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# Reliable vehicle sideslip angle fusion estimation using low-cost sensors

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ABSTRACT

This paper proposes an adaptive hybrid fusion estimation strategy using low-cost sensors to estimate vehicle sideslip angle in a wide driving-maneuver range. First, the kinematics model-based extended Kalman filter (KEKF) is designed as the basic filtering framework. To ensure the KEKF accuracy and observability in a wide range of driving maneuvers, the influence of inertial sensor drift is considered and the estimation from the bicycle dynamics-based extended Kalman filter (DEKF) is introduced as the KEKF measurement. In the DEKF, the cornering stiffness estimation algorithm is developed to adapt to the changes in tire-road conditions. Further, to reduce the adverse impact of the DEKF performance degradation in nonlinear regions caused by severe maneuvers, a fuzzy decision module is proposed to determine the degree that the KEKF utilizes the DEKF estimation as the reliable measurement. Finally, the sequential measurement-update processing algorithm is developed and the adaptive weighted fusion algorithm is executed to realize the global fusion. The results of both intensive simulations and experiments validate the feasibility and effectiveness of the proposed strategy.



## 1. Introduction

To prevent accidents and increase vehicle safety, many safety control systems, such as anti-lock braking system (ABS) and electronic stabilizing program (ESP), have been developed and introduced into modern automobiles in the past decades. Generally, these control systems require accurate and 'up-to-date' vehicle state information as critical part of the control logic [1,2]. That is, the performance and reliability of such systems are heavily dependent on the accurate measurement/estimation of vehicle state information. Especially, the vehicle sideslip angle is essential state information for a commercial viable safety control system [2–5].

Many approaches have been proposed to estimate or measure the vehicle sideslip angle in the literature. In general, they can be categorized into three methods [3,5,6].

(1) Direct measurement method. In this method, sideslip angle is measured directly through the use of speed-over-ground sensors or the high-performance multiple-antenna Global Positioning System (GPS) [7–9]. Although these sensors can provide accurate information, they are very expensive and unsuitable for large-scale commercial applications. Moreover, such sensors are very sensitive to external environments.
(2) Kinematics-based method. Generally, it utilizes low-cost in-car sensors such as inertial sensors including gyro and accelerometers. It mainly involves numerical integration from these sensors or establishes a kinematic estimator according to their configuration

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relationship [10–13]. This method only considers the kinematic features of vehicle body and can rapidly detect transient change in vehicle behavior. Thus, it can achieve good robustness against vehicle unmodeled dynamics and parameters, changes in driving maneuvers, and variations in tire-road conditions. Besides, it is economical due to large-scale commercial application of low-cost inertial sensors based on microelectromechanical system (MEMS) technology in modern vehicles. However, for numerical integration processing, it suffers from serious accumulative integration errors due to inertial sensor drift/bias [10–13], while for the kinematic estimator discussed in the literature, it becomes unobservable and can cause large estimation errors in the near-zero yaw rate driving condition [14,15].

(3) Vehicle model-based method. In this method, state filters/observers are usually designed by using a reference dynamics model, and can provide a satisfactory estimate when the model of the filters/observers is consistent with the real situation [1–3,5,15–24]. In the design of filters/observers, low-cost sensors are usually adopted. Moreover, to achieve real-time practical applications, it usually adopts a simple but effective model, i.e., the bicycle dynamic model or its variations [3,5,20–23]. The main advantage of this method is that it is relatively robust against sensor drift/bias and can achieve accurate estimation in normal driving maneuvers. However, it depends strongly on the accuracy of vehicle model and parameters. When the influence of nonlinear uncertain factors such as modeling errors and parameter or road-friction variations becomes obvious, its estimation performance deteriorates.

From the discussion above, each method has pros and cons, such as cost, sensitivity to sensor noises, and applicable conditions. The main objective of this paper is to develop a reliable and cost-effective vehicle sideslip angle estimation algorithm with a wide driving-maneuver range. With the popularity of the safety control systems in civil vehicles, it is essential to identify the vehicle sideslip angle reliably and robustly in complex driving situations based on low-cost sensors. The main contribution of this paper is that we propose an adaptive hybrid fusion estimation strategy (A-HFES) to realize reliable vehicle sideslip angle estimation under a wide range of driving maneuvers. Through the developed adaptive fusion algorithm, the A-HFES takes the advantages of both kinematics-based and vehicle model-based estimations.

For the A-HFES, the innovative aspects can be summarized as follows: (1) From the kinematics relation of vehicle strap-down inertial sensors, the kinematics model-based extended Kalman filter (KEKF) is designed as the basic filtering framework of the A-HFES. To overcome the limitations of the kinematics-based method such as accumulative errors or low observability in near-zero yaw rate driving condition, the influence of inertial sensor drift/bias is considered and the estimation from the dynamics model-based extended Kalman filter (DEKF) is introduced to act as the KEKF measurement. The DEKF is established based on a single-track bicycle model. To adapt to the changes in road conditions, a recursive least squares (RLS) algorithm is developed in the DEKF to adaptively estimate the tire cornering stiffness. (2) To reduce the adverse influence of the degradation of the DEKF estimation in nonlinear regions caused by complex driving maneuvers, a fuzzy decision module (FDM) is proposed to determine the degree that the KEKF can utilize the DEKF estimation as its reliable measurement. In actual implementation, the sequential measurement-update processing algorithm is developed to implement the KEKF filtering iteration and then the adaptive weighted fusion algorithm is executed to realize the global hybrid fusion estimation.

The remainder of the paper is organized as follows. Section 2 presents the scheme of the proposed A-HFES in general. Then, Section 3 discusses the design of A-HFES in detail. Thereafter, simulation and experimental results are provided in Section 4, where the performance of the proposed strategy is verified in typical driving scenarios. In this section, the proposed strategy is also compared with the kinematics-based and vehicle model-based methods. Finally, the conclusions are given in Section 5.

## 2. Proposed adaptive hybrid fusion estimation strategy

The proposed adaptive hybrid fusion estimation strategy (A-HFES) is mainly composed of four modules, i.e., multi-sensor module, dynamics model-based extended Kalman filter (DEKF), fuzzy decision module (FDM), and kinematics model-based extended Kalman filter (KEKF) with an improved filtering fusion algorithm, as shown in Fig. 1. This configuration is a hybrid fusion architecture, which combines both kinematics model-based and dynamics model-based estimations through proper adaptive adjustment algorithm to achieve the global fusion estimation. In the actual implementation, the KEKF adopts our improved filtering fusion algorithm, whereas the DEKF uses the standard filtering algorithm.

The multi-sensor module uses low-cost sensors including GPS, MEMS-based inertial measurement unit (IMU), and vehicle sensors (VS) to acquire real-time information of land vehicles. The low-cost GPS characterized by one antenna and low positioning accuracy becomes very popular in vehicles to provide navigation information. In the vehicles equipped with safety control systems, inertial sensors (IMU) are usually installed and work in the strap-down mode with two plane-orthogonal $x$–$y$ accelerometers and a yaw gyro. The vehicle sensors (VS) mainly include a steering angle sensor and four wheel velocity sensors, which are generally also installed in modern civil vehicles.

Based on the kinematics relation of strap-down inertial sensors, the KEKF is designed to act as the basic filtering framework of the A-HFES. To overcome the drawbacks of traditional kinematics-based method such as integration accumulative errors or insufficient observability in near-zero yaw rate conditions, the influence of inertial sensor drift and bias is taken into account during the KEKF design,