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Vehicle tyre/road interaction modeling and identification of its parameters using real-time trust-region methods

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Abstract:
Driving safety can be achieved by better understanding critical situations which may require the knowledge of interaction between vehicle tyres and the road surfaces. It is thus essential to have a good estimation of the tyre/road friction parameters in real-time. The paper deals with the trust-region based method for on-line estimation of tyre/road friction parameters. This method provides an appropriate modeling (of a vehicle and the tyre/road contact) to observe the tyre/road friction coefficients directly using measurable signals in real-time. In this work, we present a new LuGre model-based nonlinear least squares (NLLS) parameter estimation algorithm using vehicle dynamic to obtain the parameters of LuGre model based on recursive nonlinear optimization of the curve fitting errors. The proposed estimation method can also be utilized in large-scale problems with similar conditions. Very promising results have been obtained in real-time simulations for most of the driving and road situations.

Keywords: Tire/road friction estimation, vehicle dynamics, nonlinear least squares, recursive identification

1. INTRODUCTION

Since the motion of a ground vehicle is primarily determined by the friction forces transferred from roads via tyres, information about the tyre/road interaction is critical to many active vehicle safety control systems, including longitudinal control, yaw stability control and rollover prevention control systems. In particular friction formation is crucial tool for Brake Assist Systems (BAS), Electronic Stability Control (ESC-ESP) and Adaptive Cruise Control (ACC) systems that have recently become essential for active safety systems, as shown in Sharifzadeh et al. (2014a); Farroni et al. (2014b, 2013) . For instance, in the case of adaptive cruise control, estimation of friction coefficient (μ) enables the braking distances to be adjusted in real time.

With this description the real-time estimation of the tyre/road contact characteristics on roads with inhomogeneous friction properties (mixed-μ roads) is of fundamental importance in every active safety system and thus this issue has been even more important in recent years. Unlike other easily measurable parameters, such as the wheel angular speeds, vehicle acceleration and wheel load, there is currently no economically feasible sensor that can be installed in the vehicle to measure the friction parameters. Because many factors affect road friction coefficient, such as road surface conditions, tyre types, vehicle and wheel velocity (Canudas-de Wit et al., 2003), the adaptive identification of maximum friction coefficient is always a complicated and challenging issue in the automotive engineering. There are different approaches and experimental studies to the solution of this problem. An excellent review can be found in Rajamani et al. (2012).

One of the best the available solutions, is the well-known slip-based approach, which uses the road/tyre friction force models based on the wheel slip. Real-time and robust process in this case, has recently become more important. An excellent review can be found in Savaresi and Tanelli (2010).

Tanelli et al. (2009) have proposed a new real-time identification approach using linearized form of simple Burckhardt model, based on the widely-used recursive least squares (RLS) methods (Sharifzadeh et al., 2016). de Castro et al. (2012) have improved this approach by proposing more accurate linear parametrization (LP) for Burckhardt model and offering the constrained version of RLS for the estimation case. In order to obtain more reliable detections, some other prediction approaches have been proposed and the results have been presented for different road surfaces (Qi et al., 2015). Most of these approaches use simple vehicle dynamic. Also they doesn't have enough fitting with experimental data due to road and tyre changes.

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Based on the above discussion, it can be said that limited works have been reported for a real-time and robust detection of tyre/road conditions. Therefore, this work is focused on implementing computationally efficient algorithm for on-line identification of surface conditions in different tyre types and road surface conditions during braking.

In the proposed method, the LuGre model is a static one obtained from the LuGre distributed model. Then presents new LuGre model-based nonlinear least squares (NLLS) parameter estimation algorithm using the proposed static form of the LuGre to obtain the parameters of LuGre model based on recursive nonlinear optimization of the curve fitting errors. Optimization problem is solved by utilizing an interior Trust-Region method. This method is robust and gives faster convergence rate by proper initialization of the vector function (Moré and Sorensen, 1983; Conn et al., 2000). The advantage of the proposed approach is that, although uses nonlinear identification system, it still results relatively good convergence rate when is compared with the results of linear approach. This also involves more properties of real friction behavior especially due to having nonlinear scheme.

This work also presents the vehicle dynamics and tyre-surface interaction model following which the method to identify surface characteristics. The organization of the remainder of this paper is as follows. In Section 2 the four wheel vehicle model and LuGre dynamic tyre model, are presented. Simulation results and analysis based on a full-vehicle model are discussed in Section 4. Conclusive remarks are presented in Section 5.

2. SYSTEM DESCRIPTION

A simple but effective four-wheel vehicle considering vehicle/tyre/road dynamics is described in this section (Savaresi and Tanelli, 2010).The dynamic equations are the result of application of Newton-Euler law for the vehicle and wheel.

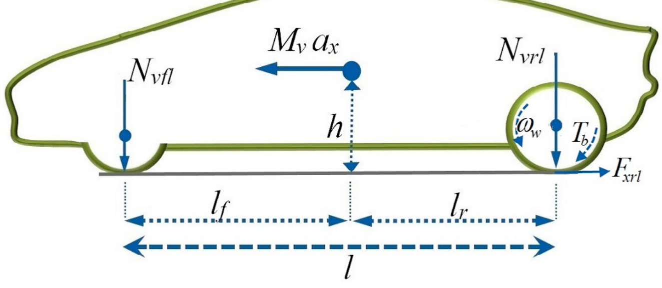

Fig. 1. Vehicle dynamics schematic.

The vehicle dynamic is given by summing the total forces applied to the vehicle with braking operation. Ignoring the road gradient and wind speed it is represented as $\dot{v}_v = \frac{-1}{M_v}\left[\sum F_{xi} + B_v v_v + D_a v_v^2\right]$, where $v_v[m/s]$ is the longitudinal velocity of the vehicle; $M_v[kg]$ is the mass of the vehicle at center of gravity (CG); $F_{xi}[N]$ denotes the tyre/road contact force for the wheel $\{i = fl, fr, rl, rr\}$, $(f = front/r = rear, l = left/r = right)$; B_v is the vehicle viscous friction; D_a is the aerodynamic drag force so that $D_a = (1/2)\zeta C_d A$, with $\xi[kg/m^3]$ being the air density, C_d the aerodynamic drag coefficient, and $A[m^2]$ the frontal area of the vehicle. The tyre/road contact force for the ith wheel, is given by $F_{xi} = \mu(\lambda)F_{Ni}$ where the coefficient of friction μ is a function of the slip λ; and $F_{Ni}[N]$ denotes the vertical wheel reaction force applied to the wheel.

As it has been previously discussed by the authors (Akbari et al., 2010; Akbari and Lohmann, 2008), the weight is transferred between the wheels during different car accelerations, thus F_{Ni} varies at the different wheels. The model force, F_{Ni} for the four wheel forces can be expressed as follows

$$F_{Ni} = \begin{cases} \frac{M_v(l_r g + h a_x)}{l}\left(\frac{1}{2} + \frac{h a_y}{d_f g}\right) & i = fl \\ \frac{M_v(l_r g + h a_x)}{l}\left(\frac{1}{2} - \frac{h a_y}{d_f g}\right) & i = fr \\ \frac{M_v(l_f g - h a_x)}{l}\left(\frac{1}{2} + \frac{h a_y}{d_r g}\right) & i = rl \\ \frac{M_v(l_f g - h a_x)}{l}\left(\frac{1}{2} - \frac{h a_y}{d_r g}\right) & i = rr \end{cases} \quad (1)$$

where a_x and a_y (leftwards positive) are the longitudinal and lateral acceleration of CG, respectively, h denotes the height of CG , l_r, l_f are distance from CG to rear and front axles with $l = l_r + l_f$ as the wheelbase of the vehicle , see Fig. 1, and d_f, d_r , are the distances between wheels on the front and rear axles, respectively.

The ith wheel dynamic by summing the rotational torque yields to

$$\dot{\omega}_{wi} = \frac{1}{J_w}\left[-T_{bi}sign(\omega_{wi}) + R_w F_{xi} + T_e\right], \quad (2)$$

where $\omega_{wi}[rad/s]$ is the angular velocity of the ith wheel, $J_w[kg.m^2]$ denotes the rotation inertia of the wheel, $T_{bi}[N.m]$ is the braking torque on the ith wheel, $R_w[m]$ is the radius of the wheel, and $T_e[N.m]$ is engine Torque on the wheel. Longitudinal Slip λ is defined as the difference between vehicle actual longitudinal velocity and wheel circumferential velocity, as $\lambda = (v_v - v_w)/max\{v_v, v_w\}$, with $v_w = R_w\omega_w$. According to the adopted definition $\lambda \in [-1, 1]$, and λ is negative in traction and positive during braking.

As experimentally investigated by Farroni et al. (2014b), the friction coefficient can be modeled with semi-empirical formulas, which generate the steady-state wheels behavior. One of the widely-used models is the Burckhardt Model, which is easy to linearize for applying recursive least squares (RLS) identification method. On the other hand, as shown in Fig. 2, increasing the vehicle speed, reduce the friction coefficient for a given road condition, which is a fact that is generally not considered in these formulas (Canudas-de Wit et al., 2003).

Therefore in order to consider the friction coefficient dependence on velocity and also to involve more properties of real friction behavior such as tyre situation, LuGre dynamic friction model (Canudas-De-Wit et al., 1995), is chosen for this case, which is accurately fitted curves that allows the adaptation to different road conditions while this model is identifying the road-tyre friction parameters. The LuGre distributed Model is given as,

$$\begin{cases} \frac{\partial z}{\partial t}(\zeta, t) + \frac{\partial z}{\partial \zeta}\dot{\zeta} = v_r - \frac{\theta\sigma_0|v_r|}{g(v_r)z} \\ F_{xi} = \frac{F_{Ni}}{L}\int_0^L(\sigma_0 z(\zeta, t) + \sigma_1\dot{z}(\zeta, t) + \sigma_2 v_r)d\zeta \end{cases} \quad (3)$$