Disturbance and phase-switch based adaptive tuning for Kalman Filter in bioprocessing

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Abstract: State estimation is central in monitoring and control of biotechnological processes, yet its performance is often limited by nonlinear dynamics, noisy measurements, and biological variability. In bioprocesses, Kalman filter tuning is commonly kept fixed through prescribed process and measurement noise covariance matrices, Q and R. This implies stationary uncertainty, despite the fact that real fermentation processes often exhibit abrupt changes in process dynamics, sensor reliability, and biological state.

This work presents an empirical adaptive Kalman filter tuning strategy for handling time-varying disturbances and model mismatch, with theoretical support adapted from Mehra (1972). Respiration-related state variables and residual errors are used to update and tune the filter online. The method is evaluated using a four-state bioreactor model adapted from Tuveri et al. (2021). Two laboratory-scale bioreactors were operated under the same initial conditions. Both followed an initial batch phase and were then supplied continuously with a low substrate concentration. After substrate depletion in the batch phase, the reactors diverged: one continued normal growth, whereas the other entered an early stationary phase, consistent with limitation of a key medium component.

This divergence provides a relevant test case for evaluating adaptive filtering under both process disturbances, such as biological variability and phase transitions, and measurement disturbances, such as sensor artifacts. Compared with fixed-covariance filtering, the proposed strategy is intended to improve estimation consistency and disturbance sensitivity while preserving a structure compatible with real-time implementation. The results implies that bioreactor monitoring, fault detection, and model-based control under nonstationary operating conditions can be substantially improved, also when substrate measurements are scarce.

Keywords: State-estimation, Model-mismatch, phase-dependent tuning, Kalman filter.

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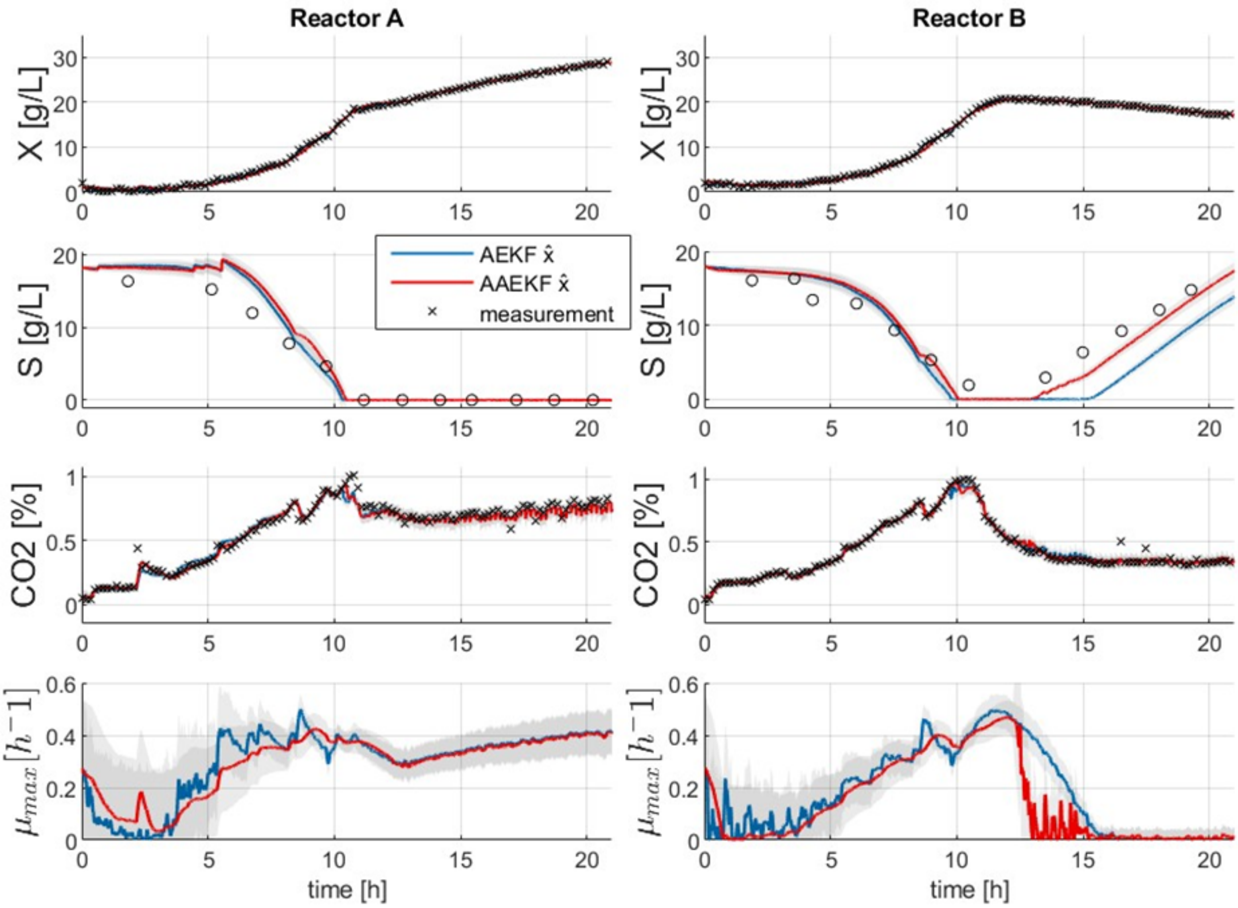

Fig. 1. Preliminary results on the estimation framework. The adapted augmented Kalman filter (AAEKF) provides a more robust and adaptive estimation than a static augmented Kalman filter (AEKF).