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State and force observers based on multibody models and the indirect Kalman filter

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ABSTRACT

The aim of this work is to present two new methods to provide state observers by combining multibody simulations with indirect extended Kalman filters. One of the methods presented provides also input force estimation. The observers have been applied to two mechanism with four different sensor configurations, and compared to other multibody-based observers found in the literature to evaluate their behavior, namely, the unscented Kalman filter (UKF), and the indirect extended Kalman filter with simplified Jacobians (errorEKF).

The new methods have some more computational cost than the errorEKF, but still much less than the UKF. Regarding their accuracy, both are better than the errorEKF. The method with input force estimation outperforms also the UKF, while the method without force estimation achieves results almost identical to those of the UKF.

All the methods have been implemented as a reusable MATLAB® toolkit which has been released as Open Source in https://github.com/MBDS/mbde-matlab.

1. Introduction

Multibody dynamics [1–4] has become a standard tool to aid the development of new products, reducing development time and cost. Multibody modules are usually available within all the main CAD-CAE software suites, thus allowing to perform offline simulations. However, the increase in computational power and the improvement of multibody simulations allowed their execution in real time, which have been used both in human-in-the-loop (e.g. [5]) and hardware-in-the-loop applications (e.g. [6]), even on inexpensive single-board computers [7]. These new applications allowed the usage of multibody models in driving simulators, virtual reality applications, controllers development, and state observers, among others.

During the last decade, the research on state observers based on multibody dynamics has been quite intense, usually in combination with nonlinear Kalman filters [8,9], although other estimation techniques have been successfully applied to multibody models, such as particle filtering [10]. This research line started with a continuous extended Kalman filter combined with the equations of multibody dynamics in [11], and continued with the application of this method to the model of an automobile [12]. However, this method had a high computational cost, not allowing to run the observer of the automobile in real time. In [13] the unscented Kalman filters [14,15] were combined with multibody models, allowing the implementation of multibody-based state observers without having to derive complicated Jacobian matrices for the transition and

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measurement matrices, since the unscented Kalman filter uses a set of deterministically chosen samples (so called sigma points in this method) to propagate the covariance matrices through nonlinear functions. However, the computational cost continued to be a problem, especially for systems with several degrees of freedom, even considering that the samples employed in the unscented transform are independent, and therefore the computations can be parallelized if several cores are available.

A model reduction technique was applied in [16] to estimate both states and inputs in multibody models, showing the application of the method to a planar half-car model. In [17] a new variation of an unscented Kalman filter and a discrete extended Kalman filter were applied to a four-bar mechanism using only measurements from inertial sensors. The results were validated experimentally, and the observers were run online in real time.

A different approach is used in [18], where a proportional-integral controller is used to calculate the forces applied to a multibody model to make it follow the signal provided by the sensors. The advantage of this approach is that the equations of the multibody model do not need to be explicitly known, and therefore this method can be applied to models build using commercial software. State observers based on linear multibody models with unilateral constraints are presented in [19–21].

In [22] a kinematic state observer is presented. The inputs of the system are obtained from accelerometers, instead of using the dynamics of model. This approach is less sensitive to modeling errors than the previous ones, but it requires more sensors. This method was extended in [23] by adding a force estimation algorithm after the kinematic estimation is performed. There are other kinematic approaches, such as [24,25] in which inertial measurements are combined with the constraints of the system to provide an improved position information.

The use of multibody dynamics has provided a systematic approach and an accurate base to develop state estimators since they include the actual geometry and the kinematic constraints of the systems under study. However, the difficulty of the combination of multibody dynamics with Kalman filters lies in their different mathematical structure, being the Kalman filters formulated for first order systems of ordinary differential equations (ODEs), while multibody dynamics is represented by a second order system of differential-algebraic equations (DAEs). In [26], several methods were presented and compared. One of the most accurate methods, and the most efficient was an indirect observer, referred to as errorEKF. This formulation allowed to run a state observer based on the multibody model of a complete car in real time [27], although the method uses simplified Jacobians, and hence the results can be improved. The description of the validation of the vehicle model used in [27] can be found in [28].

The results presented in [26] show that the errorEKF performs well in most of the tests studied, but the simplifications applied to calculate the Jacobian matrix of its plant lead to great estimation errors in some of the tests. In this work, the exact Jacobian matrix is developed, and the resulting method is accurate even in the cases studien in [26] in which the errorEKF failed to provide reliable results. Moreover, using the same terms, another method adding input force estimation is also presented. This characteristic was not present in any of the methods studied in [26]. The benefits of this method are twofold: on the one hand, it provides input force estimation, which might be the main aim of some applications. On the other hand, the force estimation is used to improve the predictions made by the multibody model, thus achieving more accuracy than the methods without force estimation. In addition, the method with force estimation provides a more natural way to incorporate corrections from acceleration measurements.

All the three methods (the original errorEKF with simplified Jacobian, its counterpart with exact Jacobian, and the augmented version with force estimation) are evaluated with position, velocity, and acceleration sensors. Two different sampling rates are considered for every set of sensors tested. An unscented Kalman filter (UKF) using the trapezoidal rule integration is also included in this study as the reference, since it was the most accurate method of those presented in [26].

In order to test the proposed methods, a four-bar mechanism has been selected because it is a simple closed-chain mechanism. In addition, a five-bar mechanism has also been used, allowing to verify the variation of computational cost with the size of the model. All the methods presented here can be applied to both open-chain and closed-chain mechanisms. However, closed-chain mechanisms were selected in this work because they allow to show all the benefits from incorporating a multibody model into a Kalman filter, such as using a reduced number of sensors (only one measurement per degree of freedom is required) while still obtaining information about the whole system. Although the methods presented here are applied to planar mechanisms, they are general and can be employed with 3D mechanisms.

From the results of the tests, we can say that the errorEKF with exact Jacobian matrix of the plant, referred to as errorEKF_EJ, provides almost the same results as the UKF with trapezoidal rule integration, but with a much lower computational cost. The method with force estimation, provides even better accuracy than the UKF. In addition, it provides the input force estimation, and it is the only method of those considered in this work which provides reliable results when considering accelerometers as the only sensors available. The computational cost is again much lower than that of the UKF.

The different algorithms considered in this work have been implemented in MATLAB® as a reusable toolbox released as Open Source.[1]

[1] See https://github.com/MBDS/mbde-matlab.