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Nonlinear vehicle side-slip estimation with friction adaptation☆

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Abstract

A nonlinear observer for estimation of the longitudinal velocity, lateral velocity, and yaw rate of a vehicle, designed for the purpose of vehicle side-slip estimation, is modified and extended in order to work for different road surface conditions. The observer relies on a road–tire friction model and is therefore sensitive to changes in the adhesion characteristics of the road surface. The friction model is parametrized with a single friction parameter, and an update law is designed. The adaptive observer is proven to be uniformly globally asymptotically stable and uniformly locally exponentially stable under a persistency-of-excitation condition and a set of technical assumptions, using results related to Matrosov's theorem. The observer is tested on recorded data from two test vehicles and shows good results on a range of road surfaces.

Keywords: Side-slip estimation; Automotive vehicles; Nonlinear observers; Velocity estimation; Friction

1. Introduction

A current focus of the automotive industry is the development of active safety systems, which assist the driver in order to avoid dangerous situations. As such systems become more advanced, they depend to an increasing extent on accurate information about the state of the vehicle and its surroundings. Much of this information can be obtained by direct measurement, but the appropriate sensors may be unreliable, inaccurate, or prohibitively expensive. Observers are therefore used to provide accurate and reliable estimates of important states.

Observers that estimate vehicle velocity usually rely on road–tire friction models, which model the friction forces between the tires of the vehicle and the road surface. As the adhesion characteristics between the tires and the road depend on the road surface, knowledge about the current road surface conditions is important for this type of observer to work properly.

Several different methods for obtaining information about road surface conditions have previously been studied. In Ono et al. (2003), a least-squares method is used on measurements of wheel angular velocity to estimate the slope of the friction force versus the tire slip. An observer for lateral velocity in Fukada (1999) includes a filtering scheme for estimating the maximum road–tire friction coefficient, based primarily on using the lateral acceleration measurement during times when this provides a good measurement of the coefficient. A similar approach is taken in Hac and Simpson (2000). In Gustafsson (1997), a Kalman filter is used to classify road surface conditions, by inspecting the ratio between slip values of the driven wheels and the normalized friction force, obtained using wheel angular velocities and engine torque. In Ray (1997), an extended Kalman filter (EKF) is combined with statistical methods in order to estimate the maximum road–tire friction coefficient, using measurements of the yaw and roll rates, wheel angular velocities, and longitudinal and lateral accelerations, as well

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as knowledge of the steering angle and total brake line pressure. Other examples of EKFs are presented in Suissa, Zomotor, and Böttiger (1994) and Best, Gordon, and Dixon (2000). In Nishira, Kawabe, and Shin (1999), wheel angular velocity, longitudinal tire slip, and wheel torque is used to generate an estimate of the wheel angular velocity and for adaptation of a friction parameter. Wheel angular velocity and torque is used in Canudas-de-Wit, Petersen, and Shiriaev (2003) for estimation of the longitudinal velocity and wheel angular velocity, and adaptation of a friction parameter. In both Nishira et al. (1999) and Canudas-de-Wit et al. (2003), convergence of the adapted friction parameters under conditions of nonzero longitudinal tire slip is studied.

In addition to accuracy and reliability, production cost is an important matter in vehicle serial production. To reduce cost, observer designs should be computationally efficient and be based on cheap sensor configurations. In Imsland, Johansen, Fossen, Grip et al. (2006), a nonlinear observer for vehicle velocity is presented with stability guarantees. The observer is computationally efficient and is based on measurements commonly available in modern cars. A significant weakness of the observer is that it relies on a friction model that must be tuned to the current road surface conditions. In Grip et al. (2006), the authors addressed this issue for a reduced-order observer for lateral velocity by presenting a method for adaptation of the friction model to different road surface conditions. In the current paper, an improved version of this adaptive observer is presented, and in Section 5, it is extended to include longitudinal velocity and yaw rate. The observer retains the advantage of being less computationally expensive than an EKF. The ultimate goal of the observer design is accurate estimation of the vehicle side-slip angle.

The stability analysis presented in this paper relies crucially on the concept of persistency of excitation (PE), introduced by Åström and Bohlin (1965). This concept has been developed in various directions to deal with situations where regressors are dependent not only on external, time-varying signals, but on the states of the system, which is the case for the system considered in this paper. One approach to dealing with state-dependent regressors is to consider a PE condition along the trajectories of the states. The drawback of this approach is that, in general, the trajectories of the states must be known in advance. Another approach is to consider the states a parameter, and to evaluate a PE condition over all values of this parameter. This idea is combined with a generalization of Matrosov's theorem in Loría, Panteley, Popović, and Teel (2005), the results of which are used in this paper. Although the specific trajectories of the states need not be known, the PE conditions resulting from this approach are in general difficult to verify. In the present case, we nevertheless offer a natural and intuitively reasonable interpretation of the PE condition, which is directly related to driving patterns and supported by experimental results.

Systems similar to the one considered in this paper have previously been investigated under PE conditions (Ortega & Fradkov, 1993; Panteley, Loría, & Teel, 2001; Zhang, Ioannou, & Chien, 1996). Another example of observer design with analysis similar to what is presented here can be found in Loría and de León Morales (2003).

1.1. Notation

Conventional notation is used for denoting estimated variables and error variables, meaning that for some variable z, $\hat{z}$ denotes its estimate and $\tilde{z} = z - \hat{z}$. When considering error dynamics, a function depending on an estimated variable $\hat{z}$ may be written as a function of the error variable $\tilde{z}$ and t, by noting that $\hat{z} = z - \tilde{z}$ and considering z a time-varying signal. For a vector z, $z_{\{i,j\}}$ denotes the vector obtained by stacking elements i and j of z. The norm operator $\|\cdot\|$ denotes the Euclidian norm. The closed ball with center 0 and radius r is denoted $\overline{B}(r) = \{z \mid \|z\| \leqslant r\}$. The minimum eigenvalue of a matrix A is denoted $\lambda_{\min}(A)$. The positive real numbers are denoted $\mathbb{R}_{>0}$.

2. Vehicle model and preliminaries

The vehicle is illustrated in Fig. 1. Of primary interest is the side-slip angle β, which is the angle between the longitudinal direction of the vehicle and the direction of travel at the center of gravity (CG). To obtain the side-slip angle, we shall estimate the longitudinal velocity v_x and the lateral velocity v_y at the CG, from which $\beta = -\arctan(v_y/v_x)$ can be calculated.

The vehicle is assumed to be moving on a flat, horizontal surface. In general, there are environmental forces, such as wind forces and air resistance, acting on the vehicle. In our model, these are disregarded; we assume that only road–tire friction forces act on the vehicle.

2.1. Friction modeling

Several semi-empirical models for road–tire friction exist, the most well-known of which is the Magic Formula (Pacejka, 2006). This paper is not based on a particular friction model;

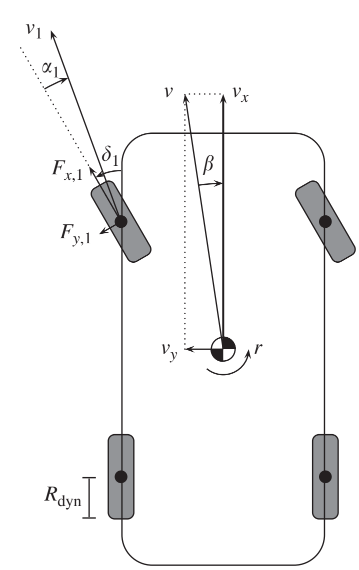

Fig. 1. Schematic overview of vehicle.