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Adaptive vibration attenuation with globally convergent parameter estimation

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ABSTRACT

Parameter estimation problems can be nonlinear, even if the dynamics are expressed by a linear model. The extended Kalman filter (EKF), even though it is one of the most popular nonlinear estimation techniques, may not converge without sufficient a priori information. This paper utilizes a globally convergent nonlinear estimation method—the double Kalman filter (DKF)—for a vibrating cantilever beam. A globally valid linear time-varying (LTV) model is required by the first stage of the DKF depending on some conditions on input and output excitation. Without considering noise, this LTV model provides the first stage and is globally equivalent to the nonlinear system. Since the neglected input and output noises can degrade the quality of estimation, the second stage linearizes the nonlinear dynamics, utilizing the nominally globally convergent estimate of the first stage, and improves the quality of estimation. Both estimation methods were applied to a cantilever beam setup in real-time. An adaptive linear quadratic regulator utilizes the estimated parameters to attenuate unknown transient disturbances. Different scenarios have been explored, providing a fair comparison between EKF and DKF. These methods have been implemented on an embedded ARM-based microcontroller unit and illustrates improved convergent properties of the DKF over the EKF. The global stability of the DKF is verified and it has been observed that it needs twice the computational cost of the EKF.

1. Introduction

The extended Kalman filter (EKF) has been proven to be an efficient nonlinear state estimation technique in many applications. It has been without a doubt the most popular state estimation technique in different engineering applications; for instance in the field of robotics and mechanical systems, see [1–3]. Its simple and practical algorithm depends on linearized state space models, and by proper tuning, its performance is sometimes comparable to sophisticated estimation techniques such as the moving horizon estimation [4], even though inherently EKF can not deal with constraints in its design. Basically,

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EKF is the solution to a least-squared optimization problem [5] and since it is incorporating nonlinear dynamics, in general, it is reasonable to expect existence of several local minimums or sub-optimal solutions.

Although EKF performs reliably in a nominal scenario, its fundamental drawback originates from the internal feedback loop; i.e. utilizing the estimated state as a linearization point. This feature, even though it simplifies the method in practical sense, makes EKF sensitive to erroneous initial guesses and/or wrong tuning parameters. This means that EKF can begin with a wrong initial guess, which is used to construct a trajectory for calculating the linearized model and consequently ends up with instability. Divergence of the EKF has been reported; see [6–10]. In other words, it is clear that EKF is not globally convergent, but it might not even be locally convergent; see [11,12] for an example. In this paper, a globally convergent estimation method achieves the conventionally true estimates for an arbitrary choice of initial state. On the other hand, a locally convergent estimation technique would require a region of states in which the initial state must be selected to guarantee convergence. Even though the initial state and tuning parameters for a nominal operating point can be selected properly, a sudden change in the structure of system dynamics might create a wrong linearization point for EKF, which potentially results in divergence. Here, we will investigate some of these scenarios in detail and propose a globally convergent estimation technique to adaptively attenuate the vibration of a cantilever beam.

Cascaded Kalman filters making use of two ore more algorithm stages have been proposed before ; e.g. in [13,14] the authors developed a dual Kalman filter for linear time-varying systems to prevent the numerical issues regarding unobservability and rank deficiency of the estimation problem. In the topic of nonlinear state and parameter estimation, a novel type of two stage state estimation approach has been recently introduced in [15], where the first stage (auxiliary estimator) provides a linearization point for the second stage. One of its variants, the double Kalman filter (DKF), has been analyzed in the continuous-time domain [16] and its global stability properties in discrete-time have been studied in [17]. Furthermore, its performance has been evaluated by a simulation study using pseudo-range measurements for position estimation [12].

The first stage of DKF employs a technique, which eliminates nonlinearities of the system using a model transformation that results in a linear time-varying (LTV) model. This model reformulation uses previous outputs and control inputs without optimally considering the input and output disturbances. Suboptimal modeling of disturbances degrades the performance, hence the second stage, a linearized Kalman filter (LKF), utilizes estimates from the first stage as its linearization point. Compared to EKF, where the previously calculated estimates define a linearization trajectory, DKF makes use of a globally convergent estimation technique in its first stage as auxiliary Kalman filter (AKF), which uses the transformed LTV model to provide the second stage with useful information for linearization; independent from the result of LKF. While technically an entire class of cascaded estimation algorithms consisting of two Kalman filter stages can be called *double*, in this paper we will use the term double Kalman filter to refer only to the combination of a first stage based on a LTV model (the AKF) that is augmented by a linearized Kalman filter (the LKF) as its second stage.

This configuration actually prevents the instability mechanisms of internal feedback, which can otherwise result in divergence for an estimation method such as EKF. Other popular nonlinear estimation methods, such as the moving horizon estimation (MHE) [4] and the unscented Kalman filtering (UKF) [18–20] are locally convergent in their nominal design. Since MHE in general is solving a non-convex optimization problem, the existence of several local solutions is expected. Also the divergence properties of the UKF has been studied in [6].

From the implementation point of view, limited resources means limited model complexity and simplified algorithms. A vibrating cantilever beam is the case study we consider in this paper and its parameters are going to be estimated and supplied to a linear quadratic regulator (LQR) for adaptive vibration attenuation. This structure may, for example, represent a flexible wing; see [21]. In these vibrating structures the scale of change in dynamics is significantly longer than the chosen sampling period.

Basically, any system can be described by a complicated nonlinear model, however, sometimes even a simple model can result in computational complexity, that is intractable for applied control problems. As we will later show, the application of such a model in control and estimation is on the verge of not being real-time feasible on current embedded microcontrollers, hence a linear model has been adopted to demonstrate the behavior of the beam, creating a joint state and parameter estimation problem that is nonlinear.

In this paper we derive a globally nominally equivalent LTV model that fully represents the original nonlinear parameter estimation problem for a vibrating structure represented by a single degree-of-freedom model. The existence of this LTV model relies on the persistent excitation (PE) of input and output signals, which is detailed in Section 2.

Furthermore, to the best knowledge of the authors, this paper presents the first experimental real-time validation of the DKF method. In addition to the real-time feasibility study itself, this work takes a look at an embedded application of the DKF on a microcontroller unit (MCU); foreshadowing its possibilities and limitations in low-cost applications.

We put forward an adaptive vibration control scheme in Section 3 making use of the proposed LTV model in a DKF parameter estimation algorithm that is combined with control. Convergence issues and practical performance of both EKF and DKF have been investigated through different implementation scenarios, and are described in Section 4.

The experimental validation of this cascade estimation configuration with a LQR controller is demonstrated on a 32-bit ARM Cortex-M4 architecture MCU. The timing analysis provides an insight in the computational complexity regarding different estimation and control techniques.

Structural changes and external additive measurement noise have also been emulated to contrast the behavior of the two estimation techniques in the adaptive vibration control of the structure in Section 5.