Trajectory tracking fault-tolerant controller design for Takagi-Sugeno systems subjects to actuator faults

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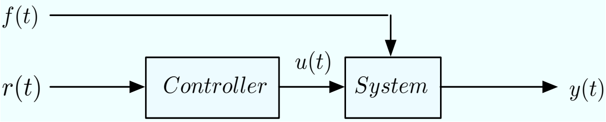
Main contribution

Objectives of the work

- System supervision
- Fault detection (FD)
- Faut isolation (FI)
- Fault estimation
- Fault effect compensation (FTC)



Hypothesis

- Non linear systems
- System without uncertainty
- Multiple-model representation

Plan

1. Brief reminders : Multi-models or multiple-models

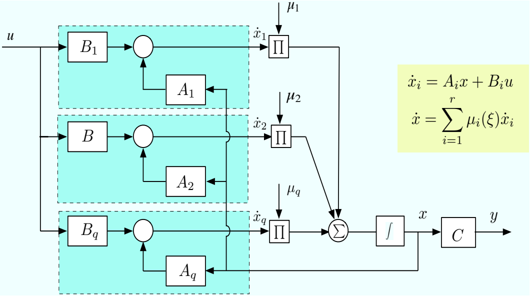
- Structure of the model

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

- Interpolation mechanism

$$\sum_{i=1}^{r} \mu_i(\xi(t)) = 1 \text{ and } 0 \leq \mu_i(\xi(t)) \leq 1, \forall t, \forall i \in \{1, ..., r\}$$

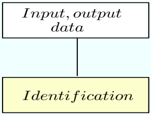
- The premise variable $\xi(t)$ can be measurable or not.



- Direct identification of the model parameters [a]

  Problems to be solved :

  - number of local models
  - structure of the weighting functions
  - data partitioning



- Linearisation of an existing non linear model [b]

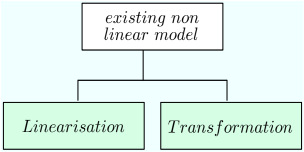
  Problems to be solved :

  - number of operating points
  - linearisation
  - structure of the weighting functions

- Transformations of an existing non linear model [c]

  Problems to be solved :

  - computation of the bounds of the variables
  - definition of the premise variables

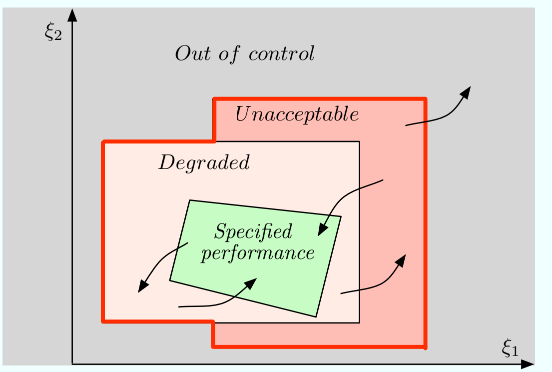


a. K. Gasso, Identification des systèmes dynamiques non linéaires : Approche multimodèle, Ph.D., INPL, France, 2000.

b. R. Murray-Smith, T.A. Johansen. Multiple model approaches to modelling and control. Taylor & Francis, 1997.

c. A.M. Nagy, G. Mourot, B. Marx, G. Schutz, J. Ragot. Model structure simplification of a biological reactor, 15th IFAC Sympo-

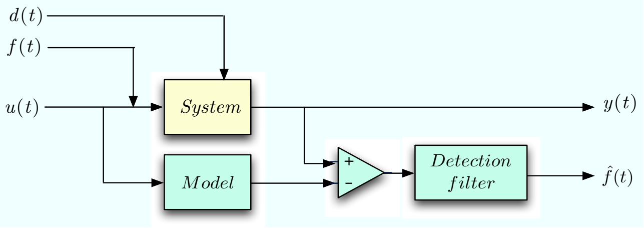
The link between Observer / Diagnosis / Control



- Estimate the state of the system
- Estimate the performances of the system
- Decide to take an action on the system

3. Principles of process diagnosis

Process diagnosis : Detect the presence of faults in spite the influence of the disturbances



- Residual : indicator signals, which are sensitive to the faults $f(t)$:

$$r(t) = W\left(y(t) - \hat{y}(t)\right), \quad r \in \mathscr{R}^h, W(.) \in \mathscr{R}^{h \times p}$$

  where $W(.)$ is a filter to design
- Fault detection : analyse residuals in order to detect abnormal events
- Fault isolation : some specific filters allow to isolate the influence of each fault on the residual.
- Fault characterisation : try to estimate $\hat{f}(t)$ from $r(t)$.

3. Fault Tolerant Control

In the presence of faults, FTC possess the ability to :

- detect and accommodate the faults
- maintain overall system stability
- maintain ≪ acceptable ≫ performances

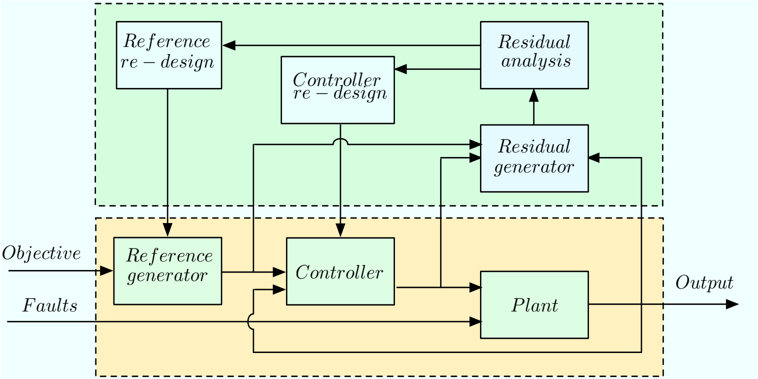


FIGURE: Reconfiguration structure

- System without fault

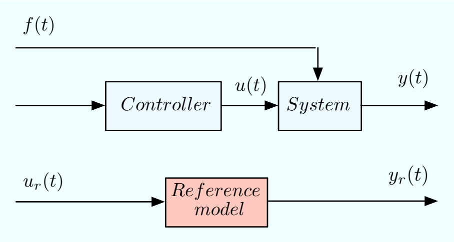
$$\begin{cases} \dot{x} = \sum_{i=1}^{r} \mu_i(\xi)(A_i x + B_i u) \\ y = \sum_{i=1}^{r} \mu_i(\xi)(C_i x + D_i u) \end{cases}$$

- Faulty system

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

- Reference model

$$\begin{cases} \dot{x}_r = \sum_{i=1}^{r} \mu_i(\xi)(A_{ri} x_f + B_{ri} u_r) \\ y_r = \sum_{i=1}^{r} \mu_i(\xi)(C_{ri} x_r + D_{ri} u_r) \end{cases}$$



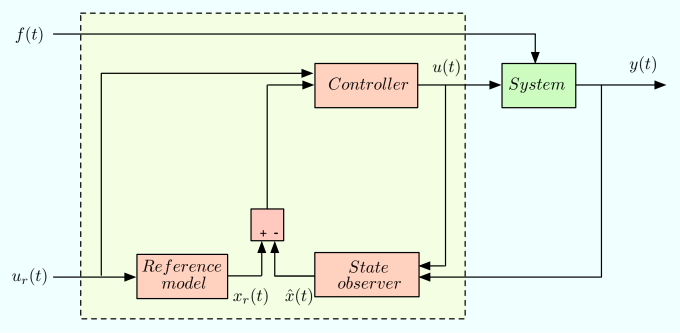
4. Problem formulation : classical controller structure

- Control strategy

$$u_f = \sum_{i=1}^{r} \mu_i(\xi) K_i (x_r - \hat{x}_f) + u_r$$

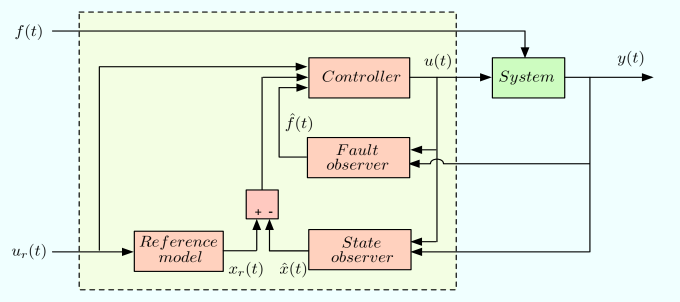
- State observer

$$\begin{cases} \dot{\hat{x}}_f &= \sum_{i=1}^{r} \mu_i(\xi) \left(A_i x + B_i u_f + H_i^1 (y_f - \hat{y}_f) \right) \\ \hat{y}_f &= \sum_{i=1}^{r} \mu_i(\xi) \left(C_i x + D_i u_f \right) \end{cases}$$



- Control strategy
$$u_f = \sum_{i=1}^{r} \mu_i(\xi) K_i (x_r - \hat{x}_f) + u_r - \hat{f}$$

- State observer
$$\begin{cases} \dot{\hat{x}}_f &= \sum_{i=1}^{r} \mu_i(\xi) \left(A_i x + B_i (u_f + \hat{f}) + H_i^1 (y_f - \hat{y}_f) \right) \\ \dot{\hat{f}} &= \sum_{i=1}^{r} \mu_i(\xi) H_i^2 (y_f - \hat{y}_f) \\ \hat{y}_f &= \sum_{i=1}^{r} \mu_i(\xi) (C_i x + D_i (u_f + f)) \end{cases}$$



4. Controller design

- Estimation errors

$$\begin{cases} e_s(t) & = & x_f(t) - \hat{x}_f(t) & : & \textit{state estimation error} \\ e_f(t) & = & f(t) - \hat{f}(t) & : & \textit{fault estimation error} \\ e_p(t) & = & x_r(t) - x_f(t) & : & \textit{tracking error} \\ e_y(t) & = & y_f(t) - \hat{y}_f(t) & : & \textit{output error} \end{cases}$$

- Dynamic of the errors

$$\begin{pmatrix} \dot{e}_p(t) \\ \dot{e}_s(t) \\ \dot{e}_d(t) \\ \dot{e}_y(t) \end{pmatrix} = \begin{pmatrix} A_\mu - B_\mu K_\mu & -B_\mu K_\mu & -B_\mu & 0 \\ 0 & A_\mu & B_\mu & -H_\mu^1 \\ 0 & -H_\mu^2 C_\mu & -H_\mu^2 D_\mu & 0 \\ 0 & C_\mu & D_\mu & -I \end{pmatrix} \begin{pmatrix} e_p(t) \\ e_s(t) \\ e_d(t) \\ e_y(t) \end{pmatrix}$$

$$\Phi_\mu = \sum_{i=1}^{r} \mu_i(\xi)\Phi_i, \quad \Phi = A, B, C, D, K, H^1, H^2$$

- Parameters adjustment $\rightarrow$ Lyapunov approach

$$A_1 = \begin{pmatrix} -2 & 1 & 1 \\ 1 & -3 & 0 \\ 2 & 1 & -8 \end{pmatrix} \quad A_2 = \begin{pmatrix} -3 & 2 & 2 \\ 0 & -3 & 0.2 \\ 0.5 & 2 & -5 \end{pmatrix} \quad B_1 = \begin{pmatrix} 0 \\ 1 \\ 0.25 \end{pmatrix}, \quad B_2 = \begin{pmatrix} 1 \\ 1 \\ -0.5 \end{pmatrix}$$

$$C_1 = \begin{pmatrix} -1 & 0.5 & 0 \end{pmatrix}, \quad C_2 = \begin{pmatrix} -1 & 0.5 & 0 \end{pmatrix}, \quad D_1 = -0.87, \quad D_2 = -0.5$$

$$\mu_1(u) = \frac{1 - tanh(0.5 - u)}{2}, \quad \mu_2(u) = 1 - \mu_1(u)$$

5. Numerical results

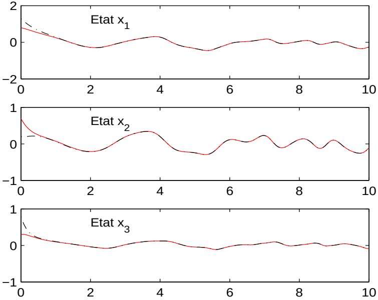


FIGURE: States with FTC

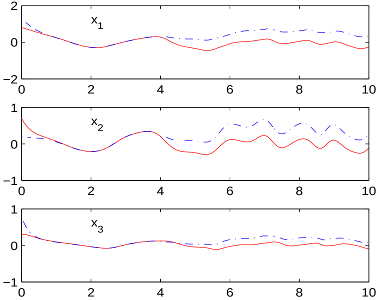


FIGURE: State with classical control

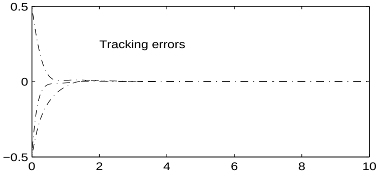


FIGURE: Tracking errors

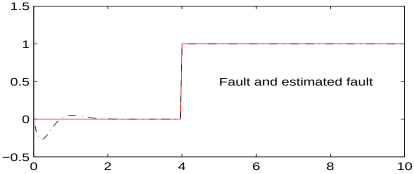


FIGURE: Fault : thrue and estimated

5. Numerical results

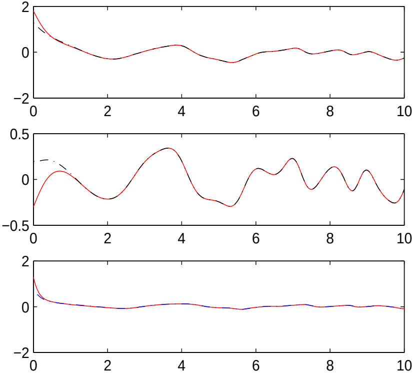


FIGURE: States

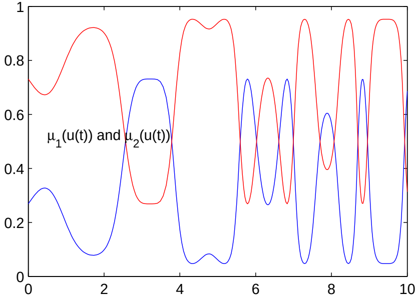


FIGURE: Weighting function

Conclusion

Contribution

- Non linear system framework
- State estimation
- Fault estimation
- Fault tolerant control

Conclusion

Future works

- Noise influence analysis

$$y = \sum_{i=1}^{r} \mu_i(\xi) C_i x + b$$

- Unmeasured weighting functions

$$\dot{x} = \sum_{i=1}^{r} \mu_i(x) (A_i x + B_i u)$$

- Bank of observers using a subset of measurements
- Fault affecting the system

$$\dot{x} = \sum_{i=1}^{r} \mu_i(x) (A_i(f) x + B_i u)$$

Ladies and Gentleman, Thank you very much for your attention !