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State Estimation Using Multibody Models and Unscented Kalman Filters

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1 Introduction

Over the last years, state estimation in mechanical systems has gained interest with the recent development of real-time state estimation using MBSs (Multibody Systems). In practice, the knowledge of the system's states allows to improve the closed-loop performances of it, reducing the use of expensive sensors by replacing them with virtual sensors, and finally improving reliability by making the system fault tolerant.

On the one hand, numerous works address the synthesis of optimal observers for linear mechanical systems through the KF (linear Kalman Filter). On the other hand, when nonlinear mechanical systems are considered, such as MBSs, only sub-optimal approaches based on the LKF (Linearized KF) have usually been adopted to ensure high-frequency and hard real-time estimation. Indeed, up to now, the use of other types of nonlinear observers using MBSs has only been investigated marginally. The lack of such observers in this field of engineering is mainly due to the difficulty in performing fast integration of the nonlinear equations of motion for MBSs, which usually involve high frequency dynamics and severe nonlinearities. In [1], it is shown how the improvements in multibody dynamics raise the possibility to employ complex models in real-time state observers. The estimation was performed through the EKF (Extended KF) in its continuous form (also known as EKBF (Extended Kalman-Bucy Filter)). Generally speaking, the EKF is the most widely used algorithm for nonlinear estimation. It makes use of the nonlinear system model to perform the time update, but propagates the mean and covariance of the states through the linearized model. As long as the system remains linear on the timescale of the updates, the linearization error and consequently the estimation error stay small and accuracy is guaranteed. However, when nonlinearities are severe, EKF often gives unreliable or divergent estimates. On top of that, the linearization requires a Jacobian matrix which could either be difficult to calculate or not exist. Implementation difficulties are particularly relevant if the system model is modeled by DAE (Differential Algebraic Equations) as it is common in MBSs.

Recent developments in Kalman filtering algorithms make possible to overcome part of the EKF shortcomings. The SPKFs (Sigma-Point Kalman Filters), also called LRKFs (Linear Regression Kalman Filters), use a set of deterministically calculated weighted samples, also named sigma-points or even regression points [2]. This set has to capture at least the first and second order moments of the actual state probability distribution. Each sigma-point is then individually propagated through the nonlinear system equations. The posterior statistics are approximated using simple functions involving the transformed sigma-points. Thereby, this approximation, that does not require the calculation of a Jacobian matrix, is more accurate than the EKF linearization. Different sigma-point set definitions lead to different filter characteristics that allow to give priority to estimation accuracy or to computational efficiency. The

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most famous variants are the UKF (Unscented KF), the CDKF (Central Difference KF) [2], the SSUKF (Spherical Simplex UKF) [3] and their respective square-root forms which allow to improve the numerical stability. Therefore, a natural approach to overcome the EKF problems when employing multibody models would be to use SPKFs. To the best of the authors' knowledge, UKFs have never been applied to the estimation of multibody models.

2 Using multibody models in Unscented Kalman filters

The aim of this work is to present the first implementation of UKFs using multibody models and to discuss their performances. The objective is not to define all the possible ways of using multibody models in UKFs but to present the most relevant. As the multibody formulation is involved, the state-space reduction method known as matrix-R method is employed to convert the DAE of the multibody model into an ODE with a dimension equal to the number of degrees of freedom of the system, as in [1]. Both implicit and explicit integration schemes have been used. The filters' state vector used in this work contains the independent coordinates (in order to minimize the computational cost) and its first time derivative. For the sake of simplicity, additive white Gaussian noise has been considered. The selection of such a multibody formulation and such a state vector leads to a straight-forward implementation of the observer with a direct physical significance that is valid for all the SPKFs. Performance comparisons between UKFs, SSUKFs, their square-root forms and EKBFs have been carried out in simulation on a 5-bar linkage. The mechanism's parameters have been obtained from an experimental 5-bar linkage and the sensor's characteristics from off-the-shelf sensors to reproduce a realistic simulation.

3 Conclusion

This work presents the development of nonlinear state observers based on the UKF family, that use multibody models. Although these filters outperform the accuracy of the EKBF by using better approximations of system nonlinearities, the computational cost related to the sigma-points is high. As a consequence, the choice of the most suitable filter depends on the application requirements and is a trade off between estimation accuracy and computational efficiency. Future works will be devoted to deeper investigations on a wider class of multibody formulations and filters, and to the experimental validation of the proposed observers.

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