Use of flexible models in extended Kalman filtering for vehicle body force estimation

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Abstract

The forces acting on a vehicle are an important area in vehicle dynamics research. Together with the vehicle state, they are essential for determining the dynamic behavior of the vehicle. Accurate knowledge of the external forces, mostly tyre forces, is of great value during the vehicle design phase, and is essential for vehicle control systems that attempt to improve vehicle handling and safety. A complete measurement of the tyre forces, however, requires an expensive and complicated sensor installation which is infeasible for mass-produced vehicles. This has motivated the development of model-based estimation approaches, in which the external forces are estimated simultaneously with the vehicle state from more easily measureable variables combined with a vehicle dynamics model.

The *Kalman filter* (KF) is probably the most popular model-based state-estimation technique [1]. For linear systems with known inputs it provides an explicit recursive solution to the minimization of the trace of the propagated covariance of the state estimates. This technique was later extended to nonlinear systems, leading to the *extended Kalman filter* (EKF). Over the years, also several variations to the KF have been proposed that can simultaneously estimate the system state and unknown inputs. The most popular technique is the *augmented Kalman filter*, in which the unknown inputs are added to the state vector and are treated as additional states to be estimated. A model for the unknown inputs has to be provided.

The classic approach is to couple the augmented-EKF with a simplified vehicle dynamics model, such as the four-wheel vehicle model [2, 3, 4, 5, 6]. The unknown tyre forces are typically modeled as a random walk process, in which the forces are assumed to follow some predetermined probability distribution function. This approach, however, leads to observability issues. The simplified vehicle dynamics model does not contain sufficient system information to differentiate between the contributions of all the different tyre forces (lateral and longitudinal for four tyres). It is thereby impossible to estimate the individual forces. In literature, this issue is typically circumvented by making a priori assumptions regarding the force distribution in order to obtain an observable system. This significantly reduces the applicability and robustness of the force and state estimates since this information is generally not available.

In order to solve this issue, the estimator can be based on a more complete vehicle dynamics model that contains the appropriate system information. Therefore, in recent years, Kalman filtering based on multibody models has been proposed [7], and applied to automotive systems [8, 9]. These studies, however, assume the external forces to be known and/or require position-level measurements which are not always feasible in practice. Furthermore, the flexible behavior of the bodies is not taken into account. It turns out that accounting for flexibility in the model allows to fuse additional sensors providing a source of information that is invaluable for estimating multiple input forces.

In light of the above statements, the authors propose a coupled state and external force estimation approach that takes body flexibility into account. The model is derived according to the floating frame of reference formulation, the flexible behavior of the body is described by a reduced order finite element model. The external forces are modeled as a random walk process. As a result, an observable system is obtained, even for multiple unknown external forces. Furthermore, the model equations are formulated in such a way that no position-level measurements are required.

The proposed approach is demonstrated by means of a numerical experiment in which the longitudinal and vertical external tyre forces acting on a flexible vehicle body model are estimated, see Figure 1.

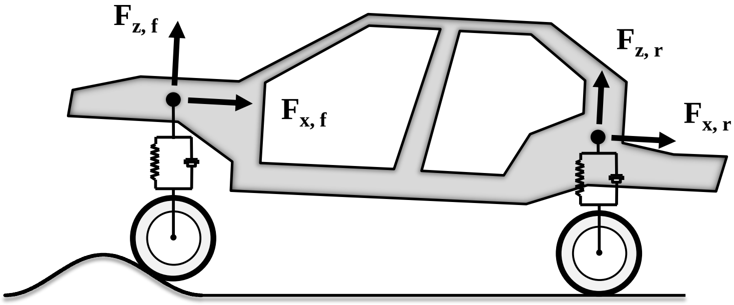

Figure 1: External tyre forces acting on a flexible vehicle body model.

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