New fault tolerant control strategy for nonlinear systems with multiple model approach

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Objective of diagnosis and fault tolerant control

Actuator fault tolerant control of nonlinear systems

- Fast fault estimation (diagnosis)
- Fault accommodation

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Proposed strategy

- Takagi-Sugeno representation of nonlinear systems
- Observer-based fault tolerant control design
- Extension of the existing results on linear systems
- Relaxed design conditions with Polya's theorem

1. Takagi-Sugeno approach for modeling
   - Takagi-Sugeno principle
   - Takagi-Sugeno model
2. Fault tolerant control design
3. Relaxed stability conditions : Polya's theorem
4. Numerical example
5. Conclusions

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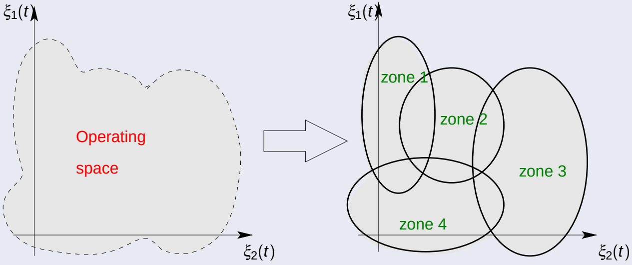
Takagi-Sugeno approach for modeling

- Operating range decomposition in several local zones.
- A local model represents the behavior of the system in a specific zone.
- The overall behavior of the system is obtained by the aggregation of the sub-models with adequate weighting functions.



Nonlinear system　　　Multiple Model representation

The main idea of Takagi-Sugeno approach

- Define local models $M_i, \quad i = 1..r$
- Define weighting functions $\mu_i(\xi), \quad 0 \leq \mu_i \leq 1$
- Define an agregation procedure : $M = \sum \mu_i(\xi) M_i$

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Interests of Takagi-Sugeno approach

- Simple structure for modeling complex nonlinear systems.
- The specific study of the nonlinearities is not required.
- Possible extension of the theoretical LTI tools for nonlinear systems.

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- Simple structure for modeling complex nonlinear systems.
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The difficulties

- How many local models ?
- How to define the domain of influence of each local model ?
- On what variables may depend the weighting functions μ_i ?

Obtaining a Takagi-Sugeno model

- Linearisation of an existing nonlinear model around operating points
  R. Murray-Smith, T. A. Johansen, Multiple model approaches to modelling and control. Taylor & Francis, 1997.
- Direct identification of the model parameters
  K. Gasso, Identification des système dynamiques non linéaires : Approche multimodèle, Ph.D., Institut National Polytechnique de Lorraine, France, 2000.
- Nonlinear transformations of an existing nonlinear model
  A.M. Nagy, G. Mourot, B. Marx, G. Schutz, J. Ragot, Model structure simplification of a biological reactor, 15th IFAC Symp. on System Identification, SYSID'09, 2009

Basic model

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} \mu_i(\xi(t))(A_i x(t) + B_i u(t)) \\ y(t) = Cx(t) \end{cases}$$

- Interpolation mechanism $\sum_{i=1}^{r} \mu_i(\xi(t)) = 1$ and $0 \leq \mu_i(\xi(t)) \leq 1, \forall t, \forall i \in \{1, ..., r\}$
- The premise variable $\xi(t)$ are measurable (like $u(t)$, $y(t)$).

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A faulty system

$$\begin{cases} \dot{x}_f(t) = \sum_{i=1}^{r} \mu_i(\xi_f(t))(A_i x_f(t) + B_i(u(t) + f(t))) \\ y_f(t) = Cx_f(t) \end{cases}$$

- $f(t)$ represents the fault vector (to be detected and accommodated).

Two kinds of actuator faults are considered :

- External signal : $u_f(t) = u(t) + f(t)$
- Internal signal : $u_f(t) = (I_{n_u} - \gamma)u(t)$ with $\gamma = diag(\gamma_1, \gamma_2, \cdots \gamma_{n_u})$

$$\begin{cases} \gamma_i = 1 \Rightarrow \text{total failure of the } i^{th} \text{ actuator} \\ \gamma_i = 0 \Rightarrow \text{the } i^{th} \text{ actuator is healthy} \\ \gamma_i \in]0\ ,\ 1[\Rightarrow \text{loss of effectiveness of the } i^{th} \text{ actuator} \end{cases}$$

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Assumptions

- **A1.** the faults are assumed to have norm bounded first time derivative

$$\left\| \dot{f}(t) \right\| \leq f_{1max}, \quad 0 \leq f_{1max} < \infty$$

- **A2.** $rank(CB_i) = n_u$
- **A3.** Total actuator failures are not considered, i.e. $\gamma_i \in [0\ \ 1[$

Fault tolerant control design

Faulty system

$$\begin{cases} \dot{x}_f(t) = \sum_{i=1}^{r} \mu_i(\xi(t))(A_i x_f(t) + B_i(u(t) + f(t))) \\ y_f(t) = C x_f(t) \end{cases}$$

Faulty system

$$\begin{cases} \dot{x}_f(t) = \sum_{i=1}^{r} \mu_i(\xi(t))\left(A_i x_f(t) + B_i(u(t) + f(t))\right) \\ y_f(t) = C x_f(t) \end{cases}$$

Objectives

- Simultaneous and fast estimation of the state $\dot{x}_f(t)$ and the fault $f(t)$
- Design of a control law based on a state feedback such as the state of the system converges asymptotically to zero if the fault is constant or to a small ball around the origin when $f(t)$ is time varying with norm bounded first time-derivative

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Fault tolerant control law

$$u(t) = -\hat{f}(t) - \sum_{i=1}^{r} \mu_i(\xi_f(t)) K_i \hat{x}_f(t)$$

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Structure of the proposed observer

$$\begin{cases} \dot{\hat{x}}_f(t) = \sum_{i=1}^{r} \mu_i(\xi_f(t))(A_i \hat{x}_f(t) + B_i(u(t) + \hat{f}(t)) + L_i e_y(t)) \\ \hat{y}_f(t) = C\hat{x}_f(t) \\ \dot{\hat{f}}(t) = \Gamma \sum_{i=1}^{r} \mu_i(\xi_f(t)) F_i(\dot{e}_y(t) + \sigma e_y(t)) \\ e_y(t) = y_f(t) - \hat{y}_f(t) \end{cases}$$

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$$u(t) = -\hat{f}(t) - \sum_{i=1}^{r} \mu_i(\xi_f(t)) K_i \hat{x}_f(t)$$

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This observer can be considered as an improvement of the classical PI observer : convergence is proved even in non constant fault situation.

K. Zhang, B. Jiang, and V. Cocquempot. Adaptive observer-based fast fault estimation. *International Journal of Control, Automation, and Systems*, 6(3) :320-326, 2008.

$$\begin{aligned}
\dot{e}_x(t) &= \sum_{i=1}^{r} \mu_i(\xi_f(t))\left(\Phi_i e_x(t) + B_i e_f(t)\right) \\
\dot{x}_f(t) &= \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i(\xi_f(t))\mu_j(\xi(t))\left(\Xi_{ij} x_f(t) + B_i e_f + B_i K_j e_x\right)
\end{aligned}$$

where

$$\begin{aligned}
e_x(t) &= x_f(t) - \hat{x}_f(t) \\
e_f(t) &= f(t) - \hat{f}(t) \\
\Phi_i &= A_i - L_i C \\
\Xi_{ij} &= A_i - B_i K_j
\end{aligned}$$

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- The stability of the system with observer based actuator fault tolerant control is studied by Lyapunov theory using a quadratic function.

$$V(t) = x_f^T(t) P_1 x_f(t) + e_x^T(t) P_2 e_x(t) + \frac{1}{\sigma} e_f(t) \Gamma^{-1} e_f(t)$$

- The notion of ISS stability is also used in order to define the radius of the convergence ball around the origin in the case of time varying faults.

Main result

Given positive scalars σ and β, if there exists symmetric and positive definite matrices $\mathscr{X} \in \mathbb{R}^{n\times n}$, $P_2 \in \mathbb{R}^{n\times n}$, $G \in \mathbb{R}^{n_f\times n_f}$ (with $n_f = n_u$) and matrices $M_i \in \mathbb{R}^{n_u\times n}$ and $N_i \in \mathbb{R}^{n\times n_y}$ and a positive scalar η solution to the optimization problem

$$\min \quad \eta \quad s.t.$$

$$\begin{pmatrix} \eta I & B_i^T P_2 - F_i C \\ (B_i^T P_2 - F_i C)^T & \eta I \end{pmatrix} > 0$$

$$\mathscr{Q}_{ij} = \begin{pmatrix} S_{ij} & B_i M_j & B_i & 0 & 0 \\ * & -2\beta\mathscr{X} & 0 & \beta I & 0 \\ * & * & -2\beta I & 0 & \beta I \\ * & * & * & \Omega_j & \mathscr{R}_{ij} \\ * & * & * & * & \Psi_{ij} \end{pmatrix} < 0$$

$$S_{ij} = XA_i^T + XA_i - B_i M_i - M_i^T B_i^T, \;\; \Omega_j = A_j^T P_2 + P_2 A_i - N_i C - C^T N_i^T$$

$$\mathscr{R}_{ij} = -\frac{1}{\sigma}(A_j^T P_2 - C^T N_j^T) B_i, \;\; \Psi_{ij} = -\frac{1}{\sigma}\left(B_i^T P_2 B_j + B_j^T P_2 B_i\right) + \frac{1}{\sigma} G$$

then the state of the system $x(t)$, the state estimation error and the fault estimation error $e_f(t)$ are bounded. Furthermore, if $f_{1max} = 0$, these variables converge asymptotically to zero. The gains of the observer and the fault tolerant control are given by F_i, $L_i = P_2^{-1} N_i$ and $K_i = M_i \mathscr{X}^{-1}$.

Objective

Reduce the conservativness of the LMI conditions by Polya's theorem

Principal

Let us consider the inequality

$$\Delta_{\xi\xi} = \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i(\xi(t))\mu_j(\xi(t))\Delta_{ij} < 0$$

Knowing that

$$\left(\sum_{i=1}^{r} \mu_i(\xi(t))\right)^p = \sum_{i=1}^{r} \mu_i(\xi(t)) = 1$$

where p is a positive integer, we obtain

$$\left(\sum_{i=1}^{r} \mu_i(\xi(t))\right)^p \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i(\xi(t))\mu_j(\xi(t))\Delta_{ij} < 0$$

Principal

For example, choosing $p = 1$ we obtain an equivalent inequality

$$\sum_{i_1=1}^{2}\sum_{i_2=1}^{2}\sum_{i_3=1}^{2}\mu_{i_1}\mu_{i_2}\mu_{i_3}\Delta_{i_1 i_2} < 0$$

Consequently, the negativity of $\Delta_{\xi\xi}$ is ensured if

$$\begin{aligned}\Delta_{11} &< 0\\ \Delta_{22} &< 0\\ \Delta_{11}+\Delta_{12}+\Delta_{21} &< 0\\ \Delta_{22}+\Delta_{21}+\Delta_{12} &< 0\end{aligned}$$

- Remark that the negativity of Δ_{12} and Δ_{21} is not required.

$\Rightarrow$

- Less conservative conditions are obtained by increasing p
- Asymptotic necessary and sufficient conditions can be obtained by chosing $p \to \infty$
- In Sala *et al.*, 2007 an approach is proposed to evaluate a finite value of p which garantees the asymptotic necessary and sufficient conditions with a given accuracy.

Theorem with p = 3

Given positive scalars σ and β, if there exists symmetric and positive definite matrices $\mathscr{X} \in \mathbb{R}^{n\times n}$, $P_2 \in \mathbb{R}^{n\times n}$, $G \in \mathbb{R}^{n_f\times n_f}$ (with $n_f = n_u$) and matrices $M_i \in \mathbb{R}^{n_u\times n}$ and $N_i \in \mathbb{R}^{n\times n_y}$ and a positive scalar η solution to the optimization problem

$$\min \quad \eta \quad s.t.$$

$$\begin{pmatrix} \eta I & B_i^T P_2 - F_i C \\ (B_i^T P_2 - F_i C)^T & \eta I \end{pmatrix} > 0$$

$$\begin{aligned}
&\mathscr{Q}_{ii} < 0, \;\; i = 1,\ldots,r \\
&3\mathscr{Q}_{ii} + \mathscr{Q}_{ij} + \mathscr{Q}_{ji} < 0, \;\; i,j = 1,\ldots,r, i \neq j \\
&3\mathscr{Q}_{ii} + \mathscr{Q}_{jj} + 3\mathscr{Q}_{ij} + 3\mathscr{Q}_{ji} < 0, \;\; i,j = 1,\ldots,r, i \neq j \\
&6\mathscr{Q}_{ii} + 3\mathscr{Q}_{ij} + 3\mathscr{Q}_{ik} + 3\mathscr{Q}_{ji} + 3\mathscr{Q}_{ki} + \mathscr{Q}_{jk} + \mathscr{Q}_{kj} < 0 \\
&i,j,k = 1,\ldots,r, i < j < k \\
&3\mathscr{Q}_{ii} + 3\mathscr{Q}_{jj} + 6\mathscr{Q}_{ij} + 6\mathscr{Q}_{ji} + 3\mathscr{Q}_{ik} + 3\mathscr{Q}_{ki} \\
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- Let us consider the nonlinear system defined by :

$$A_1 = \begin{pmatrix} 0 & 1 \\ 17.2941 & 0 \end{pmatrix},\ A_2 = \begin{pmatrix} 0 & 1 \\ 3.5361 & 0 \end{pmatrix},$$

$$B_1 = \begin{pmatrix} 0 \\ -17.65 \end{pmatrix},\ B_2 = \begin{pmatrix} 0 \\ -17.63 \end{pmatrix},\ C = I_2$$

- The weighting functions μ_i are defined as follows

$$\begin{cases} \mu_1(\xi(t)) = 1 - \frac{2}{\pi}|x_1(t)| \\ \mu_2(\xi(t)) = 1 - \mu_1(\xi(t)) \end{cases}$$

- The fault $f(t)$ is time varying and defined by

$$f(t) = \begin{cases} 0 & t \leq 20 \\ 1.4\sin(t) + 21 & 20 \leq t \leq 50 \\ 7.5\sin(2t) + 7.5 & 50 \leq t \leq 70 \\ -0.88u(t) & 70 \leq t \leq 100 \end{cases}$$

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The first simulation is performed with a classic control law $u(t) = \sum_{i=1}^{r} \mu_i(\xi(t)) K_i \hat{x}(t)$.

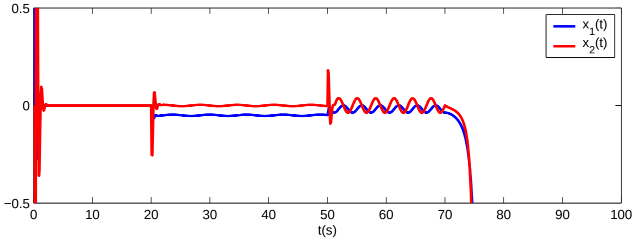

FIGURE: System states with classical control

In the second simulation, the proposed FTC law $u(t) = -\hat{f}(t) - \sum_{i=1}^{r} \mu_i(\xi(t)) K_i \hat{x}_f(t)$ is used

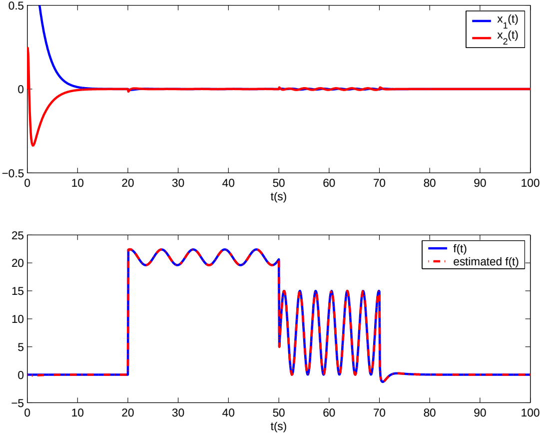

FIGURE: Fault tolerant control : states of the system (top) – fault and its estimation (bottom)

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- Study of the case where both actuator and sensor faults affect the system
- Extension to robust fault tolerant control (disturbances and modeling uncertainties).

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