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Obstacle Avoidance by Steering and Braking with Minimum Total Vehicle Force

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Abstract: In this study of automatic obstacle avoidance maneuver, a fast and precise algorithm for solving a two-point boundary value problem (TPBVP) is developed. This algorithm realizes optimal control by minimizing the total vehicle force using integrated steering and braking control. Such optimal control is characterized by three nonlinear equations that result from the application of the necessary conditions for optimality. These highly nonlinear simultaneous equations are nondimensionalized, and algebraic manipulations are performed for simplification. As a result, they are reduced to a single nondimensionalized equation with the dimensionless final time as an unknown and aspect ratio as an input that describes the relative position between the obstacle and vehicle. For a fast and robust solution process, a search interval for a numerical root solving method is set using approximating polynomials. Based on the solution of the dimensionless final time, the dimensionless total vehicle force and dimensionless jerk, both of which are essential aspects of collision avoidance maneuver, can be easily computed.

Keywords: automotive control, jerk, nondimensionalization, optimal control, vehicle dynamics.

1. INTRODUCTION

In automotive engineering, driver assistance systems for safety are considered the most essential field of study. Collision avoidance systems based on automatic braking are already available in production vehicles. Collision avoidance by pure braking is effective for cases of low vehicle speed with high tire-road friction coefficients. Obstacle avoidance by steering offers better performance for higher vehicle speed and/or on wet road surfaces. With full utilization of the vehicle friction circle, the integration of steering and braking has been demonstrated to be more effective than pure steering (Hattori et al., 2008).

Various objective functions for the optimal control of the integrated steering and braking have been studied. Shiller and Sundar (1998) used minimum longitudinal avoidance distance. In a study by Fujioka et al. (2008), a minimization of collision risk was suggested. This collision risk consists of a risk function that depends on the obstacle location, a function of time-to-collision or longitudinal avoidance distance, and a penalty function of longitudinal and lateral accelerations. The penalty function provides smooth acceleration/braking and steering actions. Minimization of the time integral of the sum of squared tire workloads, and front-wheel steering angle rate was studied by Horiuchi et al. (2006).

In a recent study, a minimization of the total vehicle force problem was proposed by Ohmuro and Hattori (2010). By minimizing the total vehicle force, the force margin is maximized, and this allows operations with some safety margin. Because of the availability of friction estimation methods, we can assume online monitoring of the maximum vehicle force. In order to estimate the friction coefficient, Muller et al. (2003) used friction coefficient versus slip data for the low slip region; Alvarez et al. (2004) used a first-order dynamic friction model called the LuGre model; Wang et al. (2004) used linear and non-linear models for low and high slips, respectively; and Nishihara and Kurishige (2011) used the grip margin derived from the brush model. Note that the obstacle avoidance maneuver can be realized if the required total force does not exceed the maximum vehicle force.

In the previous study (Ohmuro and Hattori, 2010), the application of the optimal control theory results in a two-point boundary value problem (TPBVP), that is reduced to a system of highly nonlinear equations. Because of the difficulties expected in the online solution of these highly nonlinear equations, they proposed a pair of two-dimensional maps that provide the total vehicle force along with the direction angle that constitutes the optimal control inputs. In general, use of these maps leads to inaccurate solutions, particularly in the case where the output is very sensitive to the inputs. Such accuracy could be improved by increasing map resolution at the expense of large data storage space.

For one equation in one unknown, fast root finding methods, such as Newton's, secant, and inverse quadratic interpolation, are available. Brent's method is a hybrid algorithm that includes the very stable bisection method, and is known for its combined efficiency and robustness (Brent, 1971). To a system of nonlinear equations, application of Newton's or Broyden's method may offer speed; however, there is no guarantee of convergence. Reduction to one equation in one unknown is preferable because stable con-

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vergence is mostly guaranteed with a sufficiently narrow interval determined with an approximate solution to the equation.

In this paper, minimization of the total vehicle force for the obstacle avoidance problem is reduced to finding the solution of one equation in one unknown. In order to estimate the initial guess for the root solving method, Chebyshev and least squares function approximations are performed. The dimensionless final time is obtained with high precision using Brent's method, and this leads to the determination of optimal control that is as precise as required.

2. PROBLEM FORMULATION

2.1 Obstacle Avoidance Problem

Figure 1 shows a vehicle that moves on a straight road with initial vehicle longitudinal velocity v_{x0}, and initial lateral velocity v_{y0}, at a given position. The vehicle performs a lane change in order to avoid an obstacle blocking its forward path. The longitudinal distance to the obstacle is denoted by x_f. The lateral distance at final time t_f, is given as y_f. For simplicity, the vehicle is treated as a particle with mass m. In this problem, total vehicle force F_t, is to be minimized for the lane change maneuver.

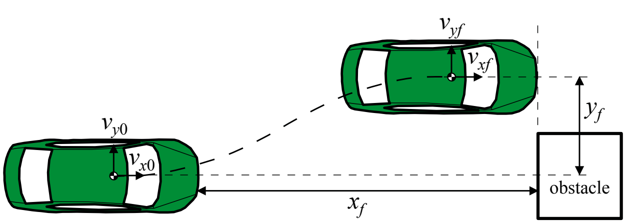

Fig. 1. Schematic diagram of lane change maneuver

Figure 2 the trade-off between total longitudinal force X_t, and total lateral force Y_t. These are the forces that a vehicle generates at a given instant. Total vehicle force F_t, is assumed to be time invariant and limited by the maximum vehicle force $F_{\max}$, that is expressed as the product of tire-road friction coefficient μ, and vehicle normal load $Z_t = mg$. Maximum force $F_{\max} = \mu Z_t$ represents the tire grip limit. Once the longitudinal and lateral vehicle forces are evaluated, tire-forces distribution schemes (Nishihara and Higashino, 2013; Ono et al., 2006) can be utilized to calculate the front and rear wheel steering angles and braking torques, but this phase is not within the scope of this study.

2.2 Optimal Control Problem Formulation

An optimal control theory is utilized for the obstacle avoidance problem (Bryson and Ho, 1975). A system model is given as

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t), t) \ \ \boldsymbol{x}(t_0) = \boldsymbol{x_0} \tag{1}$$

where $\boldsymbol{x}(t)$ and $\boldsymbol{u}(t)$ denote, respectively, the n and m dimensional vectors of the state and control variables. The control inputs and corresponding states are

$$\boldsymbol{u}(t) = \left[\frac{F_t}{m} \ \ \varphi\right]^T \tag{2}$$

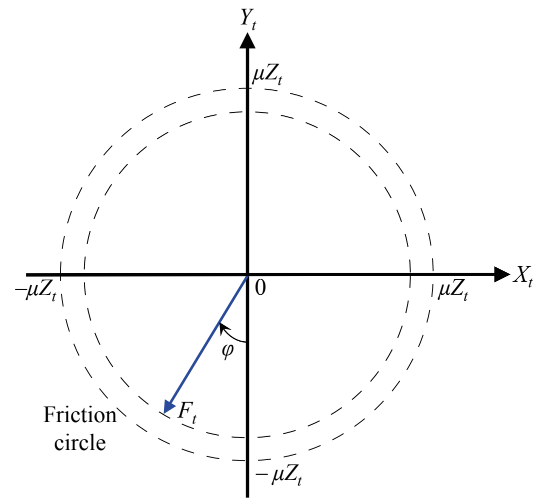

Fig. 2. Total vehicle force bounded by friction circle

$$\boldsymbol{x}(t) = [x(t) \ \dot{x}(t) \ y(t) \ \dot{y}(t)]^T \tag{3}$$

The initial conditions of the states are

$$\boldsymbol{x}(t_0) = [0 \ v_{x0} \ 0 \ v_{y0}]^T \tag{4}$$

The objective function for the obstacle avoidance lane change problem is

$$\min_{\boldsymbol{u}(t)} J = F_t \tag{5}$$

The terminal constraint is written as

$$\boldsymbol{\psi}(\boldsymbol{x}(t), t) = [x(t) - x_f \ \ y(t) - y_f \ \ \dot{y}(t)]^T \tag{6}$$

The longitudinal and lateral dynamics of the vehicle can be expressed as (7) and (8), respectively.

$$X_t(t) = m a_x(t) \tag{7}$$

$$Y_t(t) = m a_y(t) \tag{8}$$

where the longitudinal acceleration a_x, and lateral acceleration a_y, are written as

$$a_x(t) = -\frac{F_t}{m} \sin\varphi(t) \tag{9}$$

$$a_y(t) = -\frac{F_t}{m} \cos\varphi(t) \tag{10}$$

where

$$\tan\varphi(t) = \frac{-t + t_f}{-\nu_y t + \nu_y t_f + \nu_v} \tag{11}$$

Hattori and Ohmuro (2010) discussed three obstacle avoidance problems that are minimization of x_f, minimization of F_t, and maximization of y_f. These problems are related to each other such that their optimal solutions can be obtained by solving the same simultaneous equations with different parameter sets of given and unknown. We have derived a precise solution method for the minimization of x_f where $y(t_f) = y_f$ and $v_y(t_f) = 0$ are the terminal constraints, and F_t is assumed to be known prior to the lane change maneuver (Singh and Nishihara, 2016). In the present study, F_t is to be minimized for a given x_f. Note that the minimization of F_t is a dual problem of the minimization of x_f. Therefore, the simultaneous equations of the primal problem is used here. In Eqs. (12) to (16), the variables to be determined are Lagrange multiplier constants ν_y and ν_v, as well as final time t_f.