Observer design
for state and clinker hardness estimation
in cement mill

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Plan

The CRAN was set up in Nancy (France) in 1980. It totals 180 persons. The research activities concentrate on 5 principal themes :
- Systems Observation and Control
- System Identification and Signal Processing
- Dependability and System Diagnosis
- Health Engineering
- Ambient Manufacturing Systems.

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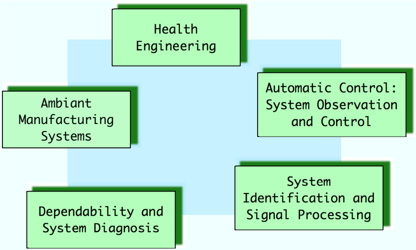
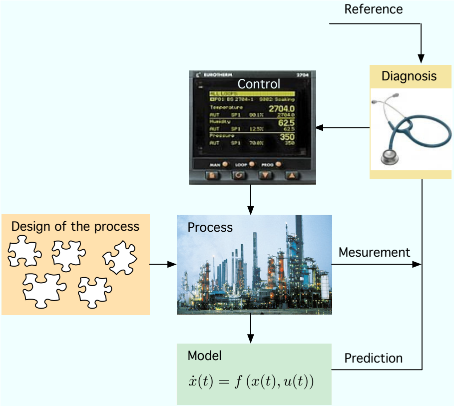



Reference
Diagnosis
Control
Design of the process
Process
Mesurement
Model
$\dot{x}(t) = f\left(x(t), u(t)\right)$
Prediction

2. A short presentation of process diagnosis

For the elaboration of a global approach for the design and the operation (supervision, maintenance, reconfiguration) of complex automated industrial systems, it is necessary :

- to guarantee the system safety, i.e. to guarantee that the system will operate according to the given specifications
- to forecast alternate modes allowing the system to continue to operate even if some parts of it are out of order
- to detect any fault, i.e. to decide that the system does not operate normally, using the overall available information on the actual behavior (obtained through the measurements) and on the expected behavior (forecast by a system model)
- to isolate the faults, i.e. to decide which function (or, at least, which component) is faulty based on data redundancy
- to identify the faults, i.e. to estimate the magnitude of the fault and to estimate its time evolution
- to compensate for the faults, i.e. to implement a fault tolerant control (that leads eventually to a degraded system performance) or reconfigure either the control architecture or the process architecture itself.

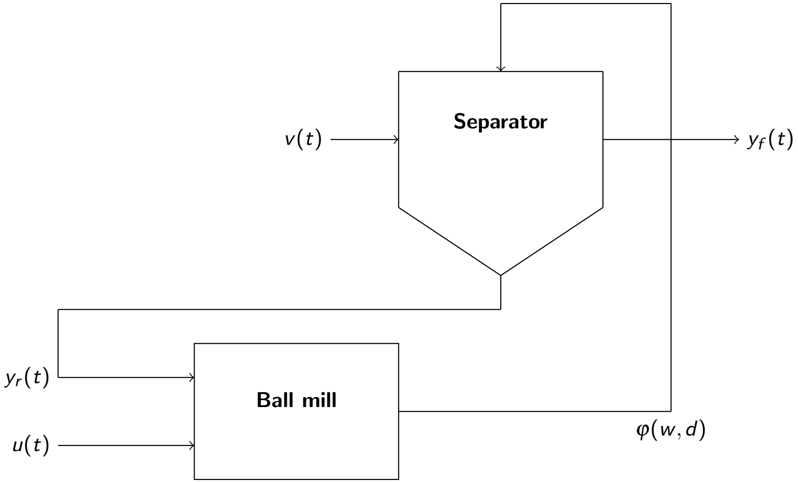


FIGURE: Cement mill process

3. System under investigation. Mathematical model

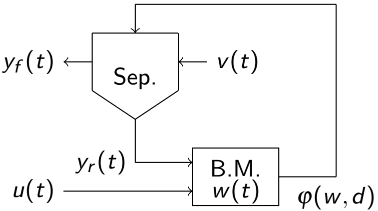


FIGURE: Cement mill process

Control	u	feeding rate
	v	separator speed
State	y_r	recycled flow
	q_e	ball mill input
	$\varphi(w,d)$	ball mill output
	$\alpha(v)$	separation function
	y_f	finished product flow
	w	load inside the mill
Perturbation	d	clinker hardness
Parameters	T_f	time constant
	T_r	time constant

$$
\begin{aligned}
&\textit{Separator} && T_f \dot{y}_f(t) = -y_f(t) + (1-\alpha(v))\varphi(w(t),d(t)) \\
&\textit{Ball-mill} && T_r \dot{y}_r(t) = -y_r(t) + \alpha(v)\varphi(w(t),d(t)) \\
&\textit{Load} && \dot{w}(t) = -\varphi(w(t),d(t)) + y_r(t) + u(t)
\end{aligned}
$$

where

$$
\begin{aligned}
\varphi(w(t),d(t)) &= p_1 w(t) \exp(-p_2 d(t) w(t)) \\
\alpha(v(t)) &= p_3 v^3(t) + p_4 v^4(t) + p_5 v^5(t)
\end{aligned}
$$

Then, the system is described by the following state equations

$$\begin{cases} \dot{x}(t) &= f(x(t), d(t)) + Bu(t) \\ y(t) &= Cx(t) \end{cases}$$

where

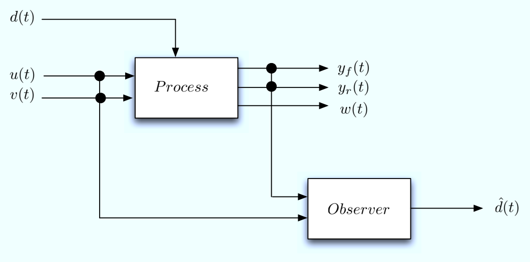
$$x(t) = \begin{bmatrix} y_f(t) \\ y_r(t) \\ w(t) \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$f(x(t), d(t)) = \begin{bmatrix} \frac{1}{T_f}(-x_1(t) + (1-\alpha(v))\varphi(x_3(t), d(t))) \\ \frac{1}{T_r}(-x_2(t) + \alpha(v)\varphi(x_3(t), d(t))) \\ x_2(t) - \varphi(x_3(t), d(t)) \end{bmatrix}$$

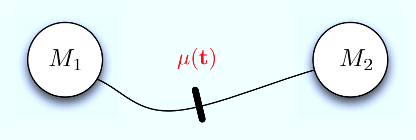
in which the hardness $d(t)$ is unknown.

$$\begin{bmatrix} \dot{y}_f(t) \\ \dot{y}_r(t) \\ \dot{w}(t) \end{bmatrix} = \begin{bmatrix} -1/T_f & 0 & 0 \\ 0 & -1/T_r & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} y_f(t) \\ y_r(t) \\ w(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u(t) + \begin{bmatrix} (1-\alpha(v)) \\ \alpha(v)\varphi(x_3, d) \\ -\varphi(x_3, d) \end{bmatrix}$$

3. System under investigation. Objectives



- Estimate the hardness $d(t)$
- Difficulty : the system is non linear
- Proposed approach : multi-model representation of the system



$$\mathscr{S}\begin{cases} M_1 & : \quad \dot{y}(t) = a_1.y(t) + b_1.u(t), \quad \textit{if} \quad y(t) > 2.5 \\ M_2 & : \quad \dot{y}(t) = a_2.y(t) + b_2.u(t), \quad \textit{if} \quad y(t) < 2.5 \end{cases}$$

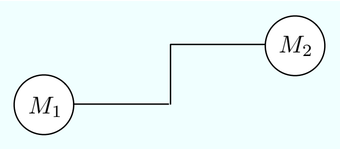
$$\mathscr{S}\begin{cases} \dot{y}(t) &= a(t).y(t) + b(t).u(t) \\ a(t) &= \mu(t).a_1 + (1-\mu(t)).a_2 \\ b(t) &= \mu(t).b_1 + (1-\mu(t)).b_2 \\ \mu(t) &= \frac{1}{2}(1 + sign(y(t) - 2.5)) \end{cases}$$

$$\mathscr{S}\begin{cases} \dot{y}(t) &= \sum_{i=1}^{2} \mu_i(t)(a_i.y(t) + b_i.u(t)) \\ \mu_1(t) &= \frac{1}{2}(1 + sign(y(t) - 2.5)) \\ \mu_2(t) &= 1 - \mu_1(t) \end{cases}$$

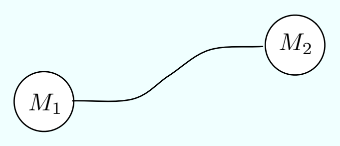
Summarizing, a multi-model, or a multiple-model, is a weighting sum of local models. These local models are chosen linear in respect to the state and control variable

Two kinds of weighting functions

- Switching



- Smooth transition



$$\dot{x}(t) = \begin{bmatrix} -\frac{1}{T_f} & 0 & \frac{z_1(t)}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -\frac{z_1(t)}{T_f} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u(t) + \begin{bmatrix} -\frac{z_2(t)}{T_f} \\ \frac{z_2(t)}{T_r} \\ 0 \end{bmatrix} d(t)$$

where the variables $z_1(x(t), d(t))$ and $z_2(t)$, later selected as premise variables, are defined by

$$z_1(t) = p_1 \exp(-p_2 d(t) x_3(t))$$
$$z_2(t) = \alpha(v(t)) p_1 x_3(t) \frac{\exp(-p_2 d(t) x_3(t))}{d(t)}$$

$$z_1^{\min} \leq z_1(t) \leq z_1^{\max}$$
$$z_2^{\min} \leq z_2(t) \leq z_2^{\max}$$

Since they are bounded, the premise variables can be written as a weighting sum of their bounds. For the first one :

$$\begin{aligned} z_1(t) &= \mu_1^0(z_1(t))z_1^{\text{min}} + \mu_1^1(z_1(t))z_1^{\text{max}} \\ &= \sum_{i=0}^{1} \mu_1^i(z_1(t))z_1^i \end{aligned}$$

where the functions μ_1^0 and μ_1^1 are defined by

$$\mu_1^0(z_1(t)) = \frac{z_1^1 - z_1(t)}{z_1^1 - z_1^0}, \quad \mu_1^1(z_1(t)) = \frac{z_1(t) - z_1^0}{z_1^1 - z_1^0}$$

and satisfy the following property :

$$\begin{aligned} &0 \leq \mu_1^0(z_i(t)) \leq 1 \\ &0 \leq \mu_1^1(z_i(t)) \leq 1 \\ &\mu_1^0(z_i(t)) + \mu_1^1(z_i(t)) = 1 \end{aligned}$$

$$\dot{x}(t) = \begin{bmatrix} -\frac{1}{T_f} & 0 & \frac{z_1(t)}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -\frac{z_1(t)}{T_f} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u(t) + \begin{bmatrix} -\frac{z_2(t)}{T_f} \\ \frac{z_2(t)}{T_r} \\ 0 \end{bmatrix} d(t) \qquad z_1(t) = \sum_{i=0}^{1} \mu_1^i(z_1(t)$$

$$\dot{x}(t) = \begin{bmatrix} -\frac{1}{T_f} & 0 & \frac{\sum_{i=0}^{1} \mu_1^i(z_1(t)) z_1^i}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -\frac{\sum_{i=0}^{1} \mu_1^i(z_1(t)) z_1^i}{T_f} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u(t) + \begin{bmatrix} -\frac{z_2(t)}{T_f} \\ \frac{z_2(t)}{T_r} \\ 0 \end{bmatrix} d(t)$$

$$\dot{x}(t) = \sum_{i=0}^{1} \mu_1^i(z_1(t)) \left(\begin{bmatrix} -\frac{1}{T_f} & 0 & \frac{z_1^i}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -\frac{z_1^i}{T_f} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u(t) + \begin{bmatrix} -\frac{z_2(t)}{T_f} \\ \frac{z_2(t)}{T_r} \\ 0 \end{bmatrix} d(t) \right)$$

The same transformation is made for the variable $z_2(t)$.

4. How to transform a non-linear model into a multi-model ?

$$\boxed{\dot{x}(t) = \sum_{i=1}^{4} \mu_i(z(t))\left(A_i x(t) + Bu(t) + E_i d(t)\right)} \quad 0 \leq \mu_i \leq 1, \quad \sum \mu_i = 1$$

$$A_1 = \begin{bmatrix} -\frac{1}{T_f} & 0 & -\frac{z_1^1}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -z_1^1 \end{bmatrix}, \quad A_3 = \begin{bmatrix} -\frac{1}{T_f} & 0 & -\frac{z_1^0}{T_f} \\ 0 & -\frac{1}{T_r} & 0 \\ 0 & 1 & -z_1^0 \end{bmatrix},$$

$$E_1 = \begin{bmatrix} -\frac{z_2^1}{T_f} \\ \frac{z_2^1}{T_r} \\ 0 \end{bmatrix}, \quad E_2 = \begin{bmatrix} -\frac{z_2^0}{T_f} \\ \frac{z_2^0}{T_r} \\ 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \quad A_2 = A_1, \quad A_4 = A_3, \quad E_3 = E_1, \quad E_4 = E_2$$

Advantage of this formulation :

- a systematic representation into a weighting sum of simple local models
- the possibility use results established for linear systems (stability, observer, control)

▷ Model of the observer

$$\begin{cases} \dot{\hat{x}}(t) & = \sum_{i=1}^{4} \mu_i(\hat{z}(t))(A_i x(t) + Bu(t) + E_i \hat{d}(t) + L_i(y(t) - \hat{y}(t))) \\ \dot{\hat{d}}(t) & = \sum_{i=1}^{4} \mu_i(\hat{z}(t)) K_i(y(t) - \hat{y}(t)) \\ \hat{y}(t) & = C\hat{x}(t) \end{cases}$$

$$\begin{cases} x_a(t) & = & [x^T(t) \quad d^T(t)]^T \\ e_a(t) & = & x_a(t) - \hat{x}_a(t) \\ \dot{e}_a(t) & = & \sum_{i=1}^{4} \mu_i(\hat{z}(t))(\mathscr{A}_i - \mathscr{M}_i \mathscr{C}) e_a(t) + \Delta(t) \end{cases}$$

where

$$\mathscr{A}_i = \begin{pmatrix} A_i & E_i \\ 0 & 0 \end{pmatrix}, \quad \mathscr{M}_i = \begin{pmatrix} L_i \\ K_i \end{pmatrix}, \quad \mathscr{C} = \begin{pmatrix} C & 0 \end{pmatrix},$$

$$\Delta(t) = \sum_{i=1}^{4} (\mu_i(z(t)) - \mu_i(\hat{z}(t))) \mathscr{A}_i x_a(t)$$

▷ Design of the observer : adjust E_i, L_i and K_i such that e_a is bounded.

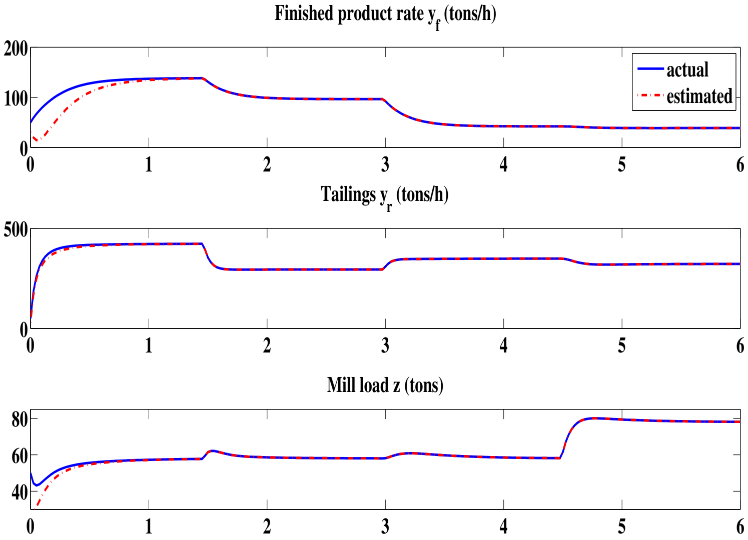


FIGURE: System states and their estimates

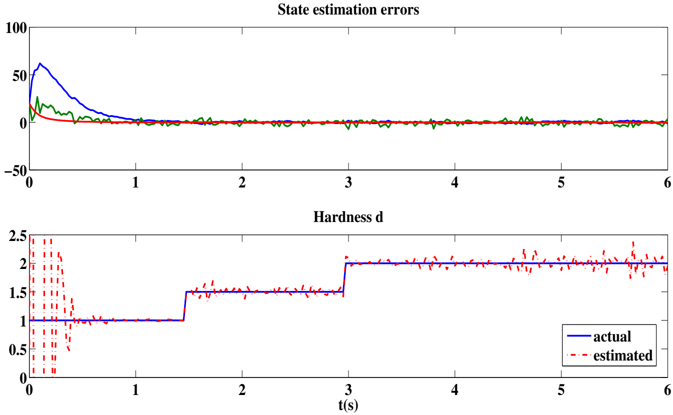


FIGURE: State estimation errors (top) and clinker hardness and its estimate with noised measurements

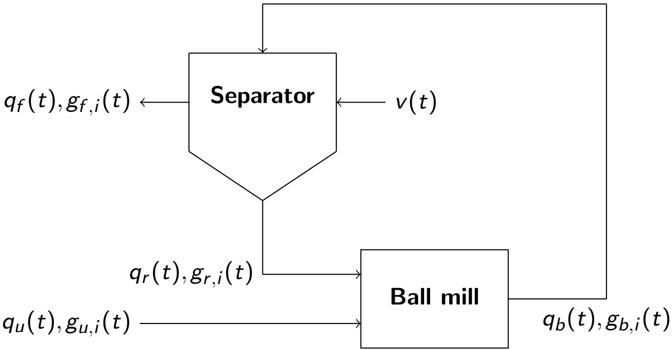


FIGURE: Cement mill process

Process equation

$$\left\{\begin{array}{lcl} T_f \dot{q}_f(t) & = & -q_f(t) + (1-\alpha(v)).q_b(t) \\ T_r \dot{q}_r(t) & = & -q_r(t) + \alpha(v).q_b(t) \\ \dot{w}(t) & = & -\varphi(t) + q_r(t) + u(t) \\ q_b(t) & = & p_1.w(t).\exp(-p_2.d.w(t)) \\ \dfrac{d(g_{b,i}(t))}{dt} & = & \dfrac{1}{w(t)}\left(q_u(t)(g_{u,i}(t) - g_{b,i}(t)) + q_r(t)(g_{r,i}(t) - g_{b,i}(t))\right) \\ & & -s_i g_{b,i}(t) + \sum_{j=i}^{N} g_{b,j}(t) s_j b_{ij}, \quad i = 1,\ldots,N \end{array}\right.$$

Control loop equation

$$\left\{\begin{array}{lcl} u(t) & = & -q_r(t) + k_1(w^*(t) - w(t)) \\ v(t) & = & k_2(q_f(t) - q_f^*(t)) \end{array}\right.$$

▷ The goal of this paper is to design an observer for mill load and clinker hardness estimation in cement mill process with only the knowledge of the feeding u, the tailings y_r and the finished product rate y_f.

▷ Work is underway to extend the proposed state reconstruction when one takes into account, in addition to flow rates, the whole particle size distributions of the product throughout the separation-grinding loop.

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