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A Bayesian Framework for Fault-Tolerant Control of Linear Systems

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Abstract

In the past decades, several techniques have been developed for the purpose of monitoring, diagnosis and control of processes. A gap is apparent between two major lines of research. On the one hand, data-driven modeling techniques are used primarily for systems where knowledge is limited or hard to come by, ranging from data mining tools such as principal component analysis to case-based reasoning. On the other hand, a full-blown library of techniques is available for situations where very good and accurate models are available. In the latter line of research, accommodation and control reconfiguration are stressed much more than in the former. Limited efforts have been made to bridge or merge the two research lines, despite similar observations in literature (Venkatasubramanian *et al.,* 2003). Motivated by this need, we take an initial step towards the integration of statistical approaches and mechanistic model-based approaches. To this end, we take an established Fault-Tolerant Control method which assumes the availability of an accurate, even exact, nominal model of the system and its faults. In this contribution, we alleviate some of these rigid assumptions by accounting for parametric uncertainty in both system and fault models by means of Bayesian uncertainty propagation. This contribution is focused on the fault diagnosis module of the original method and leaves the development for fault detection and fault accommodation for further research.

Theory and preliminary results

1. Simulated system

For reasons of clarity, a simple system is chose for our first developments. An A→B chemical reaction is simulated in a CSTR. The system is controlled by a PID controller with anti wind-up (positive concentrations). To evaluate our extended fault diagnosis method, sensor and actuator biases are introduced to the system.

2. Kalman-based FTC method in a Bayesian framework

Central to the FTC method is the generation of residual vectors, **e**(k), as the difference between the obtained measurements and their predictions based on the Kalman filter (Harvey, 1989). Under normal conditions, these residuals remain close to zero. Upon introduction of a fault, their magnitude will increase and their profiles follow a certain trajectory in time. For additive faults, like the simulated biases, these can be computed a priori up to a constant, being the magnitude of the respective bias. In this context, fault monitoring resumes to establishing whether residual vectors are too far from zero to be considered normal. Upon positive fault detection, fault diagnosis is then no more than calibrating the magnitude parameter against the observed residuals over a given time window and selecting the fault which gives the best fit. After selecting the best-fitting fault, the model in the Kalman-filter is adjusted and sensor and control are compensated for the estimated bias. We refer to Prakash *et al.* (2002, 2003) for details.

The original FTC method makes the following assumptions which may be invalid in practice

· The model structure and parameters are known exactly.

· Estimated magnitudes for the faults are taken for granted and assumed to be exact when selecting the most probable fault. Since they are estimates by definition this is not a valid.

We therefore extend the technique to account for the indicated uncertainties and make the technique more generally applicable. We limit ourselves to parametric uncertainty in this first phase of the work, i.e. we assume that the model structure is correct. Also, we concentrate on the diagnostic part of the FTC technique. A Bayesian approach is taken and we refer to the developed framework as Bayesian Fault-Tolerant Control (BayesFTC).

Figure 1 shows some of the preliminary results. The log-likelihood to observe a set of residuals, **E**, of an actuator bias, f_j, is shown, conditional to the magnitude of the bias, b. This is done for a set of CSTR model, i.e. for different realizations of the (uncertain) kinetic parameter.

3. Outlook

The proposed extension of the original Kalman-based FTC method will enable the following, once completed:

· To quantify the confidence associated with the diagnostic result

· To account for parametric uncertainties in both the nominal system model and the fault models

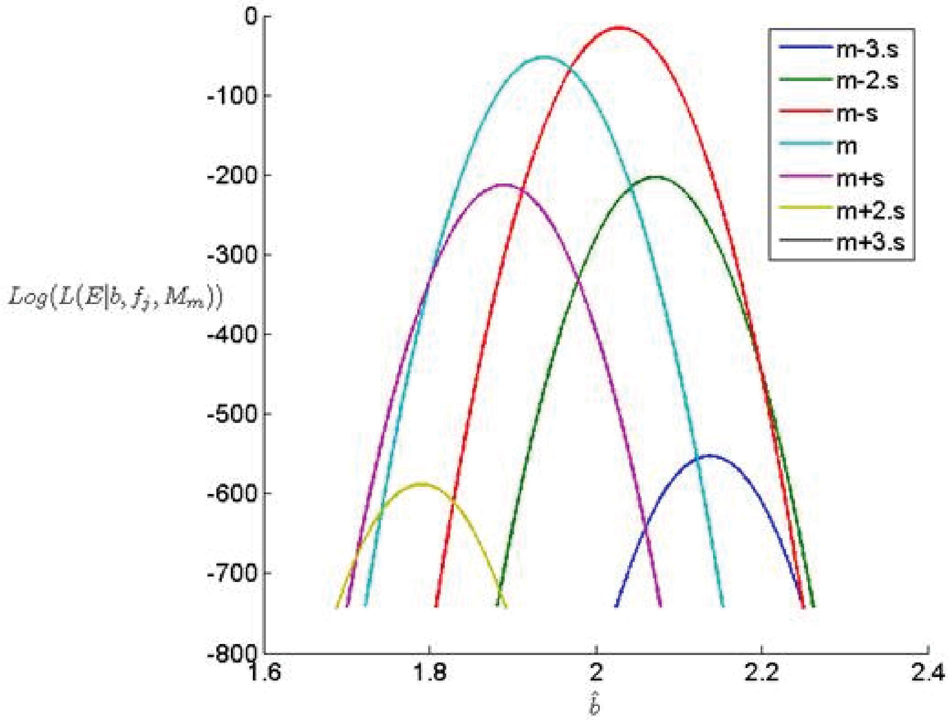

Figure 1: Conditional log-likelihood function, $L(E|b,f_j,M_m)$, for seven model realizations respectively with kinetic parameter equal to the m+/-{1,2,3}.s with m the mean estimate and s the standard deviation. Results given for likelihood evaluation for an actuator bias with an actual actuator bias present in the simulated system.

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