expected behaviour of other vehicles. The control decisions are updated at regular frequency, using the newest information regarding the state of controlled vehicles and surrounding vehicles available. A problem decomposition technique is employed to reduce the dimensionality of the original problem by introducing a finite number of sub-problems and an iterative algorithm based on Pontryagin's Principle is used to solve sub-problems efficiently. The proposed controller performance is demonstrated via numerical examples. The results show that the proposed approach can produce efficient lane-changing manoeuvres while obeying safety and comfort requirements. Particularly, the approach generates optimal lane change decisions in the predicted future, including strategic overtaking, cooperative merging and selecting a safe gap.

1. Introduction

Intelligent vehicle (IV) systems support or automate driving tasks in a safe and efficient way (Varaiya and Shladover, 1991). Different classes are categorised in literature with respect to sensing and control characteristics. Based on the differences in sensing the driving environment, we distinguish between *autonomous vehicles* and *connected vehicles*. Autonomous vehicles rely solely on on-board sensors based on cyber-physical sensing technologies, such as radar, lidar, machine vision (VanderWerf et al., 2002; Wang et al., 2014a). Connected vehicles exchange (state and control) information with each other

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via Vehicle-to-Vehicle (V2V) communication or with road infrastructure via Vehicle-to-Infrastructure (V2I) communication to improve situation awareness (Van Arem et al., 2006; Shladover et al., 2012; Monteil et al., 2013; Ge and Orosz, 2014; Wang et al., 2014b). With respect to control, the controllers or decision-making systems of IVs can be either non-cooperative or cooperative. IVs with *non-cooperative control* strategies make control decisions for their own sake, i.e. they do not consider the responses of surrounding vehicles to the control actions and there is no negotiation nor consensus in the decision-making process (Wang et al., 2014a). IVs with *cooperative control* strategies coordinate their behaviour and take into account the expected response of other vehicles when making decisions (Wang et al., 2014b). Note that with this definition, an autonomous vehicle employing a cooperative control strategy can exhibit cooperative behaviour without the need of V2V communication (Wang et al., 2014b).

Considerable efforts have been devoted to IV systems that automate longitudinal driving tasks in both autonomous vehicle systems, e.g. Adaptive Cruise Control (ACC) systems (VanderWerf et al., 2002; Kesting et al., 2008; Wang et al., 2014a), and connected vehicle systems, e.g. Cooperative Adaptive Cruise Control (CACC) systems (Van Arem et al., 2006; Shladover et al., 2012; Monteil et al., 2013; Wang et al., 2014b). Simulation and analytical studies show that IVs change macroscopic traffic operations and the resulting traffic flow characteristics of ACC and CACC systems depend on the control algorithms and parameter settings. The increase of capacity is mainly a result of shorter time headways compared to human drivers (Kesting et al., 2008; Shladover et al., 2012), while choosing a larger time headway could have negative impacts on capacity (VanderWerf et al., 2002). Regarding stability, some authors provide evidence that ACC/CACC systems improve flow stability (Hasebe et al., 2003; Van Arem et al., 2006), while others are more conservative on the stabilisation effects of ACC systems (Marsden et al., 2001; Wang et al., 2013).

Automotive studies focus on steering control, given that a desired lane change trajectory based on constant vehicle speed has been decided by the high-level controller (Falcone et al., 2007; Yoshida et al., 2008). Trajectory planning methods for autonomous vehicles have also been proposed (Hatipoglu et al., 2003; Xu et al., 2012; Soudbakhsh et al., 2013). But the expected response of surrounding vehicles to the controlled actions of the subject vehicle is not considered and the current approaches are not scalable to connected vehicles. Trajectory planning for robots have been extensively studied, with sample based methods (Luders et al., 2013), potential field based methods (Shimoda et al., 2007), meta-heuristic based methods (Hussein et al., 2012). However, vehicles operate at much higher speed than robots and the corresponding safety requirements are much higher. Road geometries, lane markings and traffic rules pose many hard constraints on the problem and lead to many local minima when travelling at centre of each lane. It is difficult to deal with these constraints and non-convexity with current approaches.

Although many attempts have been made, the issue of when and where it is optimal to change lane remains largely unresolved. The discrete lane change events relative to the continuous vehicle positions and the coupled nature between the lateral and longitudinal vehicle dynamics render the problem much more complex compared to the longitudinal control (Kita et al., 2002; Sarvi et al., 2004; Toledo et al., 2007; Kesting et al., 2007; Liu et al., 2007; Rajamani, 2011; Katzourakis et al., 2012; Marczak et al., 2013; Zheng, 2014). In addition, the increasing demand for cooperative systems calls for a scalable approach for designing both autonomous and connected vehicle systems controllers. The aforementioned makes the integrated lateral and longitudinal control of IVs a very challenging topic.

In this article, we generalise previous work on acceleration control (Wang et al., 2014a,b) to a flexible mathematical control approach for fully automated Lane-changing and Car-following Control Systems (LCCS), where discrete and continuous control variables, i.e. lane change decisions and accelerations, are jointly evaluated. The approach entails that controlled vehicles make decisions to minimise predicted cost that reflects undesirable situations. The interaction between controlled vehicles and surrounding vehicles is captured in the cost function by including proximity costs. The approach is applied to controller design for both *non-cooperative control* systems where controlled vehicles only optimise their own cost and *cooperative control* systems where controlled vehicles coordinate their decisions to optimise the joint cost. To determine the controller behaviour, the problem is formulated as a *dynamic game* where controlled vehicles make decisions based on the expected behaviour of other vehicles. A problem decomposition technique is employed to reduce the dimensionality of the original problem by introducing a finite number of continuous sub-problems. An iterative numerical solution algorithm based on Pontryagin's Principle is used to solve the formulated problem. The proposed control framework is applied to derive optimal lane change decisions and accelerations for both autonomous and cooperative controllers. The proposed controller properties and their performance are verified at the microscopic level via numerical examples.

Note that we do not aiming at developing a new driver behaviour model but propose a new predictive approach that generates lane change sequences and accelerations in the future and is applicable for both *autonomous* and *connected* vehicle systems. The optimal control decisions generated by the approach determine a *unique* and *continuous* path that can be used by the automated vehicle actuators to follow. The approach can anticipate the lane changes in the future and can deal with the interaction and cooperation of multiple vehicles in conflicting situations. The current work focuses on the mathematical formulation of the complex control problem and derivation of control algorithms, showing the generalisability and applicability of the mathematical framework. In the discussion and conclusion sections, we highlight some of the possible directions in which the approach could be extended, such as inclusion of anticipation and relaxation in lane changes, verification of the scalability of the approach to many vehicles and impact assessment of the proposed controller on dynamic traffic flow.

In the remainder, we first present the necessary assumptions regarding the LCCS controller. Then we formulate the control problem under a mathematical framework. After that, we decompose the original problem into a finite number of