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Incorporating delayed and infrequent measurements in Extended Kalman Filter based nonlinear state estimation

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ABSTRACT

This work deals with state estimation in the presence of delayed and infrequent measurements. While most measurements (referred to as *secondary* measurements) are available frequently and instantaneously, there might be a delay associated with acquiring other measurements (*primary* measurements) due to long analysis times involved. The primary measurements are usually sampled at irregular intervals and the exact delay is also unknown. The traditional fixed-lag smoothing algorithm, which has been applied for a variety of chemical processes systems, can be computationally inefficient for such situations and alternate methods to handle delays are necessary. In this paper, we analyze several existing methods to incorporate measurement delays and reinterpret their results under a common unified framework (for Extended Kalman Filter). Extensions to handle time-varying and uncertain delays, as well as out of sequence measurement arrival are also presented. Simulation studies on a linear distillation column and a nonlinear polymerization reactor are used to compare the performance of these methods based on RMSE values and computation times. A large scale nonlinear reactive distillation column example is also used to illustrate the practicality of the suggested method.

1. Introduction

The idea of incorporating delayed measurements within a Kalman filter framework has been well recognized in the automation industry. In tracking and navigation systems significant time delays get introduced due to complexity of computation or collisions from multiple sensors reporting data to the estimator. The sampling times are of the order of milliseconds and methods proposed in literature to handle delays [2,10,24,9,23,20] primarily rely on fusing the information from the delayed measurement directly into the filter once it arrives.

In chemical process systems, the problem of handling delayed measurements usually arises due to delays in measurement of certain “quality” variables. These measurements (called primary measurements) are sampled infrequently and are available with a delay, while other variables are measured frequently and the measurements are available instantaneously (secondary measurements). For example, in distillation columns the distillate and bottoms compositions often need to be analyzed in a laboratory as the use and maintenance of online analyzers is infeasible due to economic considerations, whereas *secondary measurements* such as tray temperatures are obtained frequently without any time delay. The primary variables are therefore *inferred* from the temperature measurements, which might be inaccurate due to model errors (plant-model mismatch), sensor bias or unmodeled disturbances. In such cases the primary measurements, which are available with a delay due to offline assays, need to be incorporated accurately into the estimator.

Time delays in multi-rate estimation have often been handled in literature for process systems using suitable augmentation of the states. Gudi et al. [7,8] applied multi-rate state estimation techniques with delayed measurements for a fermentation process in a bioreactor. Tatiraju et al. [21] investigated estimation strategies for a polymerization reactor in the presence of delayed measurements of the molecular weight distribution. Mutha et al. [13,14] proposed an algorithm for multi-rate state estimation in a polymerization reactor, that compensates for the slow measurements by making repeated use of the available slow measurements. Amirthalingam et al. [3] augmented the state with past measurements to handle delays in primary measurement for an identified linear model.

The state augmentation approach has been favored in the chemical and biochemical processes because the state-space formulation is retained, which simplifies the extension of delay-handling methods to other approaches, such as moving horizon estimation (MHE) [18,17], nonlinear dynamic data reconciliation (NDDR) [22], Unscented Kalman Filter (UKF), particle filters, etc. In process systems literature, the so-called fixed-lag smoothing algorithm [6] is most popular. Another popular method is to recalculate the filter

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