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Vehicle sideslip angle measurement based on sensor data fusion using an integrated ANFIS and an Unscented Kalman Filter algorithm

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ABSTRACT

Most existing ESC (Electronic Stability Control) systems rely on the measurement of both yaw rate and sideslip angle. However, one of the main issues is that the sideslip angle cannot be measured directly because the sensors are too expensive. For this reason, sideslip angle estimation has been widely discussed in the relevant literature. The modeling of sideslip angle is complex due to the non-linear dynamics of the vehicle. In this paper, we propose a novel observer based on ANFIS, combined with Kalman Filters in order to estimate the sideslip angle, which in turn is used to control the vehicle dynamics and improve its behavior. For this reason, low-cost sensor measurements which are integrated into the actual vehicle and executed in real time have to be used. The ANFIS system estimates a “pseudo-sideslip angle” through parameters which are easily measured, using sensors equipped in actual vehicles (inertial sensors and steering wheel sensors); this value is introduced in UKF in order to filter noise and to minimize the variance of the estimation mean square error. The estimator has been validated by comparing the observed proposal with the values provided by the CARSIM model, which is a piece of experimentally validated software. The advantage of this estimation is the modeling of the non-linear dynamics of the vehicle, by means of signals which are directly measured from vehicle sensors. The results show the effectiveness of the proposed ANFIS+UKF-based sideslip angle estimator.

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1. Introduction

With the recent advancements in the vehicle industry, driving safety in passenger vehicles is considered to be one of the key issues in the design of any vehicle. Electronic Stability Control (ESC) is seen as the greatest road safety innovation since the seatbelt. Hence, the market demands more research in order to improve performance of these systems.

To improve vehicle handling and stability based on ESC, the yaw rate, that is, the yaw velocity of the chassis, and the vehicle sideslip angle, the angle between the directions of the vehicle's velocity and its chassis, are controlled so that they follow their target values [1,2]. The yaw rate can be directly measured by a yaw rate sensor (gyroscope) [3,4]. In addition, the sideslip angle can be directly measured via optical or GPS sensors [5–7]. However, the drawbacks of measuring the yaw rate

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and the sideslip angle have to do with the accuracy, reliability and cost [8]. Sideslip angles cannot be directly measured using standard sensors, therefore, the measurements must be estimated by means of an observer [9–11]. For this reason, an accurate estimation of the vehicle's sideslip angle is essential for applications in vehicle dynamics and control.

Sideslip angle estimation has been widely discussed in the literature. The modeling of sideslip angles is complex due to the non-linear dynamics of the vehicle. Some authors employ physical models for the estimation of sideslip angles [12–15]. The most-cited methods are based on the bicycle dynamic model or its variations. These models generate noise-free sideslip angle estimations, but they can be sensitive to changes in the vehicle parameters. Other authors use kinematic based-models that consider the motion of a body, which are not affected by uncertainties [14,16,17]. These methods integrate the derivative of the sideslip angle, calculated from sensor signals including yaw rate, lateral acceleration and vehicle speed. Satisfactory robustness of tire properties, road friction and vehicle parameters, such as vehicle mass and moment of inertia, can be achieved. Finally, there are also authors who use combined methods which bring together the advantages of the previous two methods [9,11].

Furthermore, some authors propose methods for designing observers in order to estimate the sideslip angle from variables that can be easily measured; such as the yaw rate, lateral acceleration and velocity. Different models, such as linear [18] and nonlinear [19], and observers such as Kalman Filters [10,20] have also been considered in order to estimate the sideslip angle. A common feature of most of these observers for the estimation of the sideslip angle is that they rely heavily on an accurate tire model, which may vary during vehicle operation.

The Unscented Kalman Filtering (UKF) is a powerful tool for the state estimate of nonlinear systems [21–23]. The UKF is able to achieve good performance if the complete information of measurement noise distribution is taken as known.

The major problem for estimating the sideslip angle adequately is tire non-linearities. Nowadays, different non-linear tire models are considered in order to carry out a good modeling. The Pacejka tire model [23] is one which has been taken into consideration during recent years. There are various Pacejka tire models with different degrees of complexity. In one model, which is widely used, tire forces are considered relative to both normal forces and slip, non-linear forces.

The problem is that the tire forces also depend on road conditions (icy, wet or dry road surface). Previous studies have estimated the sideslip angle assuming that the vehicle is driven on a road with the friction coefficient constant. When, the road friction coefficient changes, the vehicle dynamics also change. If the parameters of the model are not modified in the observers, the estimation of sideslip angle could be mistaken.

The disadvantage of Kalman filters-based estimators is that the optimality of the estimation algorithm depends on the quality of a priori knowledge of the process and measurement noise statistics.

More recently, Artificial Intelligence (AI) algorithms have been proposed in order to eliminate some of its inadequacies [24–27]. AI-based algorithms have been proved to be appropriated in order to avoid issues associated with the identification and adaptation of reference model parameters. In [28–30], AI-based algorithms are used to estimate the sideslip angle based on fuzzy, Neural Network (NN) and ANFIS (Adaptive Neuro-Fuzzy Inference System), respectively.

In our previous work [30], we proposed an ANFIS-based observer to estimate the sideslip angle. It proved that the ANFIS-based estimator provides an error smaller than the NN-based and Kalman-based estimators. However, the disadvantage is that AI-based methods do not use any statistical information as input, nor do they output statistics associated with the solution, unless methods of cross-validation are applied.

In this paper, we propose a novel observer based on ANFIS and combined with a Kalman Filter, in order to estimate the sideslip angle that is used to control the vehicle dynamics and improve its behavior.

Other researches also combine AI-based techniques with Kalman Filter for estimation. In this case, The IA-based algorithm is based on the improvement of the filter performance through the adaptive estimation of the filter statistical information (covariance matrices) [31–33]. The problem is that the uncertainty learning is a difficult and complex process. In this case, we do not estimate the filter statistical information but also we estimate a “pseudo-parameter”, a “pseudo-sideslip angle”, which is introduced in Filter Kalman.

The ANFIS system estimates a “pseudo-sideslip angle” through parameters which are easily measured using actual vehicles equipped with sensors (inertial sensor and steering wheel sensor) and this value is introduced in UKF in order to filter the noise and to minimize the variance of the mean square error estimation. The ANFIS-based observer combines the benefits of both Neural Networks and Fuzzy logic. The former is adaptive and can learn from generalization and pattern recognition. The latter allows soft and steady performance [34]. In [35], an ANFIS algorithm is proposed to estimate the yaw rate, providing good results. The advantage is that the ANFIS-observer could learn from different road conditions and maneuvers.

CarSim software has been employed to test the effectiveness of the proposed algorithm [36] and its use has become widespread as simulation software in the automotive industry. The software combines traditional and modern multi-body vehicle dynamics, based on parametric modeling. The software includes a three-part graphic database of a full-vehicle model, direction and speed control and external conditions, such as, road information, drag and so on.

CarSim results obtained after training show that the proposed observer learns to estimate the sideslip angle behavior properly and reliably, without difficulty. The efficiency of the observer is demonstrated through plentiful simulation tests.

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