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Low-order self-tuner for fault-tolerant control of a class of unknown nonlinear stochastic sampled-data systems

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Abstract

Based on the modified state-space self-tuning control (STC) via the observer/Kalman filter identification (OKID) method, an effective low-order tuner for fault-tolerant control of a class of unknown nonlinear stochastic sampled-data systems is proposed in this paper. The OKID method is a time-domain technique that identifies a discrete input–output map by using known input–output sampled data in the general coordinate form, through an extension of the eigensystem realization algorithm (ERA). Then, the above identified model in a general coordinate form is transformed to an observer form to provide a computationally effective initialization for a low-order on-line "auto-regressive moving average process with exogenous (ARMAX) model"-based identification. Furthermore, the proposed approach uses a modified Kalman filter estimate algorithm and the current-output-based observer to repair the drawback of the system multiple failures. Thus, the fault-tolerant control (FTC) performance can be significantly improved. As a result, a low-order state-space self-tuning control (STC) is constructed. Finally, the method is applied for a three-tank system with various faults to demonstrate the effectiveness of the proposed methodology.

Keywords: Fault-tolerant control; Self-tuning control; Stochastic system; System identification

1. Introduction

Due to the growing demand for reliability, maintainability, and survivability in some modern control systems, the importance concept and technology has been employed in FTC [1–4]. Indeed, this requires solutions that are very costly in both hardware and development effort. For example, airplanes are required to attain survival in the presence of actuator failures or surface damage, and some robots are utilized in inaccessible

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or hazardous environments and difficult to be repaired in a short space of time. Therefore, FTC is very important from the viewpoint of safety, as well as reduced production costs.

The FTC needs to take an appropriate control action when there are large parameter variations due to faults as well as other uncertainties. The present FTC methods can be classified into two groups: passive and active. The passive FTC system uses a fixed controller and does not consider whether the fault has occurred or not. Once a fault has occurred, the passive FTC system can tolerate it by maintaining stability and some certain performance. They include methods such as integrity control, reliable control, and robust H_∞ control, etc. [5–7]. Clearly, it is a very difficult task to design such fixed controllers, hence up to the present only linear time-invariant systems have been considered. In an active FTC system, faults are detected, and the controllers are reconfigured accordingly in a real-time. They can be classified in two types: hardware redundancy and model-based analytical redundancy. The hardware redundancy uses extra components which are used as backup in case of failures. Because of the complexity of incorporating redundant hardware, model-based methods in the spirit of analytical redundancy have dominated the active FTC researches. The model-based redundancy method which is used to reconfigure the controller includes such as model-following method, adaptive control, eigenstructure assignment, pseudo-inverse, neural networks and fuzzy logic, etc. [8–15]. In the meanwhile, many fault detection and diagnosis techniques are developed to cooperate with the model-based redundancy method [15,16].

A state-space STC of the adaptive FTC against partial actuator and system failures is proposed here for a class of unknown nonlinear stochastic sampled-data systems. The proposed approach uses a modified Kalman filter estimate algorithm with a modification of parameter covariance instead of the standard recursive extended-least-squares (RELS) algorithm that estimates parameters in the STC for adapting to parameter variations. It is well-known that the high-gain controller can suppress system uncertainties such as nonlinear perturbations, parameter variations, external disturbances, so that the same self-tuning structure is then can be used with a modified estimate algorithm to repair the drawback of the control system due to abrupt and/or gradual actuator and/or system failures.

In recent years, a new state-space innovation form corresponding to the adjustable ARMAX model-based identification scheme for nonlinear stochastic system has been developed in [17]. However, the order of the ARMAX model for a nonlinear system is generally higher than the one for a linear system, therefore a significantly large number of parameters have to be estimated. This causes a higher covariance error and a higher cost for handling the nonlinear system randomness. Indeed, the structure of the new state-space innovation form for nonlinear systems is same as the one for linear systems; however, the dimensions of the estimated states are different. To date, the problem of order determination for stochastic systems is still not satisfactorily solved. Therefore, the mentioned system changes caused by the unknown system or actuator failures are more challenging for FTC in general.

To overcome the aforementioned order-determination problem and to tackle the related challenging self-tuning control problem, based on the OKID method and a suitable state transform (from the general coordinate form to the observer coordinate form), subject to an acceptable closed-loop performance, a low-order tuner is designed in this paper, for estimating the equivalent state of the unknown nonlinear stochastic system using known input–output sampled data. To prepare for the presentation, a few well-developed techniques and methods will be first briefly reviewed below.

Recall a well-known early approach for system identification based on the concept of minimum realization [18], which yields a state-space model of lowest possible dimension among all realizable systems with the same input–output relations. This result was lately subsequently extended to the eigensystem realization algorithm (ERA) [19]. ERA is a time-domain technique that directly solves for the system Markov parameters, or sampled pulse response histories, from the known input–output data of the system.

To that end, the OKID technique is an extension of ERA that permits efficient identification of large flexible structures (see e.g. [20,21]). Based on the concepts of stochastic estimation and techniques of deterministic Markov parameter identification, OKID directly generates a local linear state-space model for the underlying nonlinear system. The OKID method is a valuable tool for model linearization, which has been proved very effective in various difficult spacecraft identification problems [22].

Theoretically, for a nonlinear system with precise differential equations, a high-order linear model always gives a better approximation than a low-order one. However, for the state-space self-tuning control problem,