The Institution of Engineering and Technology Coventry

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Fault diagnosis for T-S systems in finite frequency domain : Some Results and Perspectives

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Outline

Contexte and Motivation

- Takagi-Sugeno modeling
- Unknown Input Observers : LMI design,
- Limitations: Full frequency approach

Finite Frequency Domain Approach

- Objectives & Motivation

Multiobjective synthesis : UIO-FFD

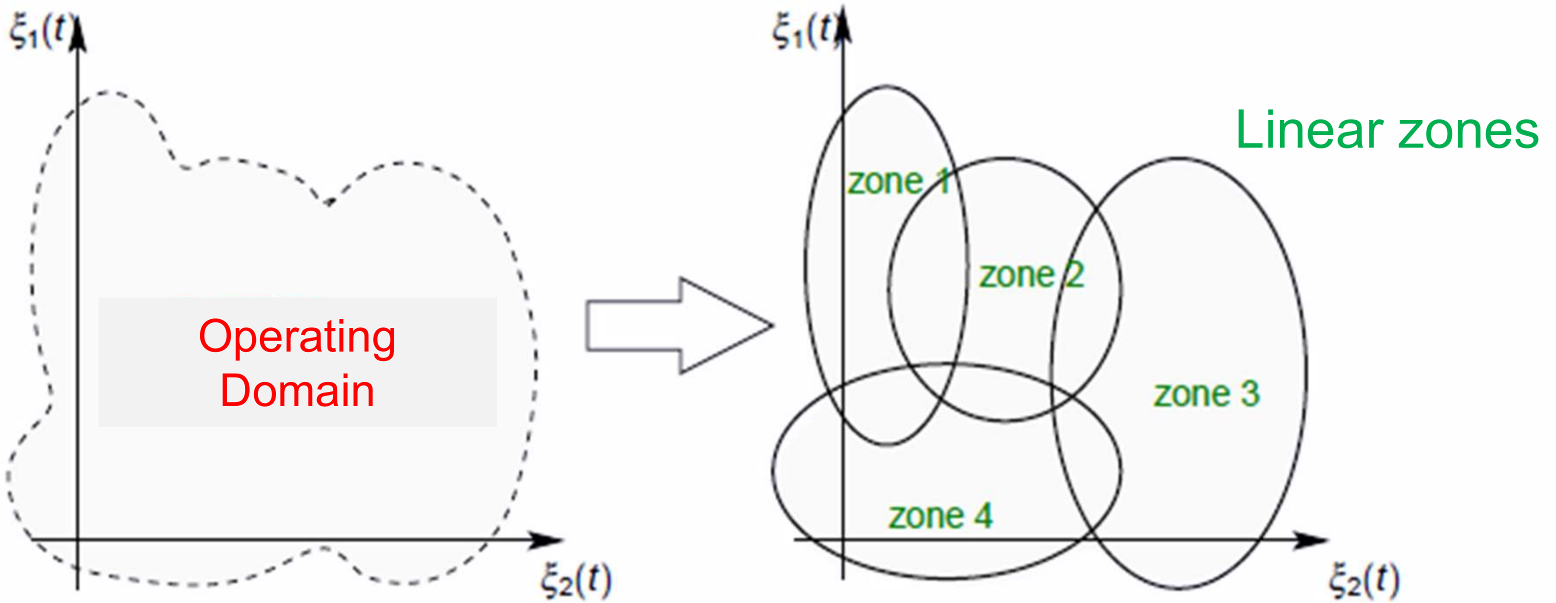
- Sensitivity
- Robustness

Perspectives

Nonlinear Systems : LPV, T-S Fuzzy Systems

$$\left.\begin{cases}\sigma x(t) = f(x(t),u(t)) \\ y(t) = h(x(t))\end{cases}\right\rangle \Rightarrow \begin{cases}\sigma x(t) = \sum_{i=1}^{n} \mu_i(\xi)\left(A_i x(t) + B_i u(t)\right) \\ y(t) = \sum_{i=1}^{n} \mu_i(\xi) C_i x(t)\end{cases}$$

$$\sigma x(t) = \dot{x}(t) \quad or \ x(t+1)$$



Nonlinear system

T-S System
[Multiple models (LTI)]

Nonlinear Systems : LPV, T-S Fuzzy Systems

$$\left.\begin{cases}\sigma x(t) = f(x(t), u(t)) \\ y(t) = h(x(t))\end{cases}\right\rangle \Rightarrow \begin{cases}\sigma x(t) = \sum_{i=1}^{n} \mu_i(\xi)\big(A_i(x)x(t) + B_i(x)u(t)\big) \\ y(t) = \sum_{i=1}^{n} \mu_i(\xi) C_i(x)x(t)\end{cases}$$

Nonlinear Systems ---- > Polynomial T-S Systems

Polynomial T-S Systems : SOS Tool

- L. Zadeh. Outline of a new approach to the analysis of complex system and decision process. IEEE transaction on Systems Man and Cybernetic-part C, 3(1), p. 28-44, 1973.
- T. Takagi, M. Sugeno. Fuzzy identification of systems and its application to modelling and control. IEEE Trans. on Systems, Man, Cybernetics, vol. 15, no.1, p. 116-132,1985.

Nonlinear Systems : LPV, T-S Fuzzy

$$\left\{\begin{array}{l}\sigma x(t) = f(x(t),u(t)) \\ y(t) = h(x(t))\end{array}\right. \Rightarrow \left\{\begin{array}{l}\sigma x(t) = \sum_{i=1}^{n} \xi_i(\theta)\big(A_i x(t) + B_i u(t)\big) \\ y(t) = \sum_{i=1}^{n} \xi_i(\theta) C_i x(t)\end{array}\right.$$

$$\sum_{i=1}^{n} \xi_i(\theta) = 1$$
$$\xi_i(\theta) \geq 0$$

LPV

$\theta \rightarrow \rho(t)$

T-S

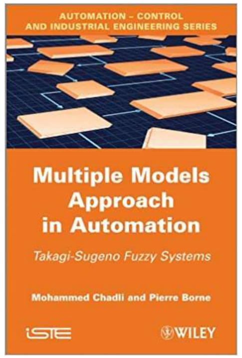
$\theta \rightarrow x(t), \rho(t)\ldots$

Switching

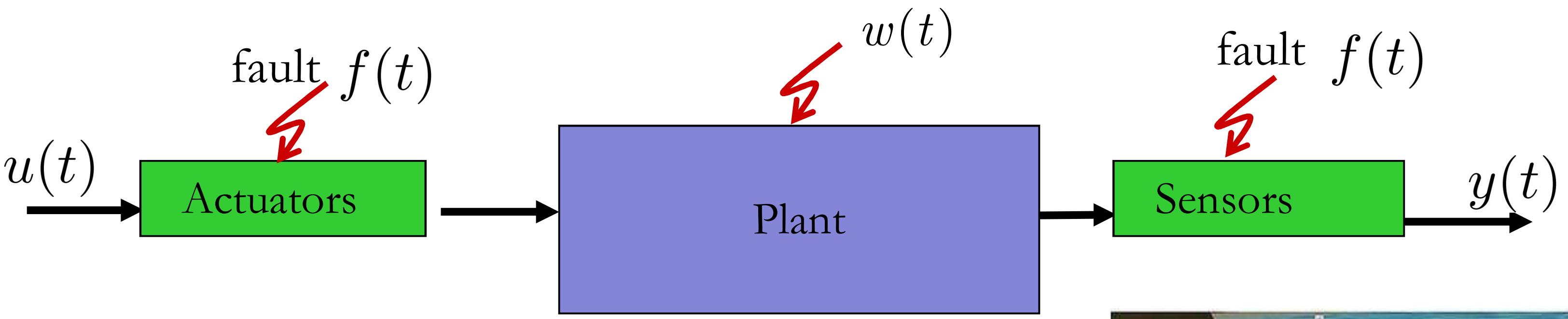
$\xi_i(\theta) \in \{0,1\}$

1. **Controller & Observer Design**
2. **FDI-FTC**
   - **Numerical tools : LMI & SOS**
   - **Reduction of conservatism**

M. Chadli & P. Borne. **Multiple Models Approach in Automation: Takagi-Sugeno Fuzzy Systems.** Wiley. p. 208. 2013.



Nonlinear Systems : Contexte



- ***f(t)*** : fault/sensor actuators
- ***w(t)*** : disturbances

Objectives:

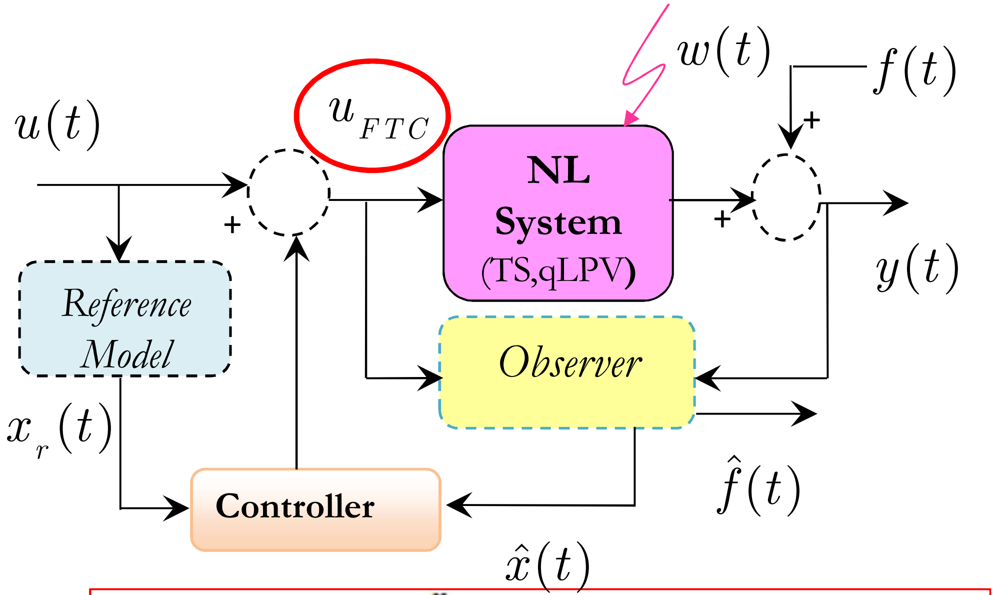
◆ **Fault Detection and Isolation of faults** (estimation?)

◆ **How to maintain/enable a system to continue operating properly in presence of faults (FTC) ?**

↳ Avoid dangerous situations

How Maintaining Security in the Presence of Faults: Example

- **Integration of contraintes s.t. saturation, delays,**
- **Reconfiguration of control laws**



$$u_{FTC}(t) = u(t) + \sum_{j=1}^{r} h_j\left(\hat{\xi}(t)\right)\left(K_j\left(\hat{x}(t) - x_r(t)\right)\right)$$

D Saifia, M Chadli, et al. Robust H∞ static output feedback control for discrete fuzzy systems with actuator saturation via fuzzy Lyapunov functions. Asian Journal of Control, 2019.

LMI design conditions

TS Systems :

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

Unknown Input Observer (UIO) :

$$\begin{cases} \dot{z}(t) = \sum_{i=1}^{n} \mu_i(\xi)\Big(N_i z(t) + G_i u(t) + L_i y(t)\Big) \\ \hat{x}(t) = z(t) - Ey(t) \end{cases}$$

Objective : $N_i,\ G_i,\ L_i,\ E\ ?$

$$s.t. \quad \lim_{t\to\infty}\Big(\hat{x}(t) - x(t)\Big) \to 0$$

LMI design conditions

$$\boxed{\begin{cases} XA_i + SCA_i - W_iC + (XA_i + SCA_i - W_iC) < 0 \\ SF = 0 \\ \left(X + SC\right)R_i = W_iF \end{cases}}$$

Observer parameters:

$$\begin{cases} E = X^{-1}S, \\ G_{i1} = \left(I + EC\right)B_i \\ N_i = \left(I + EC\right)A_i - X^{-1}W_iC \\ L_i = X^{-1}W_i - N_iE \end{cases}$$

Performances : LMI regions

LMI design conditions

Extensions : Unmeasurables variables, Disturbances

1. Unmesurable variables : continuous/discrete-time cases

$$\mu_i(\theta) \Rightarrow \mu_i(\hat{\theta}) : \quad \begin{cases} \sigma x(t) = \sum_{i=1}^{n} \mu_i(\hat{\xi}) \big(A_i x(t) + B_i u(t) + R_i \overline{u}(t) + H_i w(t) \big) \\ y(t) = \sum_{i=1}^{n} \mu_i(\hat{\xi}) \big(C_i x(t) + F_i \overline{u}(t) + J_i w(t) \big) \end{cases}$$

2. Polynomial TS system (SOS) :

$$\begin{cases} \sigma x(t) = \sum_{i=1}^{n} \mu_i(\xi) \big(A_i(x) x(t) + B_i(x) u(t) + R_i(x) \overline{u}(t) \big) \\ y(t) = C x(t) + F \overline{u}(t) + J w(t) \end{cases}$$

Other approaches:

- **Estimation of state and unknown inputs (faults)**
- **Uncertainties** $\}$ $y(t) = (C + \Delta C)x(t)$
- **Lyapunov Functions :** $P \rightarrow P_i, \ldots.$

$$\bullet \ \lim_{t\to\infty} \sup \left\| \hat{x}(t) - x(t) \right\| \leq \varepsilon \ \left(au\ lieu \lim_{t\to\infty} \left\| x(t) - \hat{x}(t) \right\| = 0 \right)$$

$$\bullet \ estimation\ of\ f(t) : polynomial\ form\ or\ any\ faults$$

$$\rightarrow descripteur\ approach : x(t) \Rightarrow \overline{x}(t) = \left[x(t)^T, \quad f(t)^T \right]^T$$

$$\rightarrow PI\ observateur$$

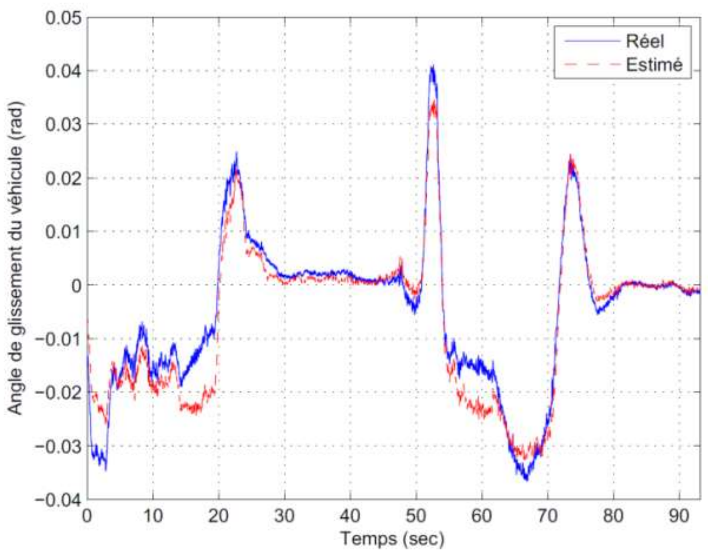
$$\bullet \ finite\ time\ estimate : \hat{x}(t) - x(t) = 0\ for\ t \geq \pi$$

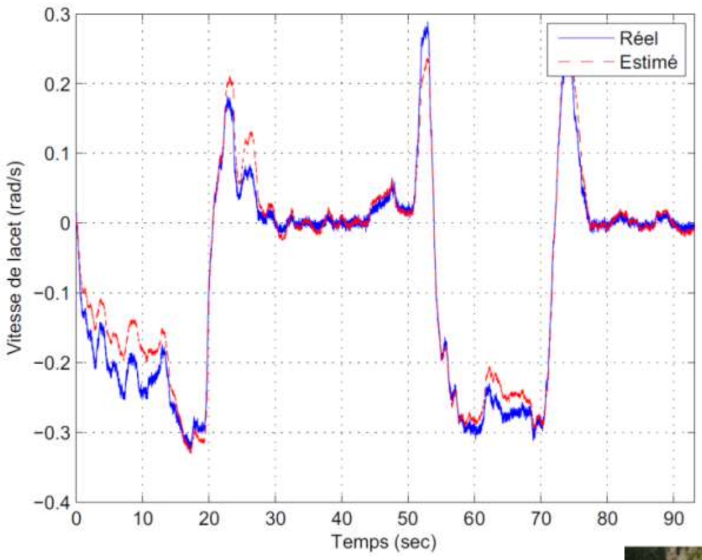
M. Chadli, A. Abdo, S. Ding. H−/H∞ Fault Detection Filter Design for Discrete-time Fuzzy System. **Automatica** 2013.

Unknown Input Observer

Vehicle application: Experimental validation

Estimation of variables (lateral dynamic)





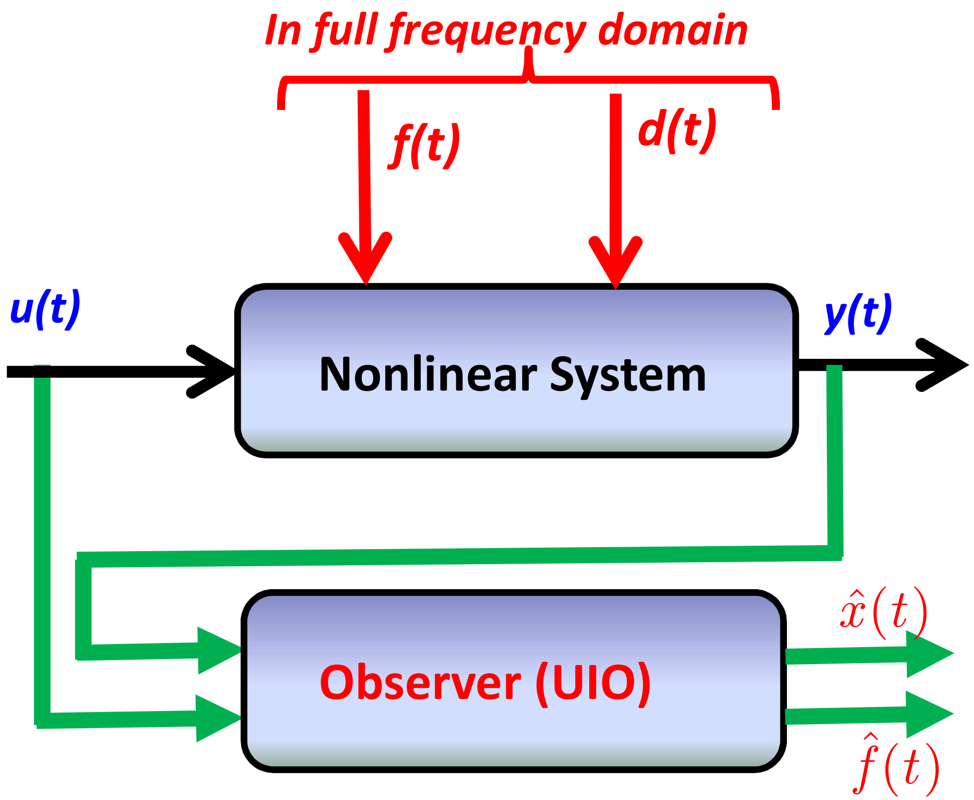
*Vehicle dynamics and road curvature estimation for lane departure warning system using robust fuzzy observers: **Experimental validation**.*
***Vehicle System Dynamics Journal, 2015**. (PhD thesis of H. Dahmani)*

Cryptography : Chaos synchronisation

*M. Chadli, I. Zelinka, T. Youssef. Unknown inputs observer design for fuzzy systems with application to chaotic system reconstruction. **Computers & Mathematics with Applications** 66 (2), 147-154.*

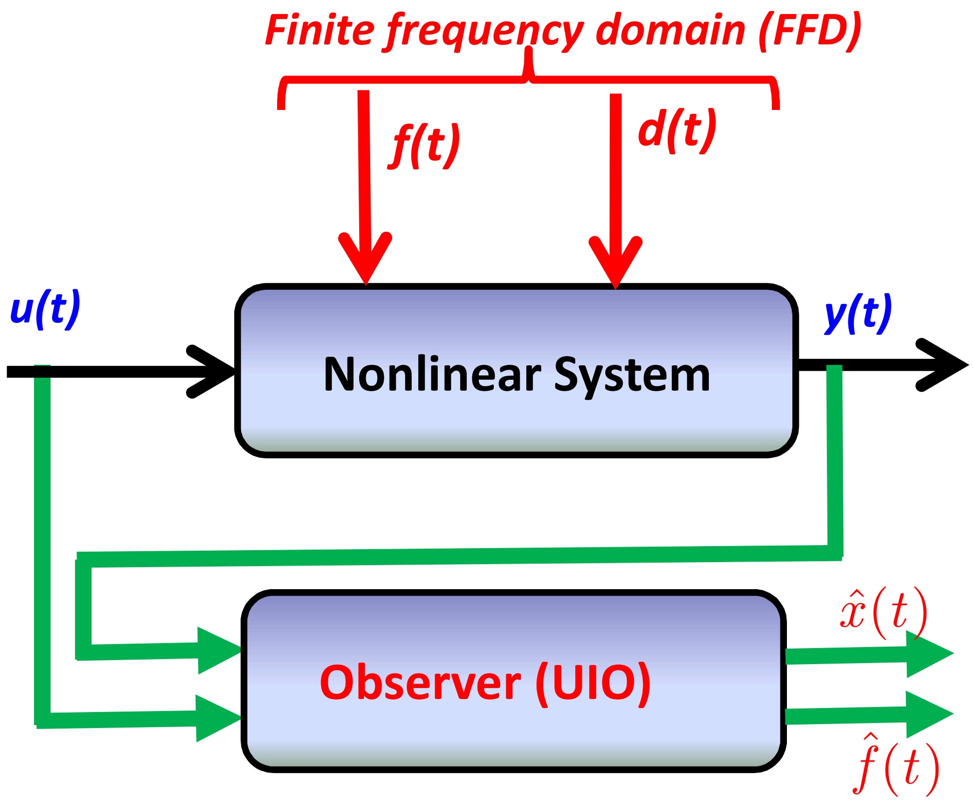
Unknown Input Observer : Limitation

- **Findings :**
  - ✓ Observer for full frequency domaine only
  - ✓ Results do not take into account the frequency domain of the signals: Conservatism



Objectives

- Incorporate the frequency range of the external signals into the synthesis conditions.
- Robust Estimation - Finite Frequency Domain (FFD)

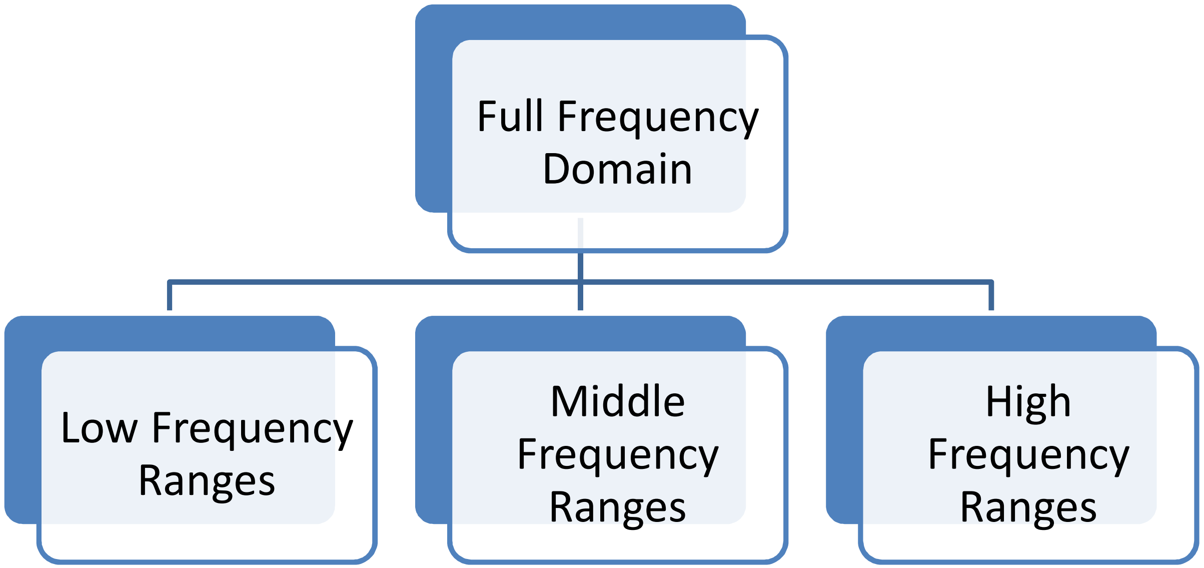


The finite frequency approach consists on incorporating the frequency range of the external signals in the design conditions

PhD thesis of A. Chibani (Nov 2016) : **IEEE-TFS 2018, Automatica 2018**

Finite Frequency Domain Approach

- The finite frequency method generally leads to more efficient results and less conservative conditions.

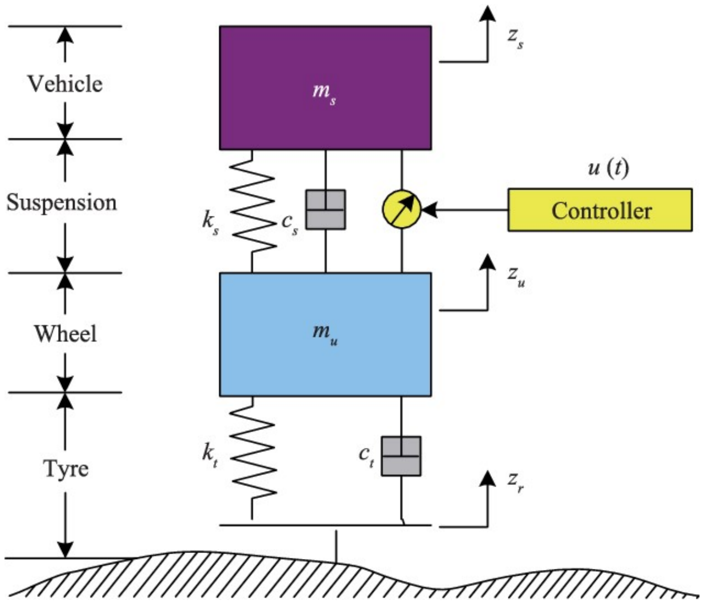


according to the frequency of the external signal

T. Iwasaki, S. Hara. Generalized KYP lemma: unified frequency domain inequalities. IEEE TAC 2005.

Finite Frequency Domain Approach

Motivation : Vertical vibrations in frequencies between 4 Hz and 8 Hz are the most sensitive range for the human body. (Norm ISO2361)



Objectives :

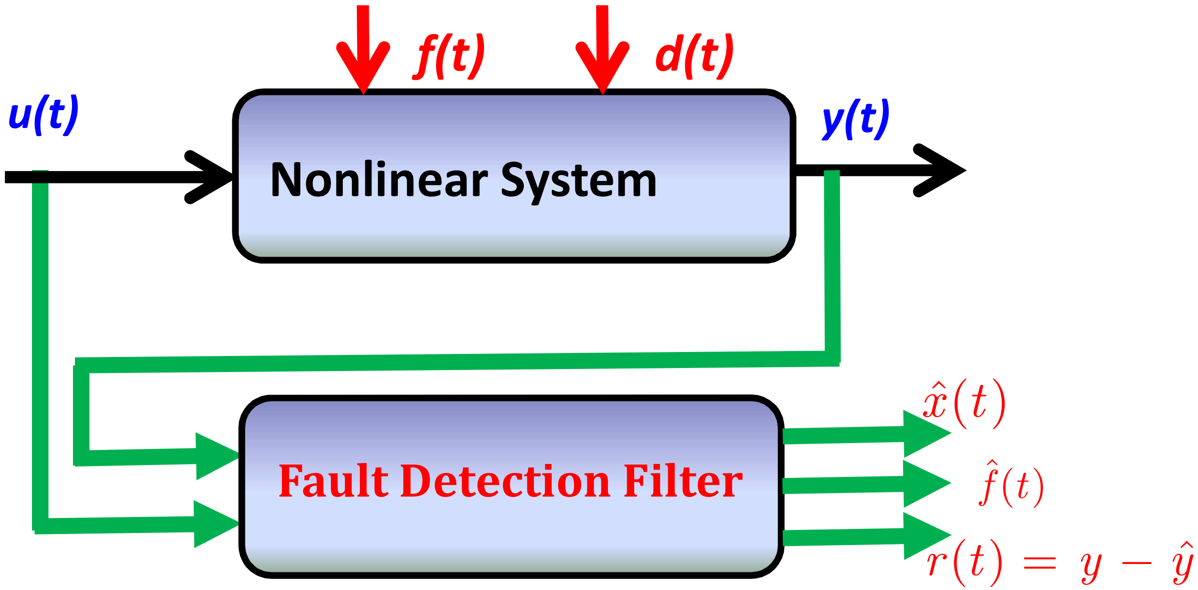
- ❑ **Incorporate the frequency range of the external signals into the synthesis conditions.**
- ❑ **Robust Estimation - Finite Frequency Domain (FFD)**

➢ **Multiobjective FDI:**

H∞ : $\|r(t)\|_2 < \gamma \|d(t)\|_2$

H_ : $\|r(t)\|_2 > \beta \|f(t)\|_2$

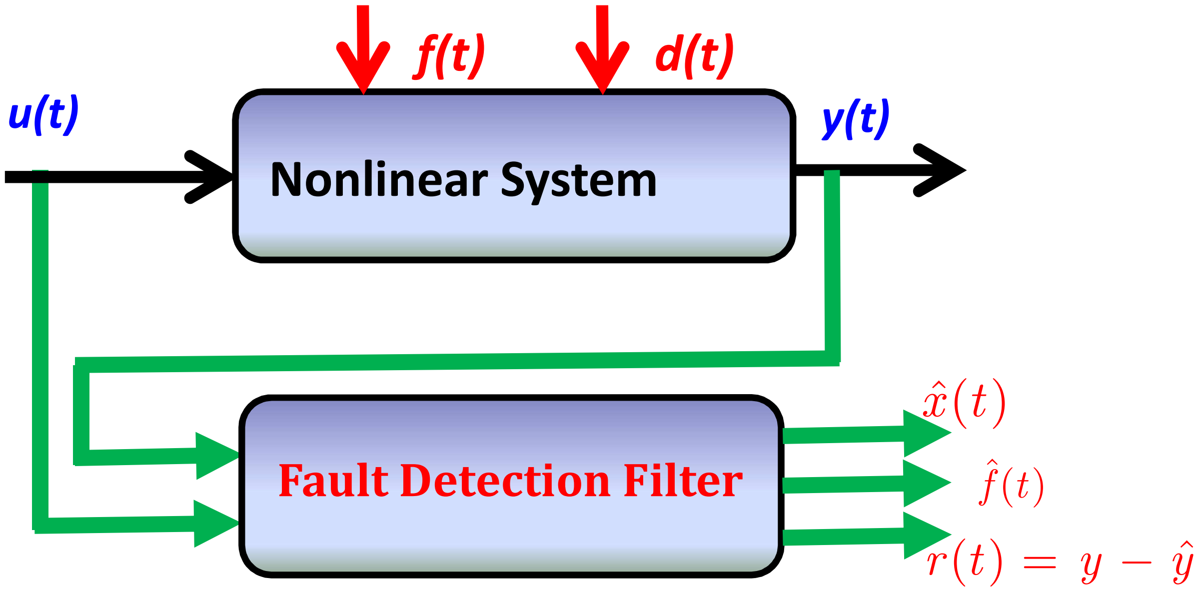
Estimation: $\hat{x}(t),\ \hat{f}(t)$



- **Illustrative Example**

  ✓ Frequency of signal $d(t)$: $\omega_d \in \Omega_d^m = \{\omega_d \in \mathbb{R} \mid \omega_{d_1} \leq \omega_d \leq \omega_{d_2}\}$

  ✓ Frequency of signal $f(t)$: $\omega_f \in \Omega_f^l = \{\omega_f \in \mathbb{R} \mid |\omega_f| \leq \omega_{f_l}\}$



Multiobjective synthesis : Preliminary results

- **For d≠0, H∞ performance:** $\|r(t)\|_2 < \gamma \|d(t)\|_2$

$$\begin{cases} \dot{e}(t) = \sum_{i=1}^{r} \mu_i\left(\xi(t)\right)\left(\mathcal{A}_i e(t) + \mathcal{B}_i d(t)\right) \\ r(t) = \mathcal{C}e(t) + \mathcal{D}d(t) \end{cases}$$

- Frequency of signal *d(t)* : $\omega_d \in \Omega_d^m = \{\omega_d \in \mathbb{R} \mid \omega_{d_1} \leq \omega_d \leq \omega_{d_2}\}$

Lemma 1.

The H∞ performance : $\|r(t)\|_2 < \gamma \|d(t)\|_2$
is garanteed in the middle frequency band $(\omega_{d_1} \leq \omega_d \leq \omega_{d_2})$
if there exist symmetric matrices P and Q > 0 such that :

$$\begin{pmatrix} \mathcal{A}_i & \mathcal{B}_i \\ I & 0 \end{pmatrix}^T \begin{pmatrix} -Q & P + j\omega_{d_c} Q \\ P - j\omega_{d_c} Q & -\omega_{d_1}\omega_{d_2} Q \end{pmatrix} \begin{pmatrix} \mathcal{A}_i & \mathcal{B}_i \\ I & 0 \end{pmatrix} + \begin{pmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{pmatrix}^T \begin{pmatrix} I & 0 \\ 0 & -\gamma^2 I \end{pmatrix} \begin{pmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{pmatrix} < 0$$

$$\left(\omega_{d_c} = \frac{\omega_{d_1} + \omega_{d_2}}{2}\right)$$

Multiobjective synthesis : Preliminary results

- **For f≠0, H_ performance :** $\|r(t)\|_2 > \beta\|f(t)\|_2$

$$\begin{cases} \dot{e}(t) = \sum_{i=1}^{r} \mu_i\left(\xi(t)\right)\left(\mathcal{A}_i e(t) + \mathcal{B}_i f(t)\right) \\ r(t) = \mathcal{C}e(t) + \mathcal{D}f(t) \end{cases}$$

- Frequency of signal *f(t)* : $\omega_f \in \Omega_f^l = \{\omega_f \in \mathbb{R} \mid |\omega_f| \le \omega_{f_l}\}$

Lemma 2.

The H_ performance : $\|r(t)\|_2 > \beta\|f(t)\|_2$
is garanteed in the low frequency band $(\omega_f \le \omega_{f_l})$
if there exist symmetric matrices P and Q > 0 such that :

$$\begin{pmatrix} \mathcal{A}_i & \mathcal{B}_i \\ I & 0 \end{pmatrix}^T \begin{pmatrix} -Q & P \\ P & \omega_{f_l}^2 Q \end{pmatrix} \begin{pmatrix} \mathcal{A}_i & \mathcal{B}_i \\ I & 0 \end{pmatrix} + \begin{pmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{pmatrix}^T \begin{pmatrix} -I & 0 \\ 0 & \beta^2 I \end{pmatrix} \begin{pmatrix} \mathcal{C} & \mathcal{D} \\ 0 & I \end{pmatrix} < 0$$

Multiobjective synthesis : FFD-UIO

- **T-S systems**

$$\begin{cases} \dot{x}(t) = A_\sigma x(t) + B_\sigma u(t) + R_\sigma d(t) + F_\sigma f(t) \\ y(t) = Cx(t) + Dd(t) + Hf(t) \end{cases}$$

$$\left(M_\sigma = \sum_{i=1}^{n} \mu_i(\xi) M_i \right)$$

✓ **UIO-Multiobjective design :**

$$\begin{cases} \dot{z}(t) = N_\sigma z(t) + G_\sigma u(t) + L_\sigma y(t) \\ \hat{x}(t) = z(t) - Ey(t) \end{cases}$$

- Estimation (IUO) : $\lim_{t\to\infty} \left(\hat{x}(t) - x(t)\right) \to 0$

- Robustnesse to d(t)≠0 : minimise γ such that $\|r(t)\|_2 < \gamma \|d(t\|_2$
  (H∞ in the middle frequency domain).

- Sensitivity to f(t)≠0 : maximise β such that $\|r(t)\|_2 > \beta \|f(t)\|_2$
  (H_ in the low frequency domain).

Multiobjective synthesis : FFD-UIO

- **T-S systems**

$$\begin{cases} \dot{x}(t) = A_\sigma x(t) + B_\sigma u(t) + R_\sigma d(t) + F_\sigma f(t) \\ y(t) = Cx(t) + Dd(t) + Hf(t) \end{cases}$$

$$\left(M_\sigma = \sum_{i=1}^{n} \mu_i(\xi) M_i \right)$$

✓ **UIO-Multiobjective design :**

$$\begin{cases} \dot{z}(t) = N_\sigma z(t) + G_\sigma u(t) + L_\sigma y(t) \\ \hat{x}(t) = z(t) - Ey(t) \end{cases}$$

✓ **Aims to achieve:**

1- For d=0 and f=0: the filtering error system is **asymptotically stable**.

2- for d≠0: the H∞ performance from *d(t)* to *r(t)* is less than a given positive scalar γ in the middle frequency domain.

3- for f≠0: the H_ performance from *f(t)* to *r(t)* is greater than a given positive scalar β in the low frequency domain.

- **Design Conditions**

T-S system:

$$\begin{cases} \dot{x}(t) = A_\sigma x(t) + B_\sigma u(t) + R_\sigma d(t) + F_\sigma f(t) \\ y(t) = Cx(t) + Dd(t) + Hf(t) \end{cases}$$

UIO structure:

$$\begin{cases} \dot{z}(t) = N_\sigma z(t) + G_\sigma u(t) + L_\sigma y(t) \\ \hat{x}(t) = z(t) - Ey(t) \end{cases}$$

Dynamic of the filtering error:

$$\boxed{\begin{aligned} &\dot{e}(t) = \sum_{i=1}^{r} \mu_i\left(\xi(t)\right)\left(N_i e(t) + (TR_i - K_i D)d(t) + (TF_i - K_i H)f(t)\right) \\ &r(t) = Ce(t) + Dd(t) + Hf(t) \end{aligned}}$$

with

$$\boxed{e(t) = x(t) - \hat{x}(t)} \qquad \boxed{r(t) = y(t) - \hat{y}(t)}$$

$$T = I_n + EC \qquad K_i = N_i E + L_i$$

Sensitivity to faults - FFD

$$\dot{e}(t) = \sum_{i=1}^{r} \mu_i\left(\xi(t)\right)\left(N_i e(t) + (TF_i - K_i H) f(t)\right)$$

$$r(t) = Ce(t) + Hf(t)$$

- For f(t)≠0, H_ performance : $\|r(t)\|_2 > \beta\|f(t)\|_2$

✓ **Aims to achieve:**

1- For d=0 and f=0: the filtering error system is **asymptotically stable**.

2- for d≠0: the H∞ performance from $d(t)$ to $r(t)$ is less than a given positive scalar γ in the middle frequency domain.

3- for f≠0: the H_ performance from $f(t)$ to $r(t)$ is greater than a given positive scalar β in the low frequency domain.

❑ Theorem : **Sensitivity to faults (H_ performance)**

The H_ performance is garanteed in the frequency domaine $\left[0, \omega_{fl}\right]$

$$\begin{pmatrix} -Q & (*) & (*) & (*) \\ P-\Xi & \Theta_f & (*) & (*) \\ 0 & \Upsilon_f & -H^T H & (*) \\ 0 & 0 & \beta I & -I \end{pmatrix} < 0 \qquad \textit{(LMI-S)}$$

with: $\Theta_f = ((\Xi + SC)A_i - W_i C) + ((\Xi + SC)A_i - W_i C)^T - C^T C + \omega_{fl}^2 Q$

$\Upsilon_f = ((\Xi + SC)F_i - W_i H)^T - H^T C$

Robustness to disturbances - FFD

$$\dot{e}(t) = \sum_{i=1}^{r} \mu_i\left(\xi(t)\right)\left(N_i e(t) + (TR_i - K_i D)d(t)\right)$$

$$r(t) = Ce(t) + Dd(t)$$

- Pour d(t)≠0, performance H∞ : $\|r(t)\|_2 < \gamma \|d(t\|_2$

✓ **Aims to achieve:**

1- For d=0 and f=0: the filtering error system is **asymptotically stable**.

2- for d≠0: the H∞ performance from $d(t)$ to $r(t)$ is less than a given positive scalar γ in the middle frequency domain.

3- for f≠0: the H_ performance from $f(t)$ to $r(t)$ is greater than a given positive scalar β in the low frequency domain.

Theorem : Robustness to disturbances

The H∞ performance is garanteed in the frequency domaine $[\omega_{d1}, \omega_{d2}]$

$$\begin{pmatrix} -Q & (*) & (*) & (*) \\ P - j\omega_{d_c} Q - \Xi & \Theta_d & (*) & (*) \\ 0 & \Upsilon_d & -\gamma^2 I & (*) \\ 0 & C & D & -I \end{pmatrix} < 0 \qquad \textit{(LMI-R)}$$

with : $\Theta_d = (\Xi + SC)A_i - W_i C + \left((\Xi + SC)A_i - W_i C\right)^T - \omega_{d_1}\omega_{d_2} Q$

$\Upsilon_d = \left((\Xi + SC)R_i - W_i D\right)^T$

✓ **Aims to achieve:**

1- For d=0 and f=0: the filtering error system is **asymptotically stable**.

2- for d≠0: the H∞ performance from $d(t)$ to $r(t)$ is less than a given positive scalar γ in the middle frequency domain.

3- for f≠0: the H_ performance from $f(t)$ to $r(t)$ is greater than a given positive scalar β in the low frequency domain.

Observer convergence conditions

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

$$r(t) = Ce(t)$$

- For d(t)=0 & f(t)=0

❑ Theorem : **Asymptotic stability of *e(t)***

$$\begin{pmatrix} -\Sigma-\Sigma^T & (*) & (*) \\ \left((\Sigma+SC)A_i - W_i C + U\right)^T & -U & (*) \\ \Sigma^T & 0 & -U \end{pmatrix} < 0 \qquad \textit{(LMI-AS)}$$

Multiobjective synthesis : FFD-UIO

LMI Design conditions : FDD

$$\max \beta, \min \gamma :$$

$$J_i - (\Sigma + SC)B_i = 0$$

$$S\begin{bmatrix} D & H \end{bmatrix} = 0$$

(LMI-R), (LMI-S), (LMI-AS)

✓ **Aims to achieve:**

1- For d=0 and f=0: the filtering error system is **asymptotically stable**.

2- for d≠0: the H∞ performance from $d(t)$ to $r(t)$ is less than a given positive scalar γ in the middle frequency domain.

3- for f≠0: the H_- performance from $f(t)$ to $r(t)$ is greater than a given positive scalar β in the low frequency domain.

If these conditions are satisfied, then the observer parameters :

$$E = \Sigma^{-1} S$$

$$G_i = \Sigma^{-1} J_i$$

$$N_i = (I + EC)A_i - \Sigma^{-1} W_i C$$

$$L_i = \Sigma^{-1} W_i - N_i E$$

A. Chibani, M. Chadli, P. Shi. Fuzzy Fault Detection Filter Design for T-S Fuzzy Systems in Finite Frequency Domain. **IEEE Transactions on Fuzzy Systems 25 (5), 1051-1061, 2018**.

Multiobjective synthesis : FFD-UIO

Illustrative example:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r=2} \mu_i(\zeta(t))\big(A_i x(t) + B_i u(t) + R_i d(t) + F_i f(t)\big) \\ y(t) = Cx(t) + Dd(t) + Hf(t) \end{cases}$$

with

$$A_1 = \begin{pmatrix} -18.5 & 5 & 18.5 \\ 0 & -20.9 & 15 \\ 18.5 & 15 & -33.5 \end{pmatrix} \quad A_2 = \begin{pmatrix} -22.1 & 0 & 22.1 \\ 1 & -23.3 & 17.6 \\ 17.1 & 17.6 & -39.5 \end{pmatrix} \quad B_1 = \begin{pmatrix} 1 \\ 0.5 \\ 0.5 \end{pmatrix}$$

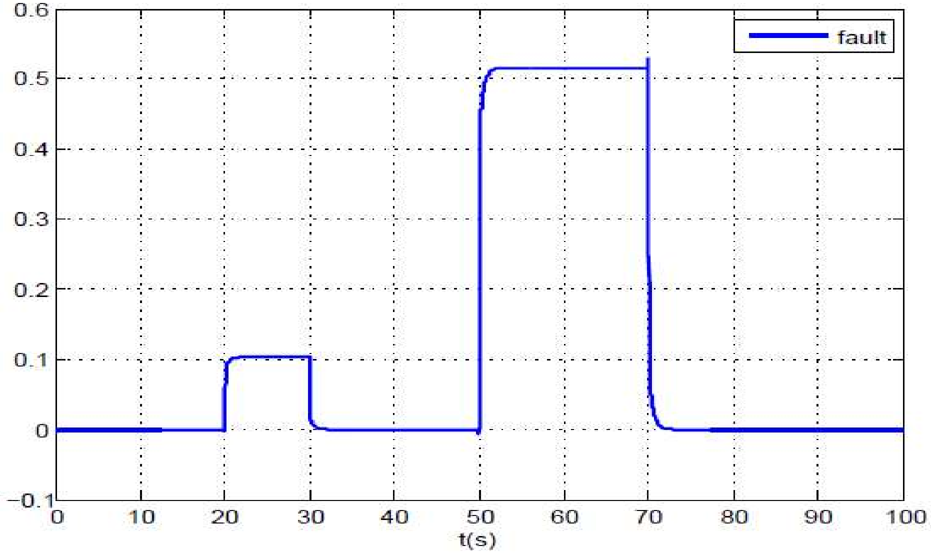
$$B_2 = \begin{pmatrix} 0.5 \\ 1 \\ 0.25 \end{pmatrix} \quad R_1 = \begin{pmatrix} 0 \\ 0.6 \\ 0.25 \end{pmatrix} \quad R_2 = \begin{pmatrix} 0.25 \\ 0 \\ 0.6 \end{pmatrix} \quad F_1 = F_2 = \begin{pmatrix} 0 \\ 0.6 \\ 0.25 \end{pmatrix}$$

$$C = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix} \quad D = \begin{pmatrix} 0.3 \\ 0.3 \end{pmatrix} \quad H = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Multiobjective synthesis : FFD-UIO

Illustrative example:

Fault f(t)



No solution (UIO) with the Full Frequency Domaine approach

Illustrative example:

- Frequency of signal $d(t)$: $\omega_d \in \Omega_d^m = \{\omega_d \in \mathbb{R} \mid \omega_{d_1} = 0.5 \leq \omega_d \leq \omega_{d_2} = 1\}$
- Frequency of signal $f(t)$: $\omega_f \in \Omega_f^l = \{\omega_f \in \mathbb{R} \mid |\omega_f| \leq \omega_{f_l} = 0.3\}$

Solution : $\gamma = 0.4401, \quad \beta = 1.4106$

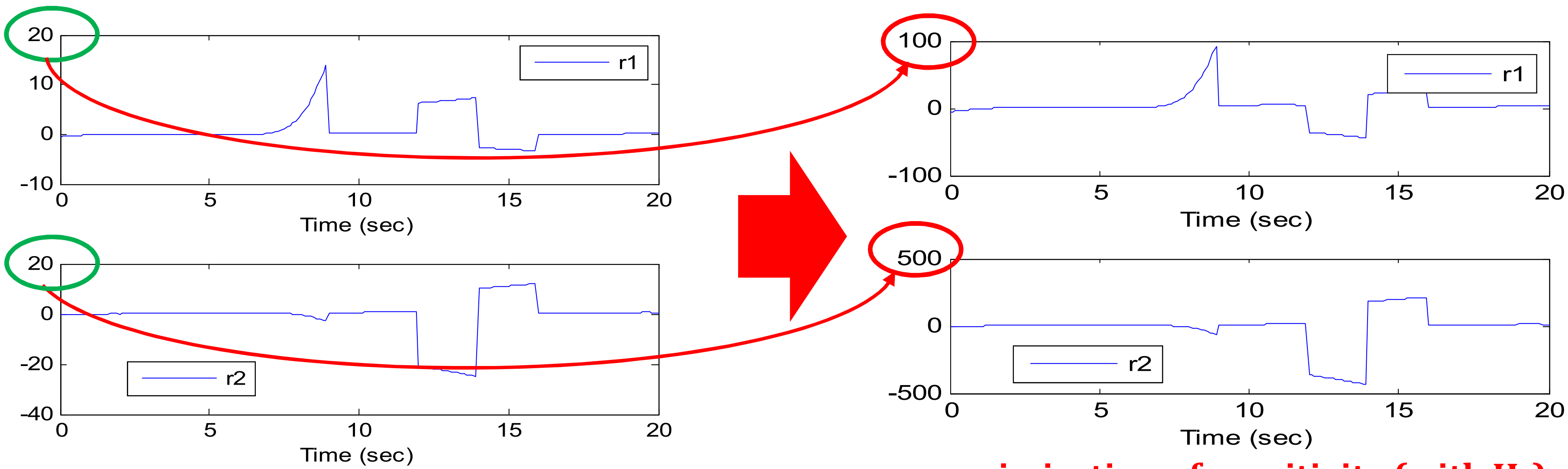
$$N_1 = \begin{pmatrix} -48.5957 & -20.4247 & -15.2247 \\ 13.5244 & -8.6546 & 7.8692 \\ -0.8131 & -0.6916 & -2.2464 \end{pmatrix} \qquad L_1 = \begin{pmatrix} -10.1464 & 8.8850 \\ -16.4256 & 18.0037 \\ -0.6673 & 0.6274 \end{pmatrix}$$

$$N_2 = \begin{pmatrix} -49.7451 & -29.8316 & -12.3870 \\ 13.4709 & -8.9321 & 9.8851 \\ -0.7446 & -0.8115 & -2.0202 \end{pmatrix} \qquad L_2 = \begin{pmatrix} -29.8558 & 28.5168 \\ -14.4456 & 15.9344 \\ -1.1722 & 1.1284 \end{pmatrix}$$

$$G_1 = \begin{pmatrix} 0.1525 \\ 0.9082 \\ -0.0231 \end{pmatrix} \qquad G_2 = \begin{pmatrix} 0.0763 \\ 1.2041 \\ -0.0115 \end{pmatrix} \qquad E = \begin{pmatrix} 1.6950 & -1.6950 \\ -0.8164 & 0.8164 \\ 1.0461 & -1.0461 \end{pmatrix}$$

Illustrative example:

Sensitivity to faults: without H_ | **Sensitivity to faults: with H_**



maximisation of sensitivity (with H_)

A. Chibani, M. Chadli, S.X. Ding, NB Braiek. Design of robust fuzzy fault detection filter for polynomial fuzzy systems with new finite frequency specifications. **Automatica 93, 42–54, 2018**.

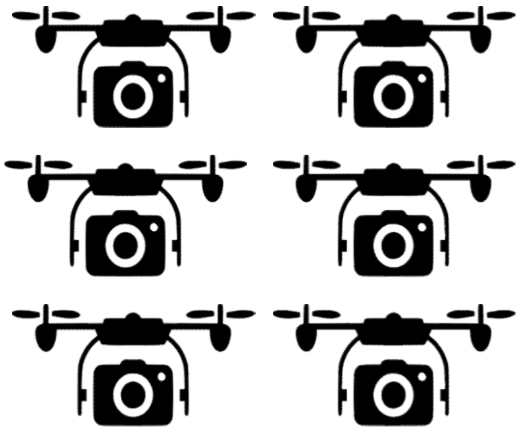
Perspectives

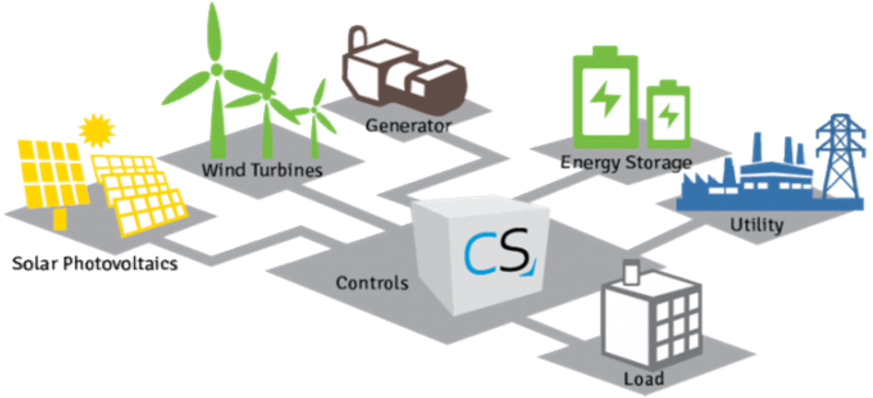
- Multi-Agents Systems

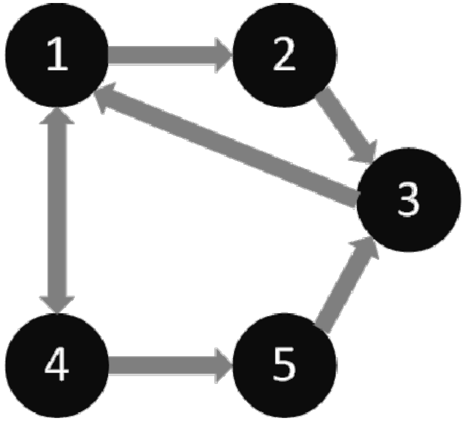
- Event-Triggered Control/Estimation for Cyber-Physical Systems

- Distributed FTC/FDI

- Fractional-order systems







Agent - i : **LPV, T-S**

Multiobjective synthesis : FFD

- Related Personal References (FFD) :

  - ✓ A. Chibani, M. Chadli, S.X. Ding, NB Braiek. Design of robust fuzzy fault detection filter for polynomial fuzzy systems with new finite frequency specifications. **Automatica 93, 42–54, 2018**.
  - ✓ A. Chibani, M. Chadli, P. Shi. Fuzzy Fault Detection Filter Design for T-S Fuzzy Systems in Finite Frequency Domain. **IEEE Transactions on Fuzzy Systems 25 (5), 1051-1061, 2018.**
  - ✓ S Marir, M Chadli, MV Basin. Bounded real lemma for singular linear continuous-time fractional-order systems. **Automatica 35, 2022.**

Thank you for your attention