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Vehicle parameter estimation using a model-based estimator

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ABSTRACT

In the last few years, many closed-loop control systems have been introduced in the automotive field to increase the level of safety and driving automation. For the integration of such systems, it is critical to estimate motion states and parameters of the vehicle that are not exactly known or that change over time. This paper presents a model-based observer to assess online key motion and mass properties. It uses common onboard sensors, i.e. a gyroscope and an accelerometer, and it aims to work during normal vehicle manoeuvres, such as turning motion and passing. First, basic lateral dynamics of the vehicle is discussed. Then, a parameter estimation framework is presented based on an Extended Kalman filter. Results are included to demonstrate the effectiveness of the estimation approach and its potential benefit towards the implementation of adaptive driving assistance systems or to automatically adjust the parameters of onboard controllers.

1. Introduction

The performance of driving assistance systems may be improved if the unknown parameters of the underlying vehicle model can be measured and updated. Weight of the vehicle, road adhesion, drag coefficient and tire cornering stiffness are examples of unknown parameters. Specifically, the mass of a vehicle plays an important role in terms of acceleration/braking, handling and comfort performance. However, it is subject to variations during operating conditions. For example, the weight of heavy duty vehicles can vary as much as 400% depending on the payload. Anti-lock Braking System (ABS), Electronic Stability Program (ESP), and Adaptive Cruise Control (ACC) are all examples of controllers that rely on the accurate value of the vehicle mass for optimal operation [1]. Current implementations work with the assumption of a maximum payload to provide passengers with the highest level of comfort and safety independently of the load conditions. Therefore, the introduction of automatic load detection systems in onboard controllers would allow them to incorporate such information to further improve their response, providing even more efficient comfort and support to the driver and passengers.

This paper presents an approach to estimate vehicle load during normal driving conditions. Thus, as the vehicle negotiates a turn or passes a slower car, its model parameters are simultaneously updated. The idea is to use virtual sensing that investigates correlations between different variables using physical relationships. A model-based estimator is presented, which is designed to deal with errors in variables and simultaneously slow and fast parameter drifts. In the context of this research, a lateral vehicle dynamic model is used to build an Extended Kalman filter (EKF) and infer estimation of the vehicle mass.

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The paper is organised as follows. Section 2 surveys related research pointing out the novel contributions of the proposed approach. In Section 3, basic concepts of lateral vehicle dynamics are recalled that serve as a basis for the model-based observer detailed in Section 4. The system recursively updates the vehicle mass providing flexibility and adaptability to the observer. Extensive results obtained from the observer in a sequence of simulations are discussed in Section 5, attesting to the feasibility of the proposed approach. Finally, Section 6 concludes the paper.

2. Related work

Vehicle parameter estimation is a critical issue connected with the integration of onboard control systems, especially when these parameters change over time or they are difficult to measure directly [2,3]. The availability of an online estimation method for the weight of a vehicle would be of great value as this parameter affects to a large extent its behaviour in terms of longitudinal, lateral and vertical dynamics. In addition, as the level of driving automation increases, there are more control modules that may benefit from on-line estimation of the vehicle's load, including longitudinal control of platoons of vehicles [4], emission reduction and transmission control [5].

In general, the methods proposed in the literature can be classified in two broad families: sensor-based and model-based methods. In sensor-based methods, an additional dedicated sensor is employed. As an example, the vehicle's weight can be estimated by monitoring the suspension deflection using strain gauges [6] or an electro-magnetic sensor [7]. Recently, Continental has announced a future generation of sensors, which will be fitted directly underneath the tread of the tire to measure the total weight of the vehicle [8]. As the contact patch of the tire increases with the vertical load, by detecting the size of the contact area, it will be possible to infer information about the vehicle's weight.

In contrast, model-based (or indirect) methods use a model of the vehicle, software algorithms and existing sensors (different from direct mass sensors) to estimate the unknown parameters. They represent a promising solution in terms of cost-effectiveness (no extra hardware). Most of the research in this field is based on longitudinal dynamic models. Examples of adaptive controllers for vehicle speed control can be found in [9,10]. Simultaneous estimation of vehicle mass and road grade has been studied by many. For example, an adaptive control scheme for longitudinal control of heavy-duty vehicles is proposed in [11], whereas [12] proposes the use of Recursive Least Squares (RLS) with multiple forgetting factors. An EKF approach is proposed in [13] using two possible measurement configurations: the first one using only the vehicle speed and the second one in conjunction with an additional longitudinal accelerometer. The advantages of using an accelerometer are also shown in [14] where a method to estimate vehicle mass and road grade using an EKF is presented. An active estimator is proposed in [15] that uses an EKF for parameter estimation and model predictive control to adjust vehicle speed. However, methods referring to longitudinal dynamics suffer from high sensitivity to environment conditions, i.e., they work well when the aerodynamic drag coefficient is known and the rolling resistance in the filter matches the road surface. An additional drawback is that they use as input the engine torque whose signal is not always reliable for example during gear shift.

A body of research also uses vertical dynamic models for vehicle mass estimation as in [16–19]. In [20] the vertical response is analysed in the frequency domain to reveal important resonance frequencies related to the value of the sprung mass. Nonetheless, these methods often assume that the terrain profile is known or can be estimated using dedicated instrumentation.

Another strand of the research on mass estimation focuses on powertrain dynamics. For example, in [21] the mass of a truck is estimated by measuring vehicle speed and torque and angular velocity of the engine during acceleration and gear shifting stages, resulting in an accuracy of about 10%.

In this work, an adaptive observer for automatic weight estimation is presented, based on a lateral dynamic model of the vehicle, which represents a novel contribution to the literature. An EKF formulation is proposed where the varying parameter is included in an "augmented" state vector of the vehicle and continuously updated using current sensory data. This formulation has general value and it may be used to track any other time-varying parameter provided that the observability condition is satisfied.

3. Vehicle model

The lateral behaviour is an important aspect in vehicle design, as it directly affects handling and comfort properties. Fig. 1 shows the two degree-of-freedom model used in this research, commonly known as the "bicycle" or "single track" model that holds under the following simplifications [22]: no weight transfer, constant longitudinal velocity u, equal internal and external dynamics so that tires of the same axle can be collapsed, linear range of the tires, rear-wheel drive, negligible motion resistance, and small angle approximation. The two degrees of freedom are the vehicle lateral velocity v and yaw rate r. The equations of motion for the single-track model are given by: