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Optimal fault detection design via iterative estimation methods for industrial control systems

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Abstract

This paper mainly focuses on the design and implementation of iterative estimation methods, and their applications to obtain the optimal fault detection for industrial control systems. More specifically, to generate residual signals with a minimum variance, minimum variance estimation is first addressed in terms of recursive least square (RLS) and Kalman filter by iterative interactions with the process environment. The optimal fault detection is then realized to provide the timely and optimal detection of potential problems by adopting these real-time minimum variance estimation schemes. Finally, the effectiveness of our schemes is demonstrated with a numerical example and experimental studies in the laboratory three-tank system.

1. Introduction

In order to meet high requirements on system performance and reliability, fault detection and diagnosis (FDD) and fault-tolerant control (FTC) are receiving considerably increasing attention, both in the research and application domains [1–7]. As mentioned in [8,9], process monitoring and fault detection is an attractive research area in the control community, in particular when the systems are embedded in safety relevant plants like aeroplanes [10], vehicles [11], networks [12–14], chemical

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processes [15] or robots [16]. Efficient process monitoring and fault detection methods result in an early and optimal detection of potential problems, so as to avoid disastrous consequences and minimize the hazards for personnel, plant and environment [17–22].

When perfect information about the process and the environment around the process is available, Least Square (LS) estimation and Kalman filter algorithms can be applied to achieve an optimal estimation of the system (state) variables, based on which residual vector with a minimum covariance can be generated. Roughly speaking, Kalman filter and the LS algorithms are based on the same principle and applied for different process types, for instance, see [23–25]. Up to now, great efforts have been made to develop these algorithms with unknown statistics knowledge [26–29]. Bayesian, maximum likelihood, correlation and covariance matching are the four major categories, which require considerable computing time and memory [29]. Refs. [30,31] proposed an iterative generalized least square (IGLS) method to update the covariance matrix, which provides potential to achieve an iterative and online real-time optimization of LS estimation. So far, numerous results have been proposed to apply LS and Kalman filter algorithms to the process monitoring and fault detection of systems with known statistics [32–34]. When it comes to unknown or changing environment, the performance of the above process monitoring and diagnosis scheme becomes poor. To our best knowledge, there are few investigations on the optimization of process monitoring and fault detection for systems under unknown environment information.

Over the last decades, application of reinforcement learning to deal with optimal control issues has received considerable attention [35–39]. It has been demonstrated that by means of reinforcement learning methods, real-time optimization of feedback control systems can be successfully achieved [35,36]. The core of reinforcement learning methods is iterative interactions between the control system and environment and real-time evaluation of the control performance.

Inspired by the reinforcement learning technique and its application to deal with control problems, the major objective of this paper is to approach the optimal process monitoring and fault detection by means of iterative optimization of minimum variance estimations in order to generate residual signals with a minimum variance. The optimization is carried out by iteratively interactions with the process environment, so as to cope with the unknown information or unavoidable changes in a real-world environment. Motivated by these observations, two topics will be mainly addressed in this paper:

- proposing an algorithm to iteratively optimize the Recursive Least Square (RLS) estimation for time-varying static processes along the lines of IGLS method and realizing the design of optimal fault detection;
- developing the iterative optimization algorithm of Kalman filter and the associated fault detection scheme for dynamic processes.

It should be pointed out that the process monitoring and fault detection algorithms are updated based on batches of process data which comprise the information of the environment knowledge. This real-time and iterative optimization procedure is of great industrial application interests.

The rest of the paper is organized as follows. In Section 2, the needed preliminaries and problem formulation are respectively introduced. The iterative optimization of RLS and its application to optimal fault detection is proposed in Section 3. The scheme of iterative optimization of Kalman filter and fault detection is discussed in Section 4. A numerical example

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