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Fuzzy Sets and Systems 297 (2016) 112–127

FUZZY sets and systems

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Sampled-data $\mathscr{H}_-/\mathscr{H}_\infty$ fault detection and isolation for nonlinear systems in T–S form: An approximate model approach

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Received 21 October 2014; received in revised form 14 May 2015; accepted 17 November 2015

Available online 27 November 2015

Abstract

A direct discrete-time design methodology for the sampled-data fault detection and isolation (FDI) problem is proposed for a nonlinear system in Takagi–Sugeno form. The generalized observer scheme is adopted, accompanied by a bank of the sensors' number of observers. A sufficient condition to find observer and residual gains, based on an accessible approximate—rather than unavailable exact—discrete-time model is proposed in terms of matrix inequalities so that it exhibits $\mathscr{H}_-/\mathscr{H}_\infty$ performance and asymptotic stability. An algorithm involving a convex optimization is presented using the cone complementary linearization technique. We show that the FDI observer ensures (modified) $\mathscr{H}_-/\mathscr{H}_\infty$ performance and Lagrange stability, when it is connected to the actual nonlinear system.

Keywords: Sampled-data fault detection and isolation (FDI); Takagi–Sugeno fuzzy system; Direct discrete-time design; Approximate discrete-time model; $\mathscr{H}_-/\mathscr{H}_\infty$ performance

1. Introduction

Recent complications of industrial processes clearly require elaboration of fault detection and isolation (FDI) methodologies. They can be classified into two aspects. The first is the data-driven approach, which is effective in situations where the precise model of a process is not feasible. Successful application to a suspension system is reported in [1] and the key-performance-indicator-based technique is improved in [2]. Evolutionary achievements in these research efforts are reviewed well in [3,4].

On the other hand, when the mathematical dynamics are accessible, the model-based approach is suitable for FDI. In particular, observer-based techniques have been widely pursued by using well-founded estimation theories. To detect a fault in this direction, the observer should be designed for the map from a fault to a residual to be as sensitive, and from a disturbance to be as robust, as possible. To isolate a fault, the map from a fault to a residual should be

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http://dx.doi.org/10.1016/j.fss.2015.11.012

non-interactive [5]. A variety of methodologies have been sought in the frames of unobservability distributions [6], $\mathscr{H}_\infty$ fault sensitivity [7], and $\mathscr{H}_\infty$ model matching [8]. Comprehensive surveys [9,10] are available that outline other diverse methodologies. Among them, an intuitive approach for detection would be an $\mathscr{H}_-/\mathscr{H}_\infty$ index [11]. A simple yet effective alternative for isolation is the generalized observer scheme [12]. However, these concentrate on linear dynamics.

Being aware that nonlinearity is the major obstacle to satisfactory FDI, several techniques have been developed for nonlinear systems via neural networks [7], the sliding mode [13], and geometric [5] approaches. Zhang et al. [14] investigated nonlinear sensor FDI when the fault is partially known. A relaxed nonlinear geometric FDI method is presented in [15]. Yoo studied a nonlinear fault detection and accommodation problem with unknown delayed faults [16]. Some results have been released for a class of nonlinear systems in Takagi–Sugeno (T–S) form. The bulk of them concern the detection problem for pure continuous- [17,18] or discrete-time dynamics [19–22].

Signal hybridism in sampled-data frameworks often causes design complexity. Thus one prefers to convert the dynamics into a homogenized-signal model in two ways and then synthesize a controller in a suitable single domain. One way to do this is direct discrete-time design [23] to construct a discrete-time controller based on the discrete-time model of a sampled-data plant. Its drawback is that the stability established in design is not guaranteed in operation because the discrete-time model is necessarily only *approximate*, rather than *exact*, owing to the general un-solvability of a nonlinear initial value problem. The other approach is to transform sampled-data dynamics into a continuous-time input-delay model [24] which guarantees the stability attained in design as expected. However, it is worth noting that the approach seems to be inapplicable to observer-based FDI: the residual is generated from the output measured in a uniform-sampling manner. Hence, an unavailable exact discrete-time model of a nonlinear plant is required again, as it was in the preceding approach. Research is needed to develop a new FDI technique for sampled-data T–S fuzzy systems in order to keep pace with the recent trend of digitalization in control technologies [23,25–30].

Motivated by the discussion above, we propose a direct discrete-time methodology for $\mathscr{H}_-/\mathscr{H}_\infty$ FDI for sampled-data nonlinear systems in T–S form based on the approximate discrete-time model. The generalized observer scheme is adopted with a bank of the sensors' number of observers. Both observer gains and residual gains (which are not necessarily constrained (symmetric or triangular) as in [11,31]) are to be found. A sufficient design condition is developed in terms of matrix inequalities. An algorithm involving convex optimization is presented using the cone complementary linearization technique [32]. A crucial point to be investigated is whether the FDI observer bank synthesized via the approximate discrete-time model indeed works well with actual nonlinear dynamics. In this respect, we show that the FDI observer bank designed so that the approximate discrete-time model has $\mathscr{H}_-/\mathscr{H}_\infty$ performance and asymptotic stability still ensures $\mathscr{H}_-/\mathscr{H}_\infty$ performance (albeit slightly degraded) and Lagrange stability of the actual nonlinear system. An example is included to visualize the theoretical analysis and design.

Notation $A = A^T \prec 0$ is a negative definite matrix. $\|x\|$ stands for a Euclidean norm while $\|x\|_{l_2}$ ($\|x\|_{\mathscr{L}_2}$) indicates the l_2 ($\mathscr{L}_2$) norm on a finite horizon $[0, k_f]$, $k_f \in \mathbb{Z}_{>0}$, ($[0, k_f T]$), where $T \in \mathbb{R}_{>0}$ is a non-pathological sampling period. The symbol $*$ denotes a transposed element in a symmetric position. An ellipsis is adopted for long symmetric matrix expressions, e.g.,

$$K^T \begin{bmatrix} \mathrm{He}\{S\} & * \\ M & Q^T * \end{bmatrix} * := K^T \begin{bmatrix} S + S^T & M^T \\ M & Q^T Q \end{bmatrix} K.$$

For any vector $y \in \mathbb{R}^m$ and matrix $C \in \mathbb{R}^{m \times n}$ we define as follows:

$$y^{\bar{p}} := \begin{bmatrix} y_1 \\ \vdots \\ y_{p-1} \\ y_{p+1} \\ \vdots \\ y_m \end{bmatrix}, \quad C^{\bar{p}} := \begin{bmatrix} C_{11} & \cdots & C_{1n} \\ \vdots & & \vdots \\ C_{p-1,1} & \cdots & C_{p-1,n} \\ C_{p+1,1} & \cdots & C_{p+1,n} \\ \vdots & & \vdots \\ C_{m1} & \cdots & C_{mn} \end{bmatrix}.$$