Fault Detection and Fault-Tolerant Control for Nonlinear Systems

Linlin Li

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Linlin Li
Duisburg, Germany

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To my parents and Wanjun

Preface

Associated with increasing demands on system safety and reliability, fault detection (FD) and fault-tolerant control (FTC) have attracted considerable attention in both research and application fields. Due to the continuously increasing system automation, integration and complexity degrees, industrial processes are typically nonlinear. Therefore, developing FD and FTC approaches for nonlinear systems belong definitely to the most remarkable and challenging topics.

This work is devoted to address the analysis and design issues of observer-based FD and FTC for nonlinear systems. In the first part of the thesis, the configuration of nonlinear observer-based FD systems is formulated by parameterizing the residual generators. Based on the parameterization form, the nonlinear observer-based FD systems are parameterized as well as the threshold settings. Furthermore, the existence conditions of the nonlinear observer-based FD systems are studied to gain a deeper insight into the construction of the FD systems.

The second part of the work focuses on the developments of FD schemes by dealing with the proposed conditions with the aid of the Takagi-Sugeno (T-S) fuzzy dynamic modelling techniques. To further improve the FD performance, an alternative fuzzy observer-based approach is proposed by making use of the knowledge provided by the fuzzy models of each local region and weighting the local residual signal by means of different weighting factors. This is motivated by the fact that unlike linear systems with unified dynamics over the whole working range, the local behavior of nonlinear systems can be significantly different.

With the FD system at hand, it is important to re-configure the controller to maintain or recover the system operations after an alarm is given. For this purpose, the third part of the work is dedicated to two FTC configurations for a class of nonlinear systems. The proposed architectures provide an integrated solution that has advantages to make the plant maintenance, repair and operations easier to handle. Finally, the derived FD and FTC approaches are verified by two benchmark processes. The application results demonstrate the effectiveness of the developed methods.

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Finally, I would like to dedicate this work to my family, especially my parents, my sister and my brother for understanding and supporting me in whatever I decide to do - especially my husband, Wanjun, for his patience and support.

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Abbreviations

Abbreviation	Expansion
CSTH	continuous stirred tank heater
EIMC	extended internal model control
FD	fault detection
FDD	fault detection and diagnosis
FDF	fault detection filter
FDI	fault detection and isolation
FE	fault estimation
FTC	fault-tolerant control
GIMC	generalized internal model control
HJI	Hamilton-Jacobi inequality
H-PRIO	high-priority
IMC	internal model control
IOS	input-to-output stable
LCF	left coprime factorization
LMI	linear matrix inequality
L-PRIO	low-priority
LPV	linear parameter-varying
LTI	linear time-invariant
NCS	networked control system
PID	proportional-integral-derivative
PD	proportional-derivative
PI	proportional-integral
RCF	right coprime factorization
ROS	robust-to-output stable
RK	Runge-Kutta
SKR	stable kernel representation
SIR	stable image representation
T-S	Takagi-Sugeno

Mathematical notations

Notation	Description
$\mathcal{U}$	a vector space of functions from a time domain to a Euclidean vector space
$\mathcal{U}^s$	the stable subset of $\mathcal{U}$
$\Sigma^{\mathbf{x}_0} : \mathcal{U} \to \mathcal{Y}$	An operator Σ with input signal space $\mathcal{U}$, output signal space $\mathcal{Y}$ and initial condition $\mathbf{x}_0$
$\Sigma_a^{\mathbf{x}_{a,0}} \circ \Sigma_b^{\mathbf{x}_{b,0}}$	the cascade connection of two systems $\Sigma_a^{\mathbf{x}_{a,0}} : \mathcal{U} \to \mathcal{Y}$ and $\Sigma_b^{\mathbf{x}_{b,0}} : \mathcal{Y} \to \mathcal{Z}$
$\mathcal{RH}_\infty$	the set of all stable transfer matrices
$\forall$	for all
$\in$	belong to
$\Longrightarrow$	imply
$\Longleftrightarrow$	equivalent to
$\lVert \cdot \rVert$	Euclidean norm of a vector
$\lVert \cdot \rVert_2$	$\mathcal{L}_2$ norm of a signal
$\hat{\mathbf{x}}$	estimate of the state vector $\mathbf{x}$
$\mathbf{x}$	a vector
$\mathbf{X}$	a matrix
$\mathbf{X}^T$	transport of $\mathbf{X}$
$\mathbf{X}^{-1}$	inverse of $\mathbf{X}$
$\mathbf{X} > \mathbf{0}$	$\mathbf{X}$ is positive definite matrix
$\mathcal{R}^n$	space of n-dimensional vectors
$\mathcal{R}^{n \times m}$	space of n by m matrices
$\mathtt{Sym}\{\mathbf{X}\}$	$\mathbf{X} + \mathbf{X}^T$
$\mathcal{B}_\delta$	space of the vector $\mathbf{x} \in \mathcal{R}^n$ satisfying $\lVert\mathbf{x}\rVert \le \delta$ for some $\delta > 0$
$V_{\mathbf{x}}(\mathbf{x})$	$\frac{\partial V(\mathbf{x})}{\mathbf{x}}$
$J(\mathbf{r})$	evaluation function
J_{th}	threshold
$\mathbf{u}_\tau$	the truncation of $\mathbf{u}$ at τ, i.e. $\mathbf{u}_\tau(t) = \mathbf{u}(t)$ if $t \le \tau$, and $\mathbf{u}(t) = \mathbf{0}$ if $t > \tau$
$\mathbf{I}_m$	m by m identity matrix
$\beta(\cdot) \in \mathcal{K}$	$\beta : \mathcal{R}_+ \to \mathcal{R}_+$ is continuous, strictly increasing, and satisfies $\beta(0) = 0$
$\beta(\cdot) \in \mathcal{K}_\infty$	$\beta \in \mathcal{K}$, and in addition, $\lim_{s\to\infty} \beta(s) = \infty$
$\beta(\cdot) \in \mathcal{L}$	β is continuous, strictly decreasing, and satisfies

	$\lim_{s\to\infty}\beta(s)=0$
$\phi(s,t)\in\mathcal{KL}$	for each fixed t the function is of class $\mathcal{K}$ and for each fixed s it is of class $\mathcal{L}$