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Cooperative vehicle path generation during merging using model predictive control with real-time optimization

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ABSTRACT

This paper proposed a cooperative merging path generation method for vehicles to merge smoothly on the motorway using a Model Predictive Control (MPC) scheme which optimizes the motions of the relevant vehicles simultaneously. The cooperative merging is a merging in where the most relevant vehicle in the main lane would accelerate or decelerate slightly to let the merging vehicle merge in easily. The proposed path generation algorithm can generate the merging path ensuring the merging vehicle can access the whole acceleration area, and do not exceed it. We have introduced a state variable to the optimization problem by which the merging point for the merging vehicle is optimized. The simulation results showed that the cooperative merging path can be successfully generated under some typical traffic situations without re-adjustment of the optimization parameters.

1. Introduction

With the advent of vehicle-to-vehicle (V2V), vehicle sensors for advanced driver assistance (ADAS) and by-wire vehicle controls, it is now possible to conceive of fully autonomous driving systems. One problem of interest is the merging of a vehicle into another lane which is filled with traffic. This is an important issue because of the following factors: merging is one of the difficult maneuvers. In particular, nonsmooth merging would cause congestion in the merging section (Papageorgiou, Papamichail, Spiliopoulou, & Lentzakis, 2008). In addition, the increase of vehicles in the slow lanes of motorways would increase the mental workload of the drivers of the vehicles in the merging lane (De Waard, Kruizinga, & Brookhuis, 2008). Elderly drivers will also increase and they will keep on driving till older ages than before (Waller, 1991; Wood, 2002). It has been shown that, it is more demanding for elderly drivers to merge into traffic than for young drivers (De Waard, Dijksterhuis, & Broohuis, 2009). De Waard et al. (2009) indicated that both an in-car support system and an extended acceleration lane will be helpful.

Athans considered the problem of merging strings of vehicles into a single lane as a linear optimal regulator problem (Athans, 1969). Milanés proposed a control algorithm to decide the best time for the merging vehicle to enter the main road and validated this method both in simulations and experiments (Milanés, Godoy, Villagrá, & Perez, 2011). Lu proposed a longitudinal control problem and established a unified model for different road layouts (Lu & Hedrick, 2003). Kachroo developed a merging control system, in which both a longitudinal controller and a lateral controller were included (Kachroo & Li, 1997).

Recently, Hidas (2005) has introduced the concept of cooperative merging. In the cooperative merging the most relevant vehicle in the main lane would accelerate or decelerate slightly to let the merging vehicle merge in easily. The cooperative merging phenomenon has never been considered in the above previous researches about automated merging and is the focus of this paper.

To merge cooperatively and smoothly, a merging path generation method based on Model Predictive Control (MPC) scheme is proposed. The merging problem is formulated into an optimization problem to optimize the motions of the relevant vehicles simultaneously. A state variable related to the merging path is introduced to the optimization problem, so that the merging path and the merging point of the merging vehicle can be optimized according to the motion of the main lane vehicle.

An appropriate available moving area, which has a similar shape to the actual acceleration area, is designed to constrain the

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movement of the merging vehicle. Using the state variable and the constraints of the motion of the merging vehicle, an optimization problem is formulated. As a result, the merging vehicle would move on the centerline of the merging lane before merging, modify its merging path in consideration of the motion of the main lane vehicle, merge at the optimal merging point, and move on the centerline of the main lane after merging. The upper and lower bounds of the accelerations of the relevant vehicles are constrained, so that the relevant vehicles can move smoothly. Three traffic scenes are computer-simulated to validate the effectiveness of the proposed method. The simulation results showed that the proposed method can generate cooperative and mild paths for the relevant vehicles in some typical situations without re-adjustment of the optimization parameters.

This paper is organized as follows: The formulation of the optimization problem used to solve the merging problem and the process of the MPC method are described in Section 2. In Section 3 we present the simulation results and analysis. And then, two possible applications of the proposed method are discussed. Section 4 contains some conclusions and some ideas of the future works.

2. Cooperative merging path generation method using MPC with real-time optimization

We consider merging of two vehicles here for simplicity (see Fig. 1). One vehicle is a merging vehicle running on the merging lane; the other is a mane lane vehicle running on the main lane. We assume that the positions and the velocities of the vehicle are measured by a sensor system installed in the road side. The control inputs for the vehicles are calculated by a computer on the road side and sent to the vehicles by some communication devices. Another possible implementation is that the positions and velocities are sent to the vehicles and calculated by on-board computers installed in the vehicles using the same algorithm on the computers. The merging vehicle and the main lane vehicle are called as the relevant vehicles of the merging problem.

2.1. Modeling of the road and the vehicles

2.1.1. Road model

To optimize the paths of the relevant vehicles under some constraints, we used MPC to solve the merging problem. The formulation of the optimization problem and the MPC scheme will be described in the following subsections. To design paths for the relevant vehicles according to the road shape, the merging lane and the main lane have to be modeled. Just as in paper (Cao, Mukai, Kawabe, Nishira, & Fujiki, 2013c), in consideration of simplicity, the centerline of the main lane and the centerline of the merging lane are modeled as l_1, and l_2 in Fig. 2. l_3 is a smooth line which converges to l_2 on the left side and converges to l_1 on the right side. In Fig. 2 and the rest parts of this paper, we denote the merging vehicle as "Vehicle1" and denote the main lane vehicle as "Vehicle2". The positions of Vehicle1 is plotted as "○" and Vehicle2 is plotted as " × ". To get the mathematical expressions of the lines, the coy-coordinate system is set as follows: the origin is set at the position of Vehicle2 when the merging is considered to start; the velocity of Vehicle2 is chosen as the X-axis. As a result the expressions of l_1, l_2, and l_3 are as (1), (2), and (3). The definitions of the symbols in these equations are shown in Table 1.

$$l_1 : y = 0, \tag{1}$$

$$l_2 : y = k(x-\beta), \quad y \geq 0, \tag{2}$$

$$l_3 : y = \frac{k}{2}\left((x-\beta) - \left((x-\beta)^2 - \frac{\alpha}{k}\right)^{1/2}\right). \tag{3}$$

2.1.2. Vehicle dynamics

In this paper Vehicle1 and Vehicle2 are simplified as two particles. Vehicle2 is assumed to run on l_1 during the merging maneuver. We assume that if no vehicle exists on the main lane, the path of Vehicle1 coincides with l_3. However, in actual merging with main lane vehicles, the merging vehicle may depart from the centerline of the lane in the merging section. To generate an adjustable merging path, we introduce a variable b into (3). b will be employed as a state variable x in (5). The x-coy-coordinate of Vehicle1 is denoted as x_{1x}, and the y-coordinate of it is denoted as x_{1y} in this paper. As a result the relationship of x_{1x} and x_{1y} turns out to be

$$x_{1y} = \frac{k}{2}\left((x_{1x}-\beta-b) - \left((x_{1x}-\beta-b)^2 - \frac{\alpha}{k}\right)^{1/2}\right). \tag{4}$$

x_{1y} depends on x_{1x} and b. b can vary the value of x_{1y} independently of x_{1x}. Therefore, the merging path can be modified using b. For example an effect of b is shown in Fig. 3. Although b is a variable, b is set as a constant in Fig. 3. When $b=0$, the merging path coincides the line l_3. The positive value of b shifts the merging path to the right of l_3. The negative value of b shifts the merging path to the left of l_3.

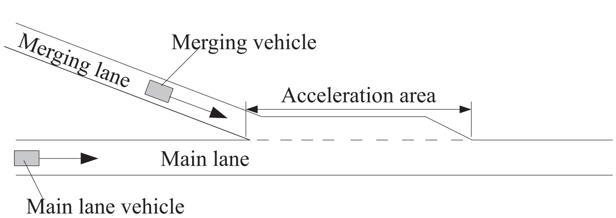

Fig. 1. The situation of the merging problem in this paper.

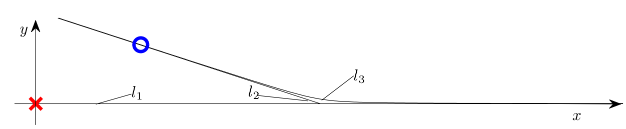

Fig. 2. Approximation method of the road.

Table 1
Definitions of the symbols included in l_1, l_2, l_3.

Symbols	Definitions
x	The x-coy-coordinate
y	The y-coordinate
k	The slope of l_2
β	The interception of l_2 on the Y-axis
α	The design parameter which determines The smoothness of the curvature

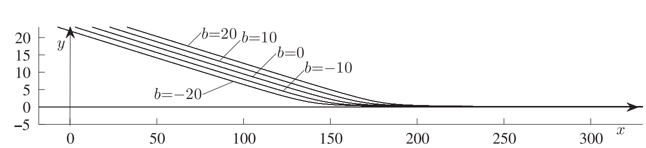

Fig. 3. The effect of the variable b (constant case).