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Research Article

A modified NARMAX model-based self-tuner with fault tolerance for unknown nonlinear stochastic hybrid systems with an input–output direct feed-through term

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ABSTRACT

A modified nonlinear autoregressive moving average with exogenous inputs (NARMAX) model-based state-space self-tuner with fault tolerance is proposed in this paper for the unknown nonlinear stochastic hybrid system with a direct transmission matrix from input to output. Through the off-line observer/Kalman filter identification method, one has a good initial guess of modified NARMAX model to reduce the on-line system identification process time. Then, based on the modified NARMAX-based system identification, a corresponding adaptive digital control scheme is presented for the unknown continuous-time nonlinear system, with an input–output direct transmission term, which also has measurement and system noises and inaccessible system states. Besides, an effective state space self-turner with fault tolerance scheme is presented for the unknown multivariable stochastic system. A quantitative criterion is suggested by comparing the innovation process error estimated by the Kalman filter estimation algorithm, so that a weighting matrix resetting technique by adjusting and resetting the covariance matrices of parameter estimate obtained by the Kalman filter estimation algorithm is utilized to achieve the parameter estimation for faulty system recovery. Consequently, the proposed method can effectively cope with partially abrupt and/or gradual system faults and input failures by the fault detection.

1. Introduction

The state-space self-tuning control methods [1,2] have been shown to be effective in designing advanced adaptive controllers for linear multivariable stochastic systems [3]. In those approaches [1,2], the standard Kalman state-estimation algorithm [4] has been embedded into an online parameter estimation algorithm. They utilize state-space self-tuners based on innovation models, where (i) the equivalent internal states can be estimated successively; (ii) the stable/unstable and minimum/nonminimum-phase multivariable systems can be controlled accurately; (iii) the self-tuners are simple, reliable and robust; and (iv) the adaptive Kalman gain can subsequently be obtained.

Polynomial expansions are used extensively in nonlinear system analysis, where the system has no the input–output direct feed-through term. If the response of a system is dominated by nonlinear characteristics, it is general necessary to use a nonlinear model, and this immediately raises the problem of what class of models to use. The traditional NARMAX model, which was first introduced and rigorously derived by [5], provides a unified representation for a wide class of nonlinear stochastic systems [6]. The NARMAX model is not restricted to polynomial systems and can be expanded as a rational model [7]. The advantage of the rational model is the efficiency with which it can severely describe nonlinear characteristics with a few parameters. These results can be related to the models introduced by Sontag [8]. When they are extended to the unknown stochastic case, these models provide a class of rational models [7] which can be used as the basis of parameter estimation algorithms.

Over the past decades, there has been a growing interest in the singular system. The applications of singular system in large-scale systems, circuits, power systems, economics, control theory, robots, and other areas [9,10] are extensively. The tracker and fault tolerance control for the linear singular system is given in [11]. Actually, the singular system can be converted into an equivalent regular system which may have a direct transmission term from input to output. Indeed, the singular system without the

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impulse mode is just a special class of the regular system with the direct transmission term from input to output. To the author's knowledge, the NARMAX model-based state-space optimal tracker with fault tolerance for the regular nonlinear sampled-data system containing the direct transmission term from input to output has not been proposed in literature.

The setting of initial parameters of the NARMAX model is important to reduce the time of the on-line identifying process, so the observer/Kalman filter identification (OKID) [12,13] is applied to estimate the initial parameters of the NARMAX model and order determination for the online recursive extended-least-squares (RELS) identification in this paper. The well-known process of on-line system identification of ARMA/NARMAX model-based state-space self-tuning control for the system without input–output feed-through term requites the one-step past control input and some other measurements to determine the current control input. However, for the case of the system with input–output feed-through term, it requires to have the current control input, which implies there is a causal problem. To overcome this problem, a modified NARMAX model-based system identification for the unknown nonlinear system with the input–output feed-through term will be proposed in this paper. The OKID [12,13] is performed in off-line, so there is no causal problem to identify the input–output feed-through term. However, it does not work for the on-line case. To the author's knowledge, no on-line OKID has been proposed in literature. The identified observer of the state-space self-tuning control is in the state-space innovation form; however, the one identified by the OKID is in the general coordinate form. So, the transformation between these two will be briefly introduced in this paper. Then, based on the modified NARMAX model and its corresponding state space innovation form, a digital controller design to deal with the system with a direct transmission term [11] is presented.

One point must be noticed that the state-space self-tuning control (STC) scheme for nonlinear stochastic hybrid systems proposed by Guo et al. [14] estimates the system parameters at every sampling instant, then designs an adaptive controller based on the estimated parameters also at every sampling instant. The framework of the state-space STC seems to agree with that of the active fault tolerance in a real time. For faulty system recovery, we use the modified Kalman filter estimation algorithm by utilizing the modified covariance matrices from estimated errors to improve the parameter estimation [15], instead of utilizing the estimated covariance matrices which is obtained from the RELS algorithm in the conventional STC scheme for adapting parameter variations. About the faults, abrupt faults and gradual faults are considered in this paper.

This paper is organized as follows. Problem description and motivation of this paper is given in Section 2. Section 3 summaries some preliminary for the proposed method. Section 4 presents the modified NARMAX (in polynomial) model-based state-space self-tuner for unknown nonlinear stochastic hybrid systems with the input–output feed-through term. In Section 5, a fault tolerance scheme by modifying the conventional state-space self-tuning control approach for the unknown multivariable stochastic system with input–output feed-through term is proposed. Finally, an illustrative example is shown in Section 6.

2. Problem description and motivation

Consider the class of continuous-time nonlinear stochastic systems as follows:

$$\dot{x}(t)=f(x(t))+g(x(t))u(t)+w'(t), \tag{1a}$$

$$y(t)=h(x(t))+d(x(t))u(t)+v'(t), \tag{1b}$$

where $f:\Re^n\to\Re^n$, $g:\Re^n\to\Re^{n\times m}$, $h:\Re^n\to\Re^p$, $d:\Re^n\to\Re^{pm}$, $u(k)\in\Re^m$ is the control input, $x(k)\in\Re^n$ is the state vector, $y(t)\in\Re^p$ is the measurable output vector, $w'(t)$ and $v'(t)$ are uncorrelated white noise processes. The on-line system identification methodologies of ARMAX and/or NARMAX (in polynomial and/or rational) model-based state-space self-tuning control with/without fault tolerance for the known/unknown linear/nonlinear system without input–output feed-through term estimate the current system parameters and state at time index $t=kT$ based on control input up to time index $t=kT-T$, $u(kT-T)$, and output measurements up to either $t=kT-T$ or $t=kT$. Then, determine the current control parameter $u(kT)$ based on the estimated state $\hat{x}_o(kT)$, where $\hat{x}_o(kT)$ denotes the estimated current state for the constructed observer represented in the observer canonical form, so that the system output $y(t)$ can well track the desired reference $\Gamma(t)$ at time index $t=kT+T$, i.e. $y(kT+T)\cong\Gamma(kT+T)$, but not $y(kT)\cong\Gamma(kT)$. The interpretation of this comment is that the current $u(kT)$ is determined by the current state $\hat{x}_o(kT)/x(kT)$, which implies $y(kT)$ determined by $u(kT-T)$ exists already. So, $u(kT)$ cannot affect $y(kT)$ anymore. The above observation shows that one needs $u(kT-T)$ first, then identifies the system parameter/state, and determines the current control input $u(kT)$ finally, which is the well-known on-line process of the system identification methodology for the state-space self-tuning control.

However, when the system has the input-output feed-through term, one needs to have the current control input $u(kT)$ first for the on-line system identification, then determines the control input $u(kT)$ later, which induces the so-called casual problem. To overcome this problem, a modified NARMA model-based system identification for the unknown nonlinear system with the input–output feed-through term will be proposed in this paper.

The structure of the state-space STC scheme includes a parameter and state estimator and a controller design. A typical state-space STC structure is illustrated in Fig. 1.

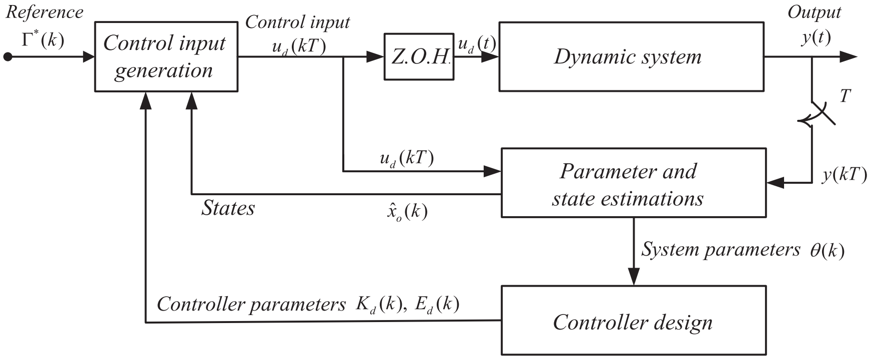

Fig. 1. Block diagram of a typical state-space self-tuning control.