EA 4353

Indirect adaptive MPC supervised by fuzzy logic: application to a diesel engine

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Outline

- Motivation & objective
- Remind on MPC and IAMPC
- Performance criteria considered
- IAMPC supervised by fuzzy logic
- Application to a diesel engine
- Conclusion & future work

1 - Motivation & objective

- **Model Predictive Control**
  - Model-based approach
  - Optimal control
  - Constraints

  - Parameters computation (off-line/on-line)
  - Performances robustness
  - Fault tolerance

Objective: to design a MPC structure

- dedicated to systems with time-varying parameters

- computing on-line the controller parameters from desired performance criteria

2 - Plant model

- **Discrete-time model of the plant considered:**

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k), \\ y(k) = C_d x(k), \end{cases}$$

- **Discrete-time augmented model:**

$$\begin{cases} x_a(k+1) = A x_a(k) + B\Delta u(k) \\ y(k) = C x_a(k), \end{cases} \quad \text{with} \quad \begin{cases} x_a(k) = [\Delta x(k) \quad y(k)]^T \\ \Delta u(k+1) = u(k+1) - u(k) \\ \Delta x(k+1) = x(k+1) - x(k) \end{cases}$$

and $A = \begin{bmatrix} A_d & O_d^T \\ C_d A_d & 1 \end{bmatrix} \quad B = \begin{bmatrix} B_d \\ C_d B_d \end{bmatrix}, C = [O_d \quad 1], O_d = [0 \quad 0 \quad \cdots \quad 0].$

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3 - Model Predictive Control

- **Cost function to minimize:**

Since $\hat{Y} = Fx_a(k) + \Phi\Delta U$

$$J = (Y_{des} - \hat{Y})^T (Y_{des} - \hat{Y}) + \Delta U^T \overline{R} \Delta U$$

with

$$\begin{cases} Y_{des}^T = [y_{des}(k+1), y_{des}(k+2), \ldots, y_{des}(k+HP)] \\ \hat{Y}^T = [\hat{y}(k+1|k), \hat{y}(k+2|k), \ldots, \hat{y}(k+HP|k)] \\ \Delta U^T = [\Delta u(k), \Delta u(k+1), \ldots, \Delta u(k+HC)] \\ \overline{R} = \lambda I_{HC \times HC} \end{cases}$$

- **Resulting control signal:**

From $\frac{\partial J}{\partial \Delta U} = -2\Phi^T \left(Y_{des} - Fx_a(k)\right) + 2\left(\Phi^T\Phi + \overline{R}\right)\Delta U$ ⇒

$$\boxed{\Delta U = (\Phi^T\Phi + \overline{R})^{-1}\Phi^T (Y_{des} - Fx_a(k))}$$

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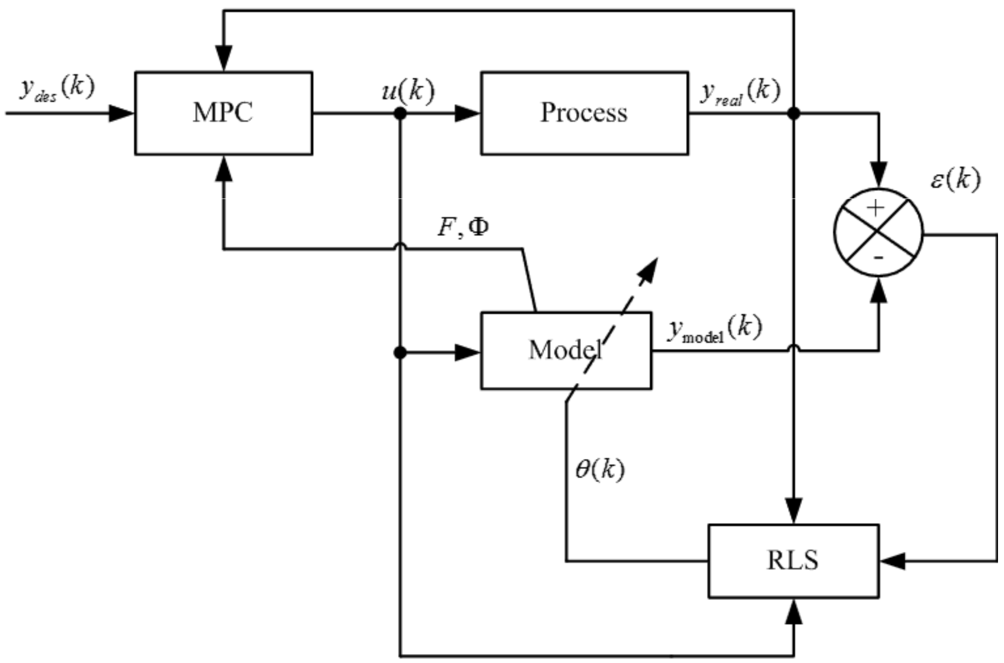
4 - Indirect Adaptive MPC

- **Principle [8]:**
  - Structure



- **On-line identification:**
  - RLS method

$$y_{\text{mod}}(k) = \theta^T \phi(k)$$

with

$$\phi(k) = \begin{bmatrix} -y(k-1) \\ \vdots \\ -y(k-n_1) \\ u(k-d-1) \\ \vdots \\ u(k-d-n_2) \end{bmatrix}.$$

$$\theta^T = \left[a_1, \ldots, a_{n_1}, b_1, \ldots, b_{n_2}\right]$$

➡ Control performances are not guaranteed

5 - Performance criteria considered

- **Stability degree indicator (SDI)**

$$SDI(k) = 1 - \max\left(|p_1|, |p_2|, \ldots, |p_{n_A}|\right),$$ where p_1, p_2, … are the poles of A_d

- **Output Convergence Time (OCT) and Relative Error Threshold (RET)**

$$\left|\frac{y_{real} - y_{des}}{y_{des}}\right| \leq RET,$$

- **Control signal variance (VARU)**

$$VARU(k) = \overline{u(k)^2} - \left[\overline{u(k)}\right]^2$$

- **Computation conditioning of the optimal control signal [9]**

$$trace(\ \Phi^T \Phi\ )$$

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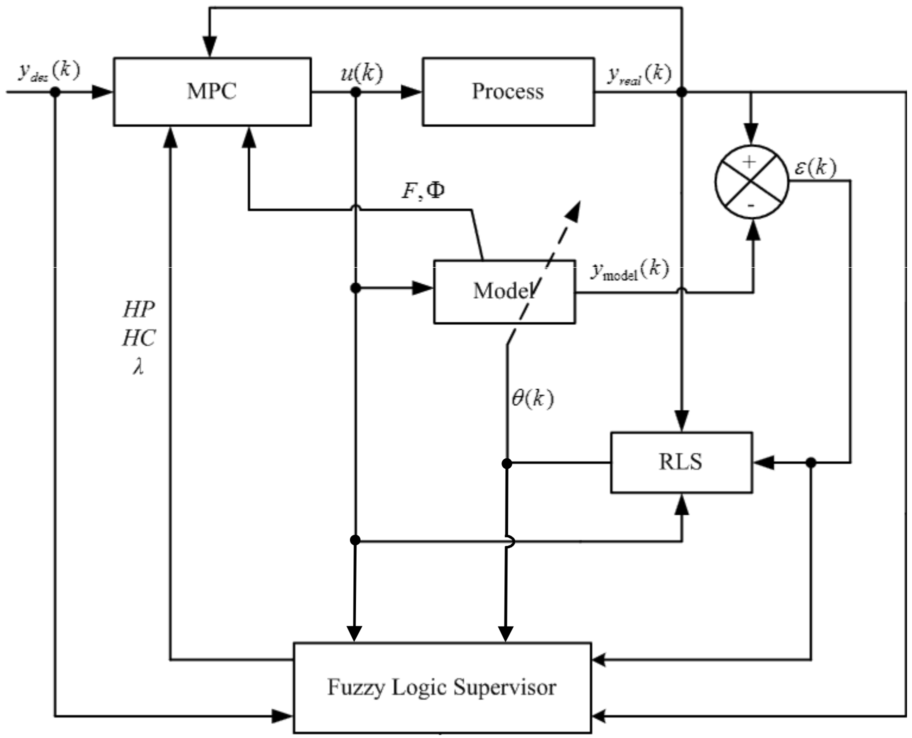
5 – Proposed IAMPC + FLS

- **Structure:**



- **Controller parameters computation:**
  - If $\varepsilon(k) \geq S_1$: RLS algorithm activation
  - If $\varepsilon(k) \geq S_2$: FL supervisor activation

with $S_2 \geq S_1$

5 – Proposed IAMPC + FLS

- **Performance criteria computation:**

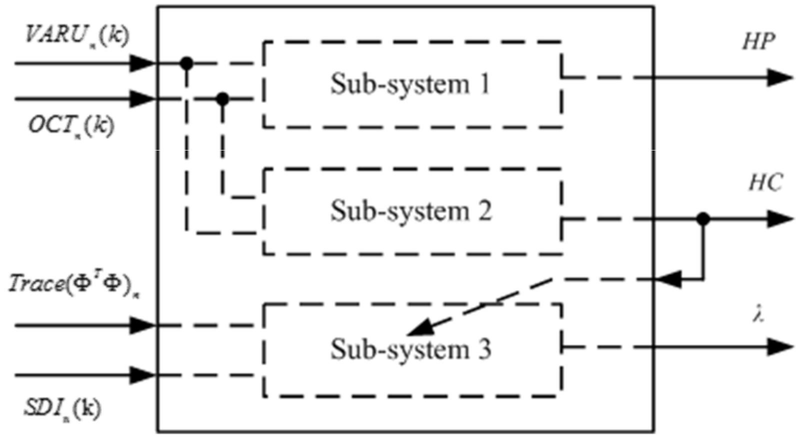
$$SDI_n(k) = \frac{SDI(k) - SDI_{\min}}{SDI_{\max}}$$

$$OCT_n(k) = \frac{OCT(k) - OCT_{\min}}{OCT_{\max}}$$

$$VARU_n(k) = \frac{VARU(k) - VARU_{\min}}{VARU_{\max}}$$

$$trace(\Phi^T\Phi)_n(k) = \frac{trace(\Phi^T\Phi)(k) - trace(\Phi^T\Phi)_{\min}}{trace(\Phi^T\Phi)_{\max}}$$

- **Fuzzy part of the supervisor:**



5 – Controller parameters computation

- Rules table for *HC*:

		$OCT_n(k)$		
		Small	*Middle*	*Big*
$VARU_n(k)$	*Small*	**Middle**	**Big**	**Very Big**
	Middle	**Small**	**Middle**	**Big**
	Big	**Very Small**	**Small**	**Middle**

- Rules table for *HP*:

		$OCT_n(k)$		
		Big	*Middle*	*Small*
$VARU_n(k)$	*Small*	**Very Small**	**Small**	**Middle**
	Middle	**Small**	**Middle**	**Big**
	Big	**Middle**	**Big**	**Very Big**

- Rules table for *λ*:

		$SDI_n(k)$		
		Small	*Middle*	*Big*
$\frac{\text{Trace}(\phi^T\phi)_n}{HC}$	*Small*	**Middle**	**Small**	**Very Small**
	Middle	**Big**	**Middle**	**Small**
	Big	**Very Big**	**Big**	**Middle**

- Quantification of *HC* and *HP*:

$$HC(k) = round\left[HC_n(k)(HC_{\max} - HC_{\min}) + HC_{\min}\right]$$

$$HP(k) = round\left[HP_n(k)(HP_{\max} - HP_{\min}) + HP_{\min}\right]$$

5 - Linear inequality constraints

- **Constraints on control signals [12]**

$$U^{\min} \le U \le U^{\max}$$
$$\Delta U^{\min} \le \Delta U \le \Delta U^{\max}$$

$$\Rightarrow \begin{bmatrix} -I \\ I \\ -I \\ I \end{bmatrix} \Delta U \le \begin{bmatrix} -U^{\min} + u(k-1) \\ U^{\max} - u(k-1) \\ \Delta U^{\min} \\ \Delta U^{\max} \end{bmatrix} \Leftrightarrow M \Delta U \le \gamma$$

- **Cost fonction to minimize**

Since $\hat{Y} = F x_a(k) + \Phi \Delta U$ $\Rightarrow$ $J = 0.5 \cdot \Delta U^T \Omega \Delta U + \Delta U^T \Psi + \eta^T (M \Delta U - \gamma),$

where
$$\begin{cases} \Omega = \Phi^T \Phi + \overline{R} \\ \Psi = -\Phi^T (Y_{des} - F x_a(k)). \\ \eta = -\left(M \Omega^{-1} M^T\right)^{-1} \left(\gamma + M \Omega^{-1} \Psi\right) \end{cases}$$

- **Resulting control signal [11]**

$$\boxed{\Delta U = -\Omega^{-1} \left(\Psi + M^T \eta\right)}$$

6 – Application to a diesel engine

- 1st set point

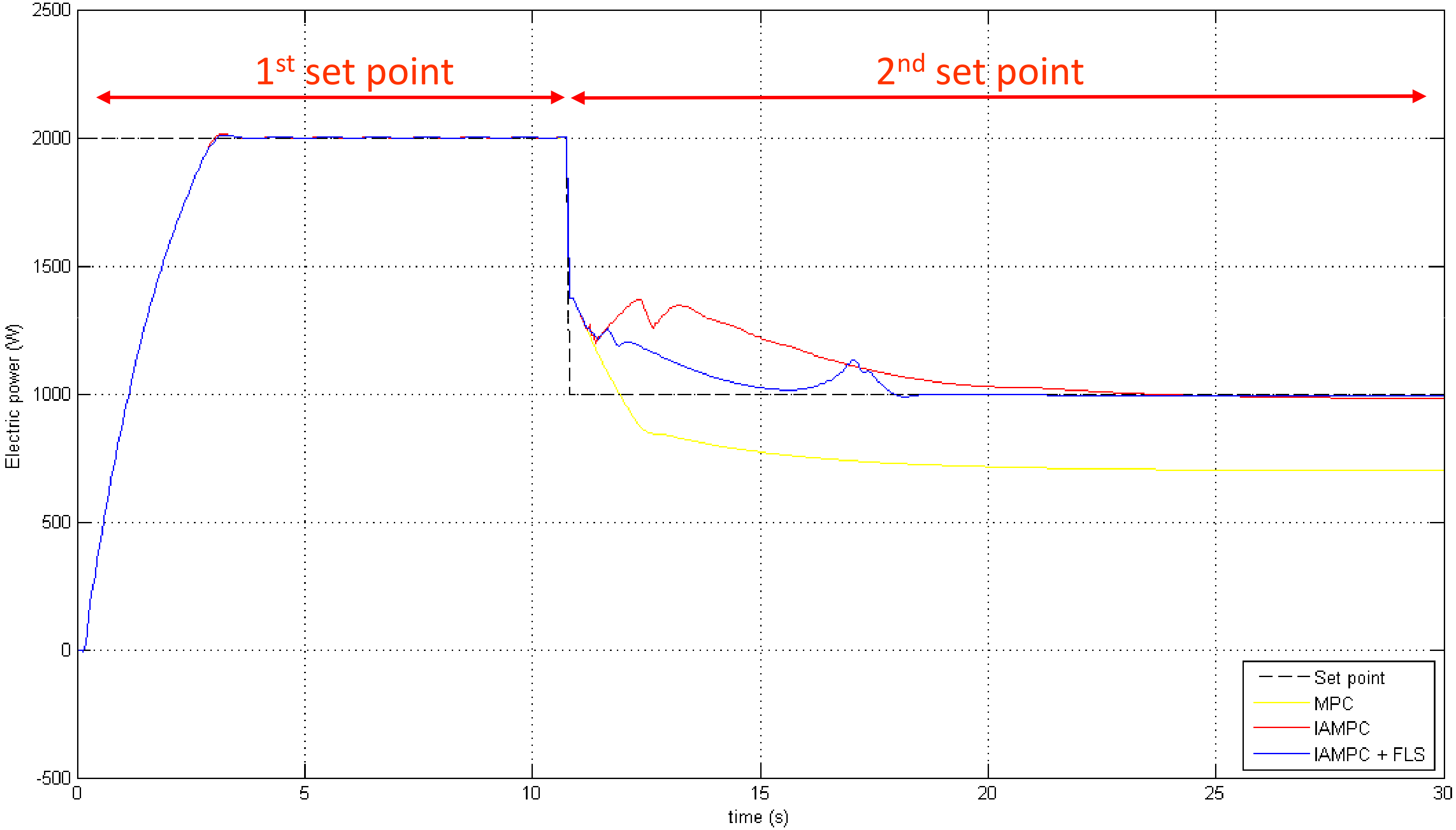
$$\begin{cases} P_{gen\_des} = 2kW \\ T_{res} = 7.6Nm \\ \dfrac{P_{gen}(k)}{V_{act}(k)} = \dfrac{q^{-1}\left(-1.947q^{-1} + 7.43q^{-2} + 19.09q^{-3}\right)}{1 - 0.4393q^{-1} - 0.3034q^{-2} - 0.01875q^{-3} - 0.1933q^{-4}} \end{cases}$$

- 2nd set point

$$\begin{cases} P_{gen\_des} = 1kW \\ T_{res} = 8.9Nm \\ \dfrac{P_{gen}(k)}{V_{act}(k)} = ? \end{cases}$$

6 - Results (1/4)

- Desired power and output signals vs. time



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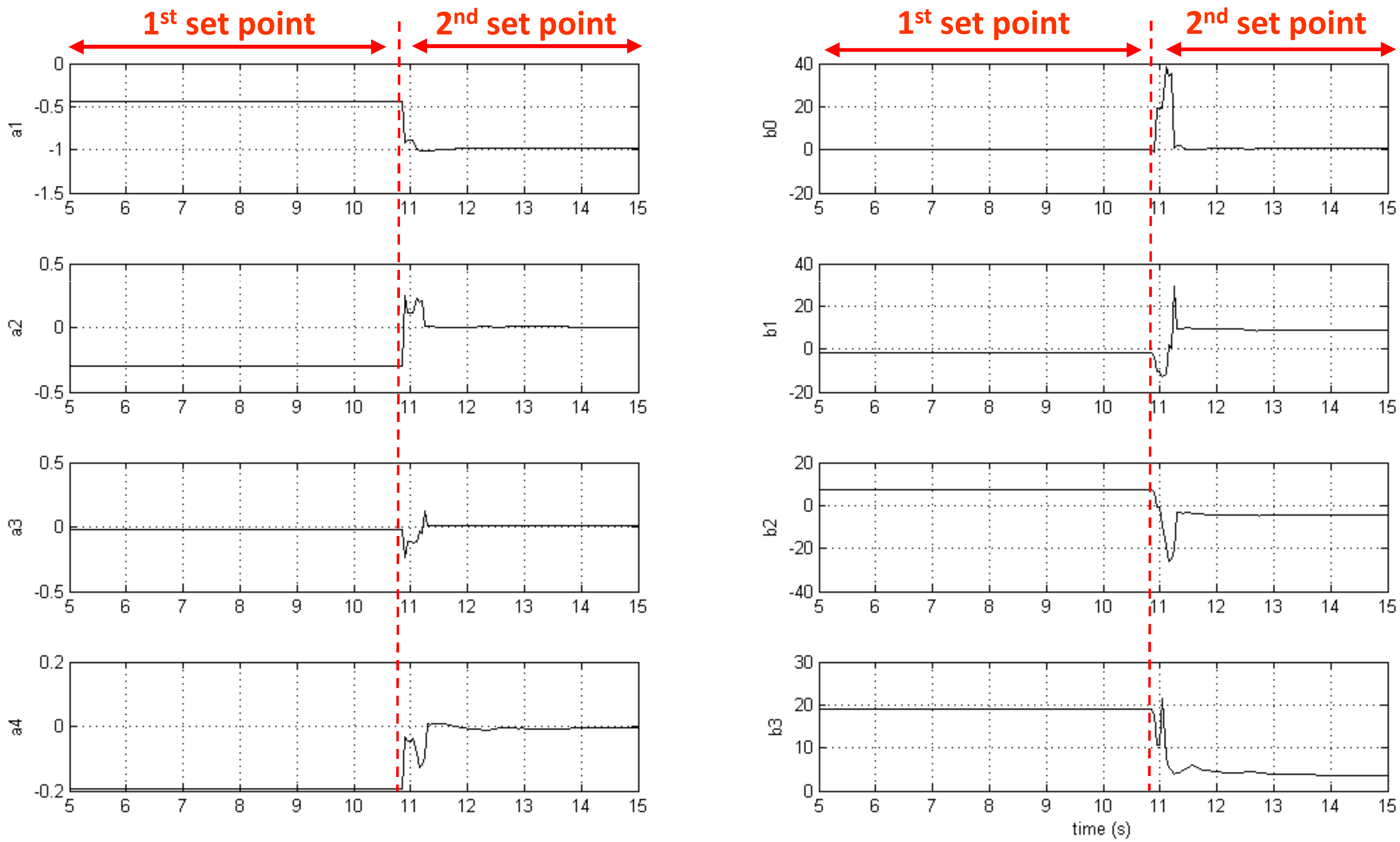
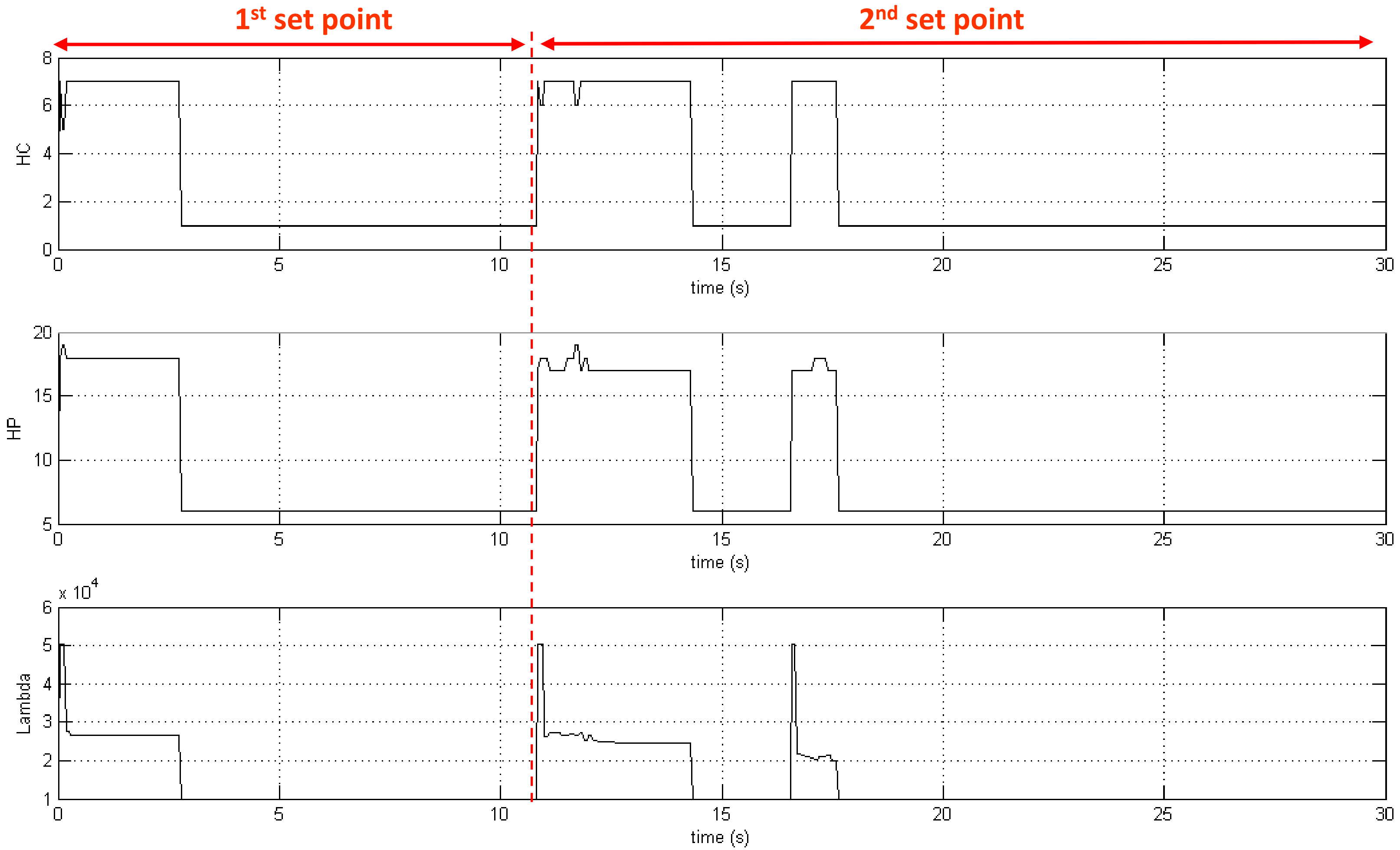
6 - Results (2/4)

- Model parameters vs. time



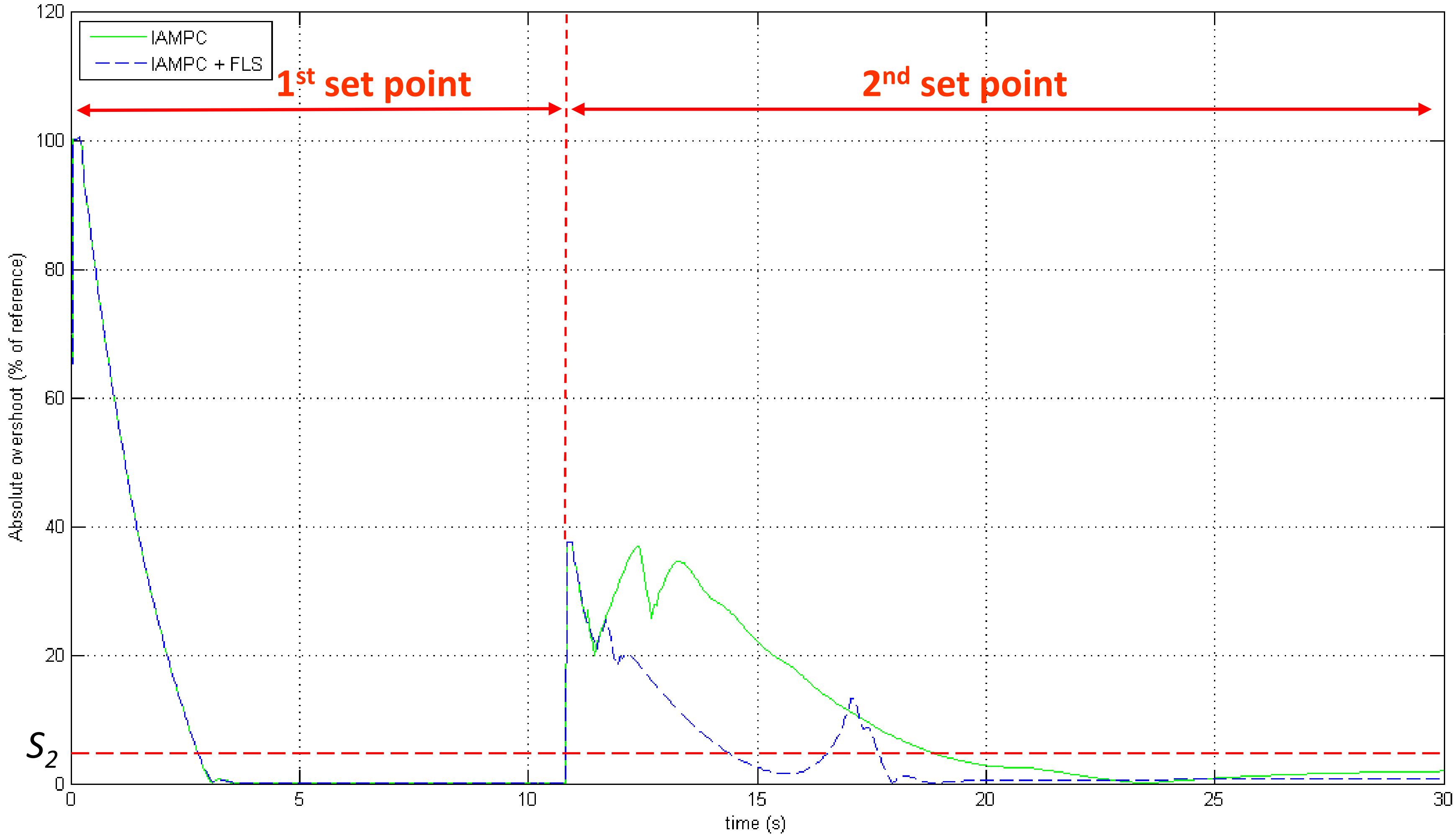
6 - Results (3/4)

- **Predictive controller parameters vs. time**



6 - Results (4/4)

- Absolute overshoot vs. time with S_1= 2.5% and S_2= 5%



7 - Conclusion and future work

1) Design of an adaptive predictive controller

- On-line parameters computation

- Performance criteria

2) Application to a plant with varying parameters

3) Performance comparison with MPC & IAMPC

1) Application of IAMCP + FLS to:

- Unstable systems

- MIMO systems

2) Coupling with a fault detection algorithm

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