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A GAUSSIAN PARTICLE FILTER BASED ON DIFFERENTIAL ALGEBRA FOR NONLINEAR FILTERING PROBLEMS IN CELESTIAL MECHANICS

Abstract

The nonlinear filtering problem consists of estimating the state of a nonlinear stochastic system from noisy observation data. Nonlinear filtering plays an important role in various space-related applications, such as vehicle navigation, orbit determination, target tracking, etc. However, estimation in nonlinear systems is extremely difficult. The optimal Bayesian solution to the problem requires the propagation of the full probability density function. However, for most nonlinear models and non-Gaussian noise problems, closed-form analytic expressions for the posterior distributions do not exist in general. Therefore, any practical estimator must use an approximation of some kind. Different types of approximations have been developed. In case of nonlinear filtering problems the most widely used filter is the Extended Kalman Filter (EKF). The EKF belongs to a class of filters called Gaussian filters that provide Gaussian approximation of the filtering and predictive distributions. Higher-order filters as well as all the EKF variations are also included into this class. These filters have been successfully applied to many problems, but in some cases, depending on the nature of the nonlinearities, they diverge or provide poor accuracy. On the other hand, another class of filters, i.e., sequential importance sampling filters, can provide higher accuracy in describing the posterior distribution, but are computationally intensive. In this paper, we introduce a new Gaussian filter based on Differential Algebra (DA) called the DA-based Gaussian Particle Filter (DAGPF). Essentially, the DAGPF solves the prediction problem through Monte Carlo simulation, which approximates the probability distribution by averaging a large set of random samples. Differential algebra can enhance and speed up the approach of classical Monte Carlo simulation by replacing thousands of integrations with fast polynomial evaluations. The statistics derived from the propagated samples is then used to obtain the information required for the measurement update step, which includes the predicted measurement, the covariance matrix between the state and the measurement, the covariance matrix of the measurement, and so on. As the EKF, the DAGPF approximates the posterior distribution by single Gaussians. The filter performance has been critically analysed by numerical simulations. The navigation problem of a spacecraft in LEO is considered as test case. The problem is modelled in the 2-body frame and both the case of linear and nonlinear measurement is considered. Comparisons are made with the EKF, the Unscented Kalman Filter (UKF), and Particle Filter (PF). The paper will show the theoretical approach and discuss the obtained results.