Research on Economic Performance Assessment and Diagnosis of Industrial MPC

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Petrochemical Industry

1. **Pillar industry in the world**
   - The first major pillar industry in the world
   - **$14.9 trillion** gross output in the world (2013)
   - China as number one

2. **Big energy producer, Big energy user**
   - **15%** of total energy consumption
   - **15%~20% above the average energy consumption level**

MPC: Enabling Technology of Saving Energy and Increasing Profit

Outline

1. Why CPA
2. CPA of PID Loop
3. Economic PA of Industrial MPC
4. On-line EPI of Industrial MPC
5. MPM Detection of MPC with Mutual Information

MPC: Model Predictive Control

Control System: Big Investment

1. **Typical Control Loop Investment: $25,000 (ABB Company)**
   - Hardware: Including valve, sensor, controller etc.
   - Software: Control algorithm, SCADA system etc.

2. **Typical Petrochemical Process: 10^2~10^3 Loops**

Improperly Working Control System

However:

1. Fewer and fewer adequately educated control engineer

2. Average control engineer responsible > 100 loops

Short of Maintenance

Control Performance Reality: Not Good

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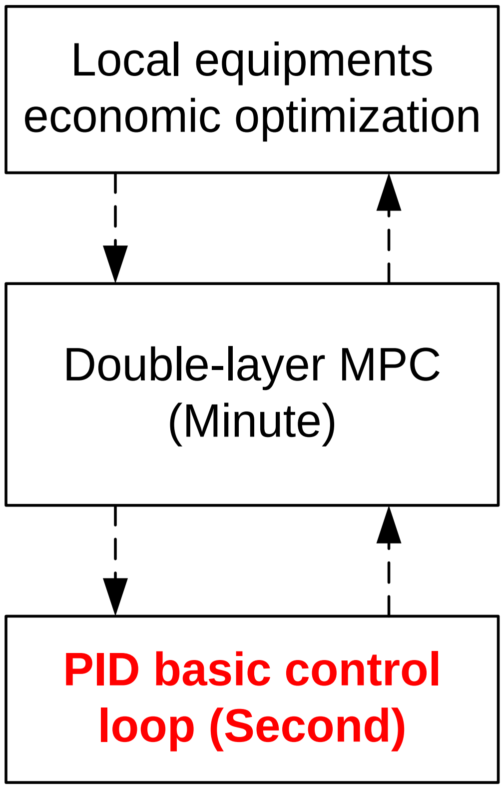
5. Model-Plant Mismatch Detection of MPC using Mutual Information

MPC: Model Predictive Control

PID Loop: Basis of MPC



PID: Execute MPC command

↓

Good PID prerequisite for Good MPC

↓

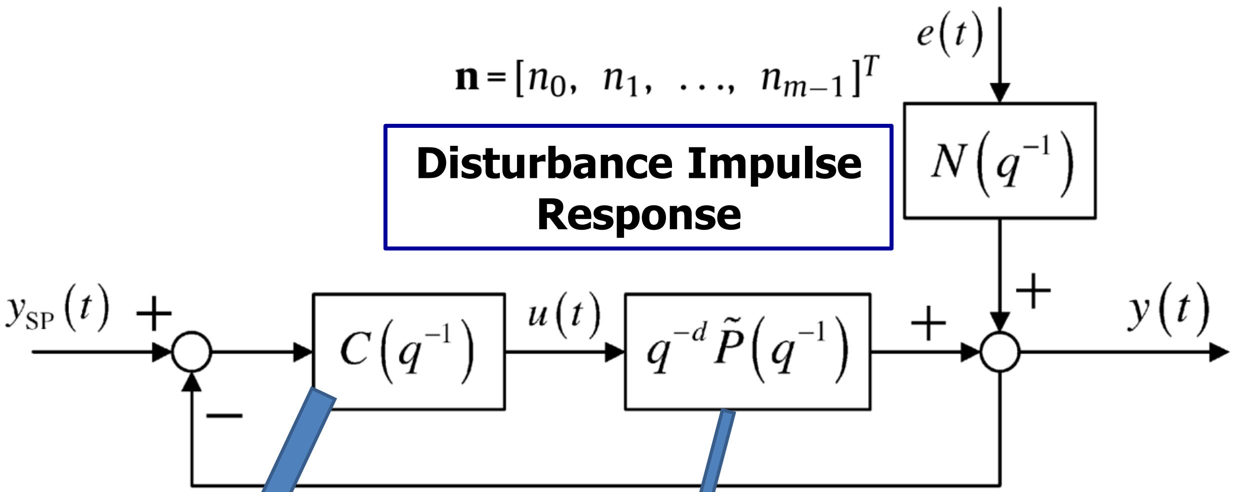
Regulatory performance of PID:

How accurate can PID follow MPC command?

Ruowei Fu, Lei Xie, Zhihuan Song, Yong Cheng. **PID control performance assessment using iterative convex programming**. Journal of Process Control, 2012, 22: 1793-1799.

PID Regulatory Performance

Measured by Loop Output Variance



$$\sigma_y^2 \approx \mathbf{n}^T(\mathbf{I}+\mathbf{SC})^{-T}(\mathbf{I}+\mathbf{SC})^{-1}\mathbf{n}$$

$$C_{\mathrm{PID}}(q^{-1}) = \frac{c_1 + c_2 q^{-1} + c_3 q^{-2}}{1 - q^{-1}}$$

$$\mathbf{S} = \begin{bmatrix} s_0 & 0 & 0 & \cdots & 0 \\ s_1 & s_0 & 0 & \cdots & 0 \\ s_2 & s_1 & s_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ s_{m-1} & \cdots & \cdots & s_1 & s_0 \end{bmatrix}$$

Process Step Response

- **Nonparameter-Model Based**
- **Applied to any order process**

Good or Bad?

CPA of PID

Good or Bad?

Find the benchmark:
Minumum Output Variance

$$\min_{\mathbf{C}} \ \mathbf{n}^T(\mathbf{I}+\mathbf{SC})^{-T}(\mathbf{I}+\mathbf{SC})^{-1}\mathbf{n}$$

Nonconvex!

CPA of PID

Good or Bad?

$$\min_{\mathbf{C}} \ \mathbf{n}^T(\mathbf{I}+\mathbf{SC})^{-T}(\mathbf{I}+\mathbf{SC})^{-1}\mathbf{n}$$

Nonconvex!

Schur Complement

$$\begin{aligned} \min_{\mathbf{A},\mathbf{x},\mathbf{V},z} \quad & z \\ \text{s.t.} \quad & z \geq 0, \quad \mathbf{A} = \mathbf{H}((\mathbf{G}\mathbf{G}^T)\odot(\mathbf{Q}\mathbf{V}\mathbf{Q}^T))\mathbf{H}^T \\ & \begin{bmatrix} \mathbf{A} & \mathbf{n} \\ \mathbf{n}^T & z \end{bmatrix} \succeq \mathbf{0}, \\ & \mathbf{V} \succeq \mathbf{0}, \quad \begin{bmatrix} \mathbf{V} & \mathbf{x} \\ \mathbf{x}^T & 1 \end{bmatrix} \succeq \mathbf{0} \\ & \text{trace}(\mathbf{V}) \leq \mathbf{x}^T\mathbf{x}. \end{aligned}$$

Nonconvex Constraints

CPA of PID

Good or Bad?

$$\min_{\mathbf{C}} \ \mathbf{n}^T(\mathbf{I}+\mathbf{SC})^{-T}(\mathbf{I}+\mathbf{SC})^{-1}\mathbf{n}$$

Nonconvex!

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& \begin{bmatrix} \mathbf{A} & \mathbf{n} \\ \mathbf{n}^T & z \end{bmatrix} \succeq \mathbf{0}, \\
& \mathbf{V} \succeq \mathbf{0}, \quad \begin{bmatrix} \mathbf{V} & \mathbf{x} \\ \mathbf{x}^T & 1 \end{bmatrix} \succeq \mathbf{0} \\
& \text{trace}(\mathbf{V}) \leq \mathbf{x}^T\mathbf{x}.
\end{aligned}$$

Lagrange method & Fixed-point Alg.

Nonconvex Constraints

CPA of PID

Good or Bad?

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&\text{trace}(\mathbf{V}) \leq \mathbf{x}^T\mathbf{x}.
\end{aligned}$$

Nonconvex Constraints

Lagrange method & Fixed-point Alg.

$$\begin{aligned}
&\mathbf{x}^{(k)} = \operatorname*{argmin}_{\mathbf{A},\mathbf{x},\mathbf{V},z} \quad z + \lambda(\text{trace}(\mathbf{V}) - (2\mathbf{x}^{(k-1)^T}\mathbf{x} - \mathbf{x}^{(k-1)^T}\mathbf{x}^{(k-1)})) \\
&\text{s.t.} \quad z \geq 0, \quad z \leq [\sigma_y^2]^{(k-1)}, \\
&\mathbf{A} = \mathbf{H}((\mathbf{G}\mathbf{G}^T)\odot(\mathbf{Q}\mathbf{V}\mathbf{Q}^T))\mathbf{H}^T, \\
&\begin{bmatrix} \mathbf{A} & \mathbf{n} \\ \mathbf{n}^T & z \end{bmatrix} \succeq \mathbf{0}, \quad \begin{bmatrix} \mathbf{V} & \mathbf{x} \\ \mathbf{x}^T & 1 \end{bmatrix} \succeq \mathbf{0}, \\
&\mathbf{V} \succeq \mathbf{0}, \quad [\mathbf{V}]_{1,1} = 1, \quad \mathbf{x} = [\mathbf{V}]_1,
\end{aligned}$$

CPA of PID

$$\mathbf{x}^{(k)} = \underset{\mathbf{A},\mathbf{x},\mathbf{V},z}{\operatorname{argmin}} \quad z + \lambda(\operatorname{trace}(\mathbf{V}) - (2\mathbf{x}^{(k-1)^T}\mathbf{x} - \mathbf{x}^{(k-1)^T}\mathbf{x}^{(k-1)}))$$

Good or Bad?

Succesive Convex Problem

$$\mathbf{V} \succeq \mathbf{0}, \quad [\mathbf{V}]_{1,1} = 1, \quad \mathbf{x} = [\mathbf{V}]_1,$$

Lagrange method & Fixed-point Alg.

$$\min_{\mathbf{C}} \ \mathbf{n}^T(\mathbf{I}+\mathbf{SC})^{-T}(\mathbf{I}+\mathbf{SC})^{-1}\mathbf{n}$$

Nonconvex!

Schur Complement

$$\min_{\mathbf{A},\mathbf{x},\mathbf{V},z} \quad z$$

$$\text{s.t.} \quad z \geq 0, \quad \mathbf{A} = \mathbf{H}((\mathbf{G}\mathbf{G}^T)\odot(\mathbf{Q}\mathbf{V}\mathbf{Q}^T))\mathbf{H}^T$$

$$\begin{bmatrix} \mathbf{A} & \mathbf{n} \\ \mathbf{n}^T & z \end{bmatrix} \succeq \mathbf{0},$$

$$\mathbf{V} \succeq \mathbf{0}, \quad \begin{bmatrix} \mathbf{V} & \mathbf{x} \\ \mathbf{x}^T & 1 \end{bmatrix} \succeq \mathbf{0}$$

$$\operatorname{trace}(\mathbf{V}) \leq \mathbf{x}^T\mathbf{x}.$$

Nonconvex Constraints

CPA of PID

Succesive Convex Problem

$$\mathbf{x}^{(k)} = \underset{\mathbf{A},\mathbf{x},\mathbf{V},z}{\operatorname{argmin}} \quad z + \lambda(\operatorname{trace}(\mathbf{V}) - (2\mathbf{x}^{(k-1)^T}\mathbf{x} - \mathbf{x}^{(k-1)^T}\mathbf{x}^{(k-1)}))$$

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$$\mathbf{V} \succeq \mathbf{0}, \quad [\mathbf{V}]_{1,1} = 1, \quad \mathbf{x} = [\mathbf{V}]_1,$$

Algorithm 1. The proposed iterative convex programming approach

Initialization: (i) Set the numerical tolerance ϵ and the maximum number of iterations $K^{(\max)}$; (ii) Compute an initial point $\mathbf{x}^{(0)}$ according to Section 4.2; (iii) Set the iteration number $k = 1$.
Repeat:
Step 1: Solve the convex problem (19) to obtain the solution $\mathbf{x}^{(k)}$.
Step 2: Compute the output variance $[\sigma_y^2]^{(k)}$ with the obtained PID parameters $\{c_1^{(k)}, c_2^{(k)}, c_3^{(k)}\}$, and record the obtained results.
Step 3: Update the iteration number $k = k + 1$.
Until: $|f(\mathbf{x}^{(k)}) - f(\mathbf{x}^{(k-1)})| < \epsilon$ or $k > K^{(\max)}$.

Readily Solved!

CPA: Compare current loop output variance with the benchmark

CPA of PID

Test on 100 typical single-loop

Case	BKRs	σ_y^2 (Algorithm 1)	$[c_1, c_2, c_3]$ (Algorithm 1)	λ	Time
1	3.0728	**3.0728**	[2.8407, −4.4056, 1.7485]	1	16.0
2	0.0310	0.0311	[1.9556, −3.6286, 1.6746]	1	170.6
3	3.0238	3.0442	[0.6315, −1.2380, 0.6065]	10^3	4.3
4	3.4065	3.4081	[0.1353, −0.2521, 0.1169]	10	108.7
5	13.8077	**13.8077**	[0.7253, −1.2081, 0.5190]	10^3	466.8
6	87.7520	**87.7380**	[0.8305, −1.3958, 0.6070]	10^4	261.6
7	0.4247	**0.4247**	[8.0823, −13.1663, 5.5814]	1	296.2
8	3.2032	**3.2032**	[6.5331, −9.2362, 3.3574]	1	75.1
9	0.4268	**0.4268**	[8.2316, −13.7790, 5.9699]	1	202.2
10	0.0024	**0.0024**	[6.2862, −8.8138, 3.1626]	10^{-2}	513.8

⋮

Can obtain the benchmark accurately & quickly

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MPC: Model Predictive Control

MPC Performance Assessment (PA)

More Important & Challenging!

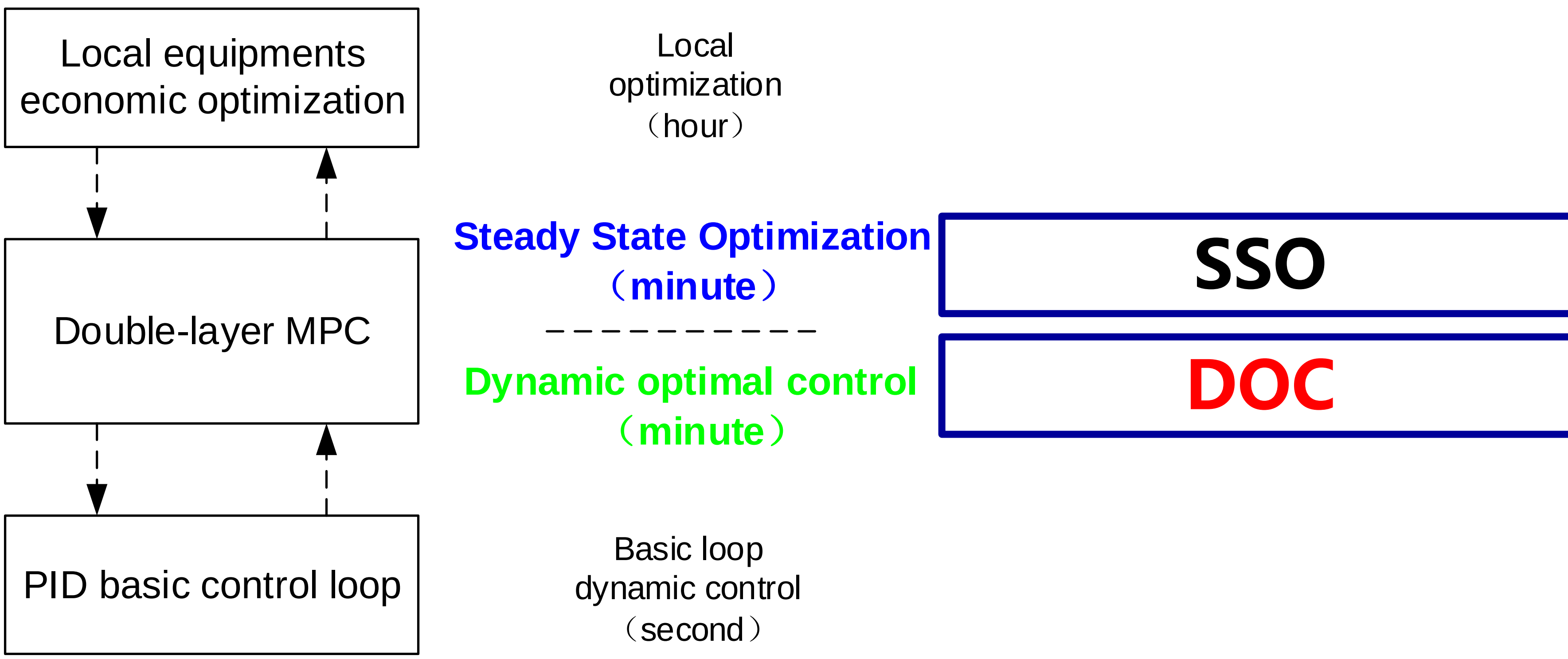
1. **Widely applied petrochemical industry**
   - > 50 new projects/year in China
   - > 400 in service in China

2. **Control objective of MPC is highly related to economic profit of plant**

3. **Performance may degrade quickly**
   - Typical 6 months good-performance-period after commissioning

Industrial MPC

Double-Layer Structure of Industrial MPC



Zhao, C., Y. Zhao, H. Su and B. Huang (2009). **"Economic performance assessment of advanced process control with LQG benchmarking."** Journal of Process Control 19(4): 557-569.

Liu, Z., Y. Gu and L. Xie (2012). **"An improved LQG benchmark for MPC economic performance assessment and optimisation in process industry."** Canadian Journal of Chemical Engineering 90(6): 1434-1441.

DOC PA based on LQG

Given $E\{u^2\} \le \alpha$, what is minimum of $E\{y^2\}$?

Varying λ
Solving the LQG problem

Obtain the MPC Performance Limit Curve

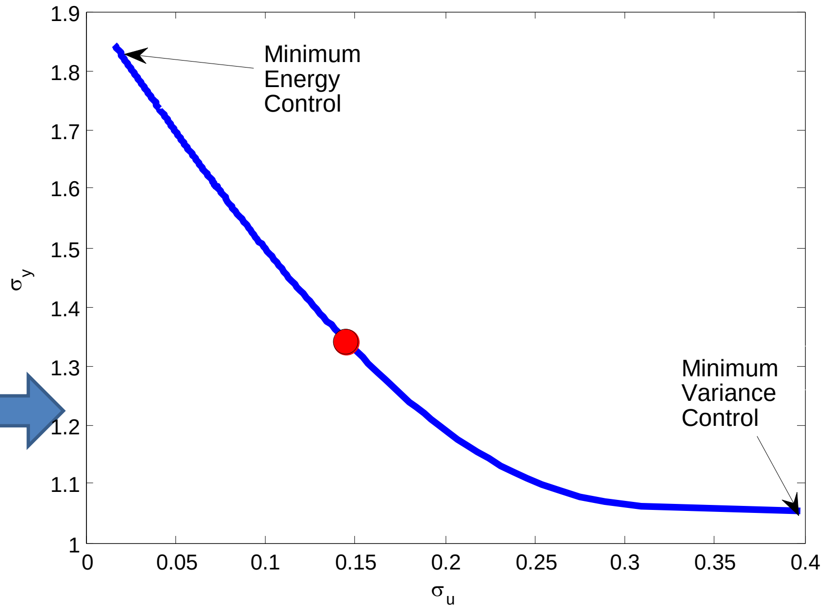
$$\Phi = E\left[\left\|\mathbf{y} - \mathbf{y}^s\right\|_Q\right] + \lambda E\left[\left\|\mathbf{u} - \mathbf{u}^s\right\|_R\right]$$

$s.t.$

Process Dynamic Model

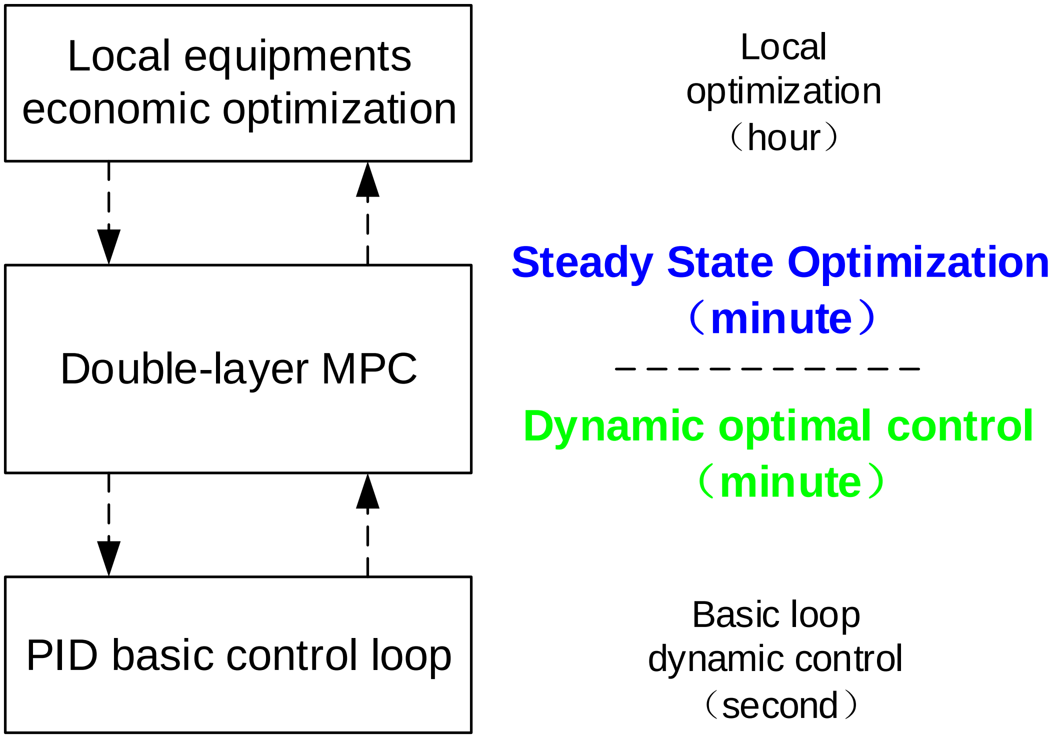
$$U_{i,\min} \le u_i \le U_{i,\max}$$

$$Y_{j,\min} \le y_j \le Y_{j,\max}$$



Economic PA of
Double-Layer Industrial MPC

Double-Layer Structure of Industrial MPC



What is the best coordination of the two layers?

Economic Performance Assessment

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Economic PA of
Double-Layer Industrial MPC

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$$s.t. \mathrm{D}y_j^s = \sum_{i=1}^{m} k_{ij} \mathrm{D}u_i^s$$

$$\Delta u_i^s = u_i^s - u_i^{s0}$$

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$$Y_{j,\min} + z_{\alpha_j/2}\sigma_{y_j} \le y_j^s \le Y_{j,\max} - z_{\alpha_j/2}\sigma_{y_j}$$

$$U_{i,\min} + z_{\alpha_i/2}\sigma_{u_i} \le u_i^s \le U_{i,\max} - z_{\alpha_i/2}\sigma_{u_i}$$

$$\sigma_Y \ge 0$$

$$\sigma_U \ge 0$$

$$\sigma_Y = f(\sigma_U)$$

Steady State Optimization (SSO)

$$\Phi = E\left[\left\|\mathbf{y} - \mathbf{y}^s\right\|_Q\right] + \lambda E\left[\left\|\mathbf{u} - \mathbf{u}^s\right\|_R\right]$$

$s.t.$

Process Dynamic Model

$$U_{i,\min} \le u_i \le U_{i,\max}$$

$$Y_{j,\min} \le y_j \le Y_{j,\max}$$

I/O Variances determined in DOC

Dynamic Optimal Control (DOC)

Economic PA of **Double-Layer Industrial MPC**

$$\max_{y_j^s, u_i^s, \sigma_{y_j}, \sigma_{u_i}} \Delta J = \sum_{j=1}^{p} C_y^{(j)} y_j^s - \sum_{i=1}^{m} C_u^{(i)} u_i^s$$

$$s.t. \mathrm{D}y_j^s = \sum_{i=1}^{m} k_{ij} \mathrm{D}u_i^s$$

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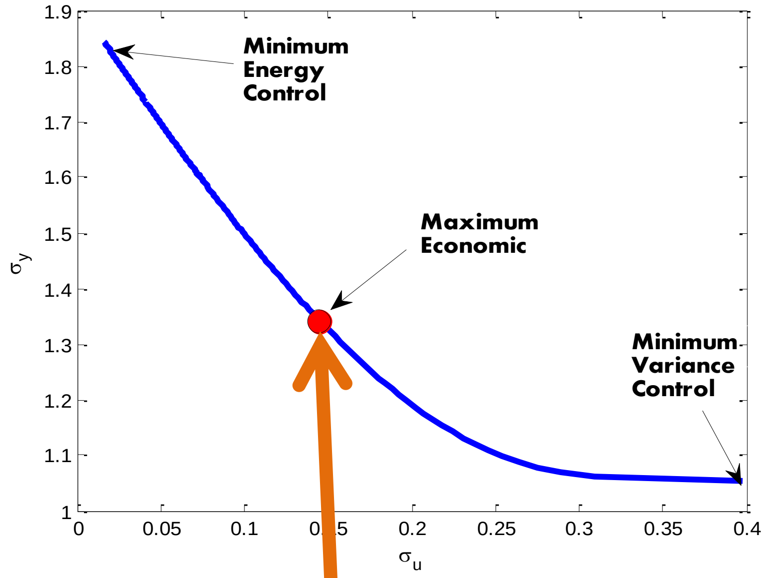


Best I/O Variances Coordination based on LQG Benchmark

SSO

DOC

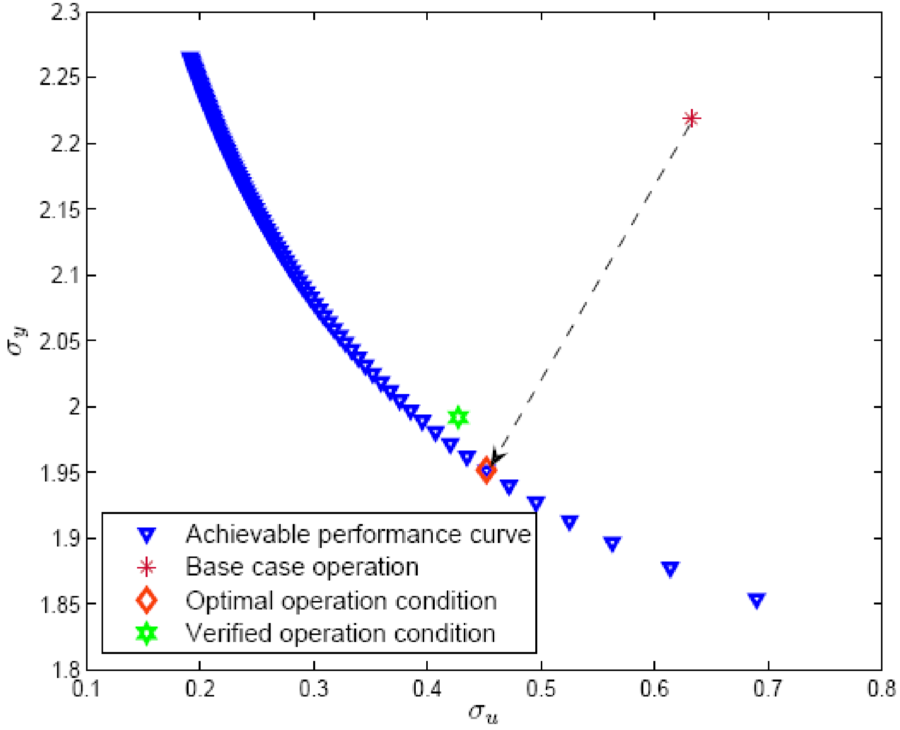
Economic PA of Double-Layer Industrial MPC

Economic Assessment Indexes

$$\eta_E = \frac{\Delta J_E}{\Delta J_I} \leq 1$$

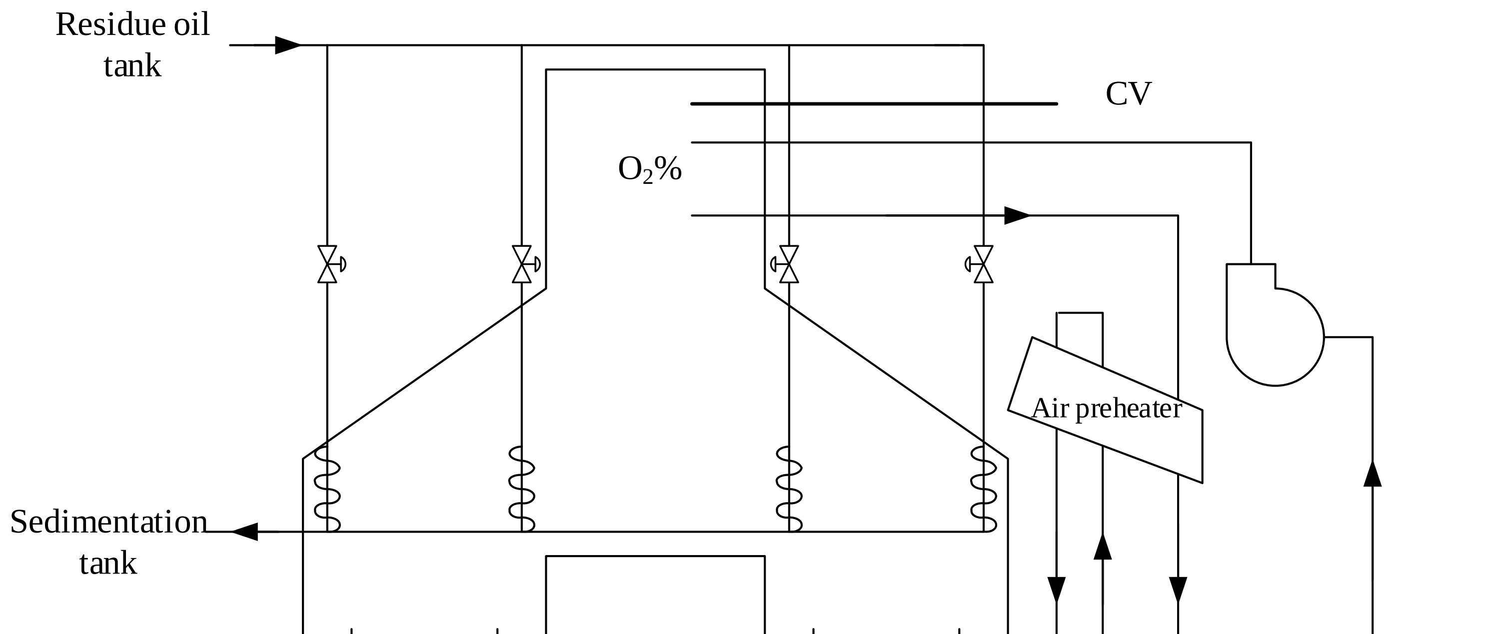
ΔJ_E: **Obtained economic performance**

ΔJ_I: **Ideal economic performance**



Economic PA of Double-Layer Industrial MPC

Application on Delayed Coking Furnace Control :



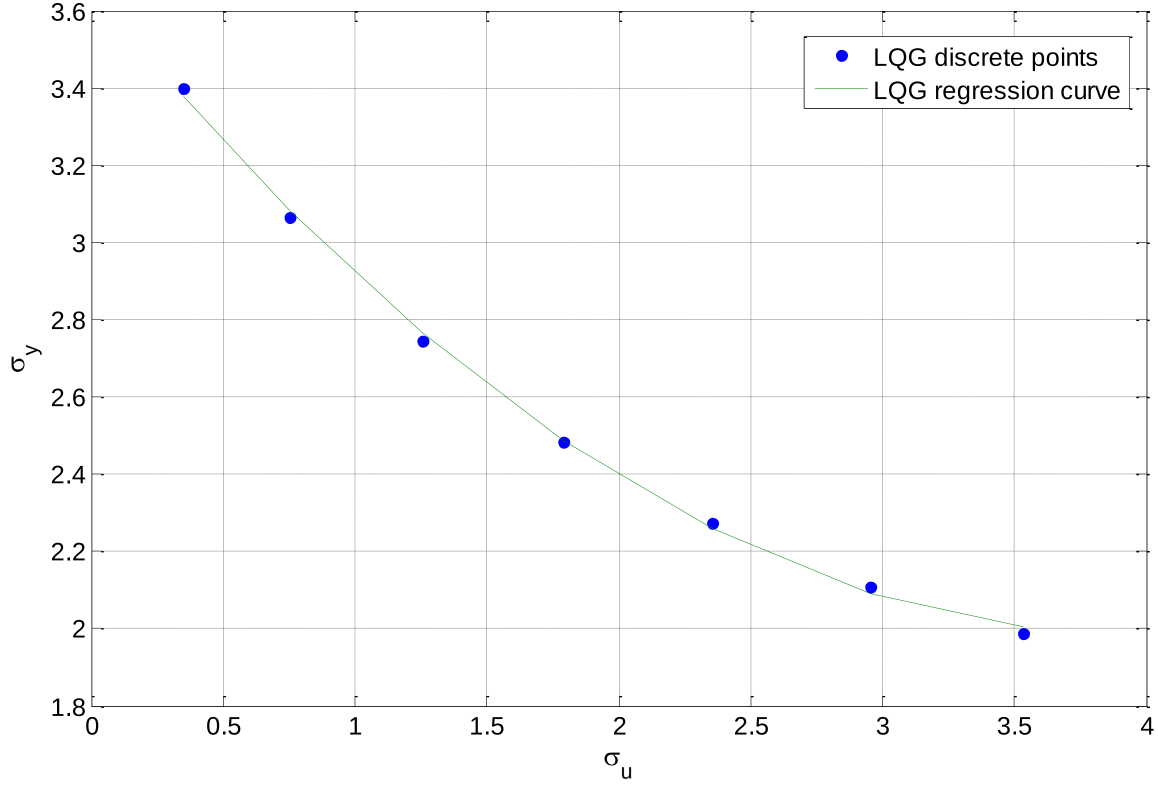
$$\text{Max } \eta_e = 100 - [(c_1 + c_2 \cdot \theta_{air}) \cdot (y^s + c_3 \cdot (y^s)^2) - c_4] - \beta$$

η_e : Furnace Thermal Efficiency

y : Furnace Outlet O_2 Concentration

Economic PA of **Double-Layer Industrial MPC**

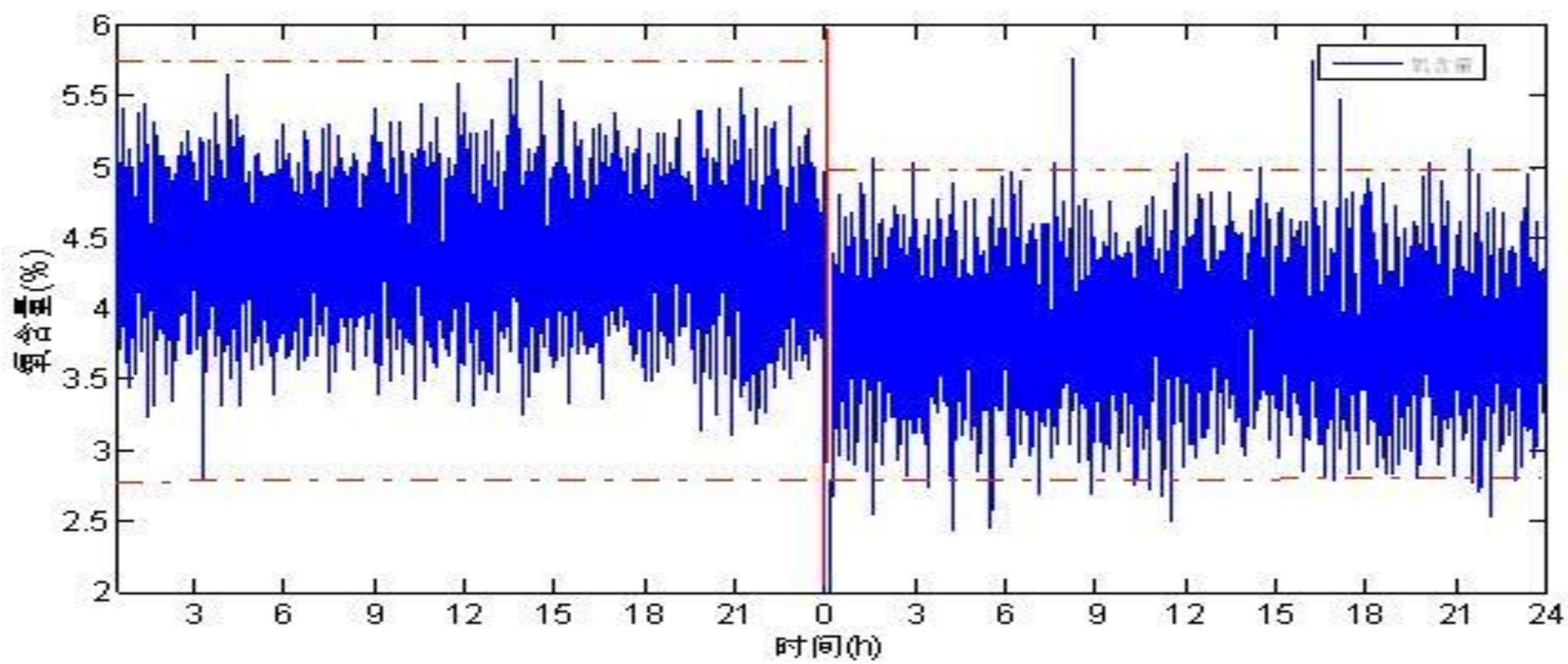
Delayed Coking Furnace Control



LQG Benchmark Curve

Economic PA of
Double-Layer Industrial MPC

Delayed Coking Furnace Control



Furnace Output O_2: 4.6% → 3.5%
Thermal Efficiency: 86.5% → 87.1%

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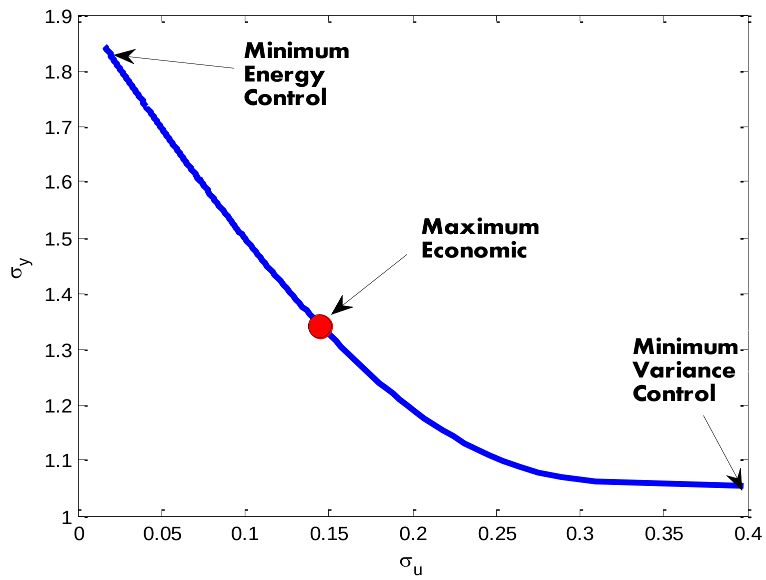
MPC: Model Predictive Control

On-line Performance Improvement of Double-Layer Industrial MPC

1. Requires an accurate process model
2. Computationally demanding

Off-line Performance Assessment



LQG Benchmark

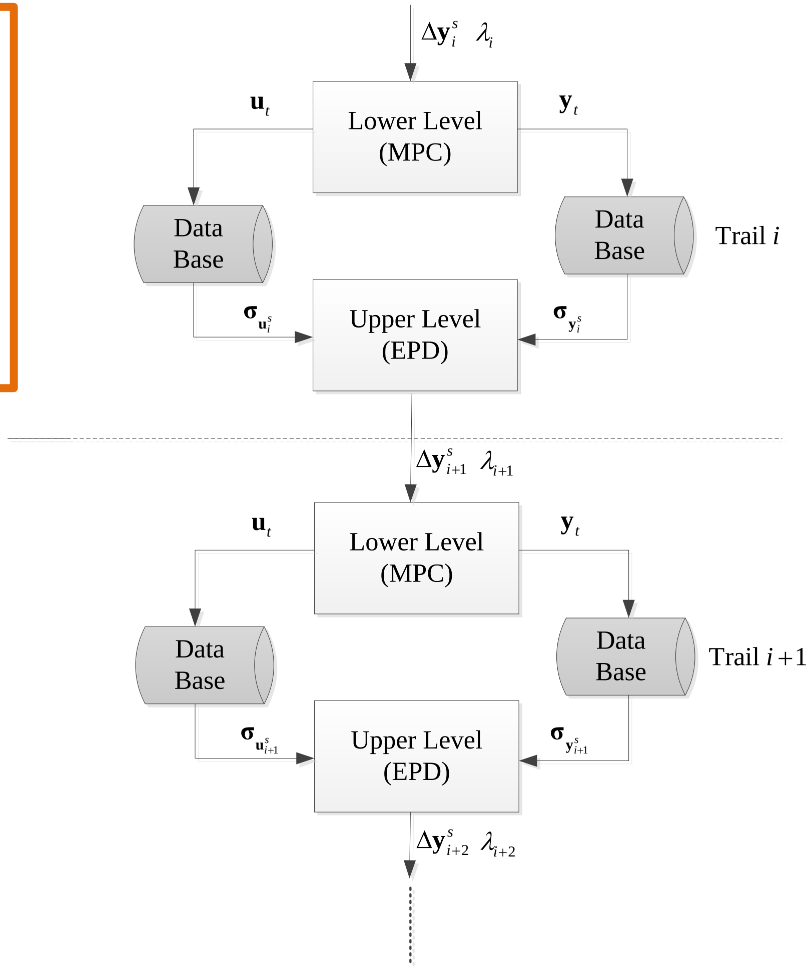
X. Cai, P. Sun, J. Chen, L. Xie, **ILC strategy for progress improvement of economic performance in industrial model predictive control systems,** Journal of Process Control, 24 (2014) 107-118.

On-line Performance Improvement of Double-Layer Industrial MPC

Iterative Learning Control (ILC)

- Data-Driven
- Model-Free

On-line Economic Performance Improvement (EPI)



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On-line Performance Improvement of Double-Layer Industrial MPC

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$$s.t. \, \mathrm{D}y_j^s = \sum_{i=1}^{m} k_{ij} \mathrm{D}u_i^s$$

$$\Delta u^s = u^s - u^{s0}$$

Find Active Constraints

$$Y_{j,\min} + z_{\alpha_j/2}\sigma_{y_j} \le y_j^s \le Y_{j,\max} - z_{\alpha_j/2}\sigma_{y_j}$$

$$U_{i,\min} + z_{\alpha_i/2}\sigma_{u_i} \le u_i^s \le U_{i,\max} - z_{\alpha_i/2}\sigma_{u_i}$$

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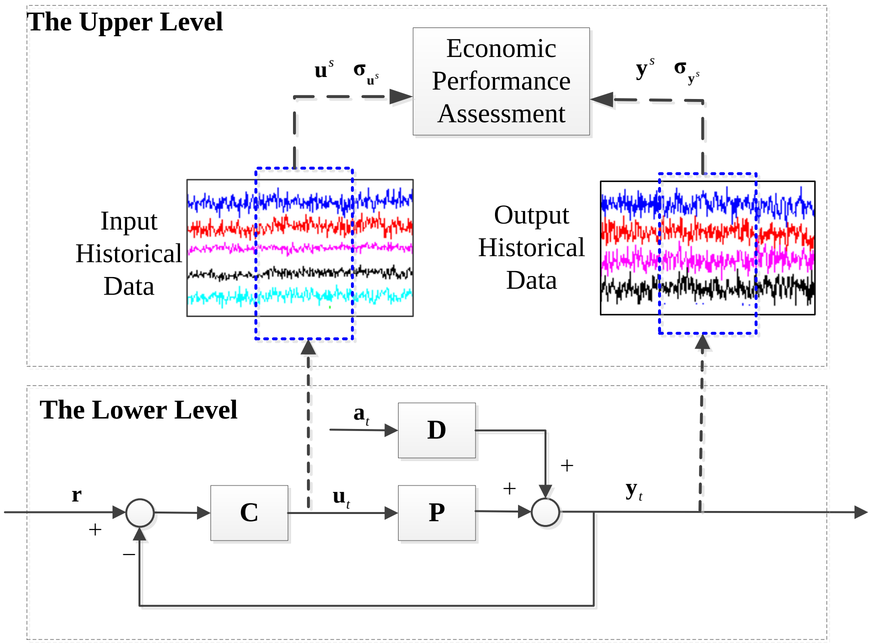
SSO



I/O variance from the operation data

On-line Performance Improvement of Double-Layer Industrial MPC

$$\max_{y_j^s, u_i^s, \sigma_{y_j}, \sigma_{u_i}} J = \sum_{j=1}^{p} C_y^{(j)} y_j^s - \sum_{i=1}^{m} C_u^{(i)} u_i^s$$

$$s.t. \Delta y_j^s = \sum_{i=1}^{m} k_{ij} \Delta u_i^s$$

$$\Delta u^s = u^s - u^{s0}$$

Find Active Constraints

$$Y_{j,\min} + z_{\alpha_j/2}\sigma_{y_j} \le y_j^s \le Y_{j,\max} - z_{\alpha_j/2}\sigma_{y_j}$$

$$U_{i,\min} + z_{\alpha_i/2}\sigma_{u_i} \le u_i^s \le U_{i,\max} - z_{\alpha_i/2}\sigma_{u_i}$$

$$\sigma_Y \ge 0$$

$$\sigma_U \ge 0$$

$$\sigma_Y = f(\sigma_U)$$

SSO

Sensitivity Analysis

ILC-based DOC Weights Retuning

$$\Phi = E\left[\left\| \mathbf{y} - \mathbf{y}^s \right\|_Q\right] + \lambda E\left[\left\| \mathbf{u} - \mathbf{u}^s \right\|_R\right]$$

$s.t.$

Process Dynamic Model

$$U_{i,\min} \le u_i \le U_{i,\max}$$

$$Y_{j,\min} \le y_j \le Y_{j,\max}$$

DOC

On-line Performance Improvement of **Double-Layer Industrial MPC**

$$\max_{y_j^s, u_i^s, \sigma_{y_j}, \sigma_{u_i}} \quad J = \sum_{j=1}^{p} C_y^{(j)} y_j^s - \sum_{i=1}^{m} C_u^{(i)} u_i^s$$

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$$\Delta y_j^s = y_j^s - y_j^{s0}$$

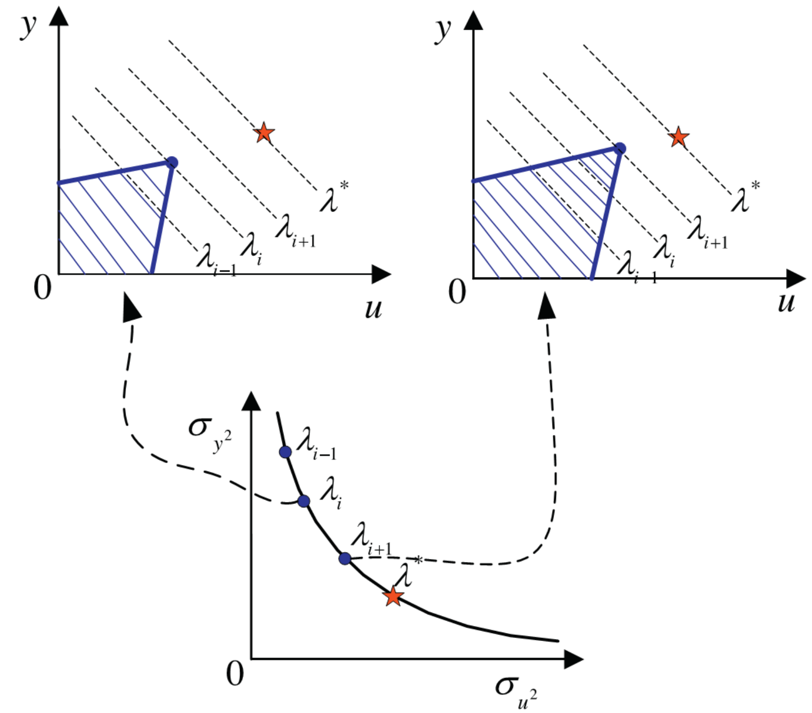
Active Constraints Relaxed

$$\sigma_Y \geq 0$$

$$\sigma_U \geq 0$$

$$\sigma_Y = f(\sigma_U)$$

SSO



I/O Variances Re-distributed

On-line Performance Improvement of Double-Layer Industrial MPC

Improved Economic Performance

$$s.t. \Delta y_j^s = \sum_{i=1} k_{ij} \Delta u_i^s$$

$$\Delta u_i^s = u_i^s - u_i^{s0}$$

$$\Delta y_j^s = y_j^s - y_j^{s0}$$

Active Constraints Relaxed

$$\sigma_Y \geq 0$$

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$$\sigma_Y = f(\sigma_U)$$

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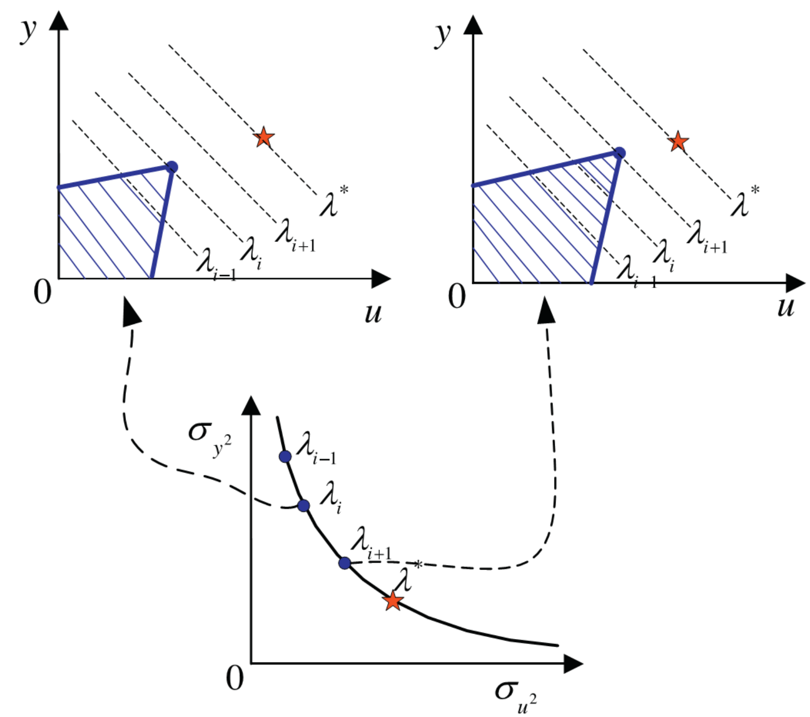

I/O Variances Re-distributed

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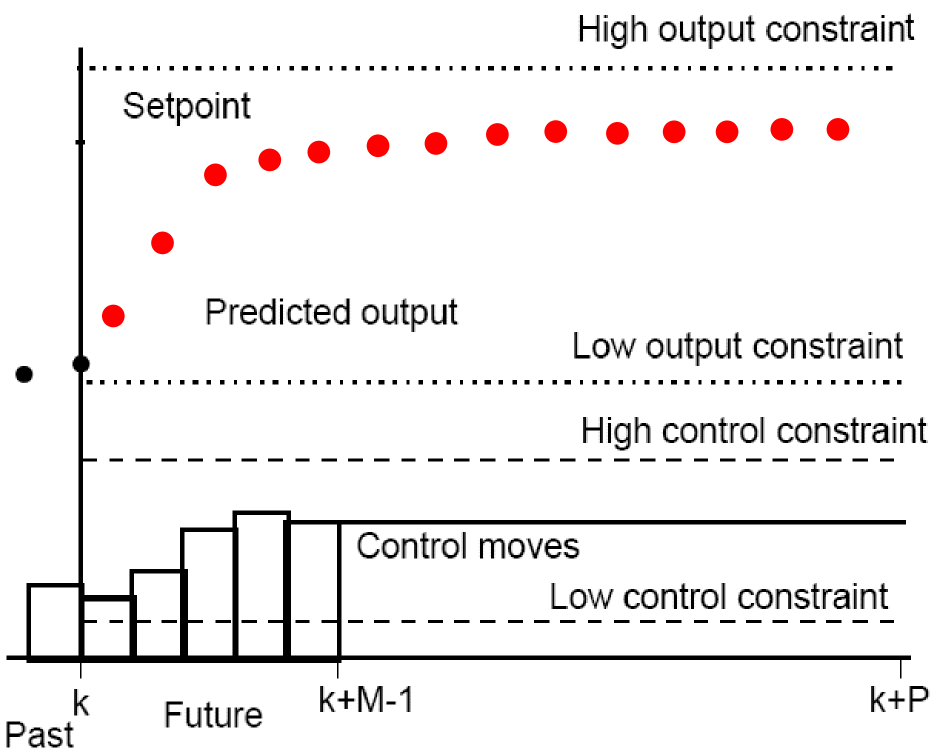
5. **Model-Plant Mismatch Detection of MPC using Mutual Information**

MPC: Model Predictive Control

MPM Detection for MPC Using MI

1. **Model is the core of MPC**
   - MPC heavily relies on an accurate model to predict the process behavior
2. **Model Plant Mismatch (MPM) is the No.1 root cause of poor MPC control performance**



G. Chen, L. Xie, J. Zeng, J. Chu, Y. Gu, Detecting Model–Plant Mismatch of Nonlinear Multivariate Systems Using Mutual Information, Ind Eng Chem Res, 52 (2013) 1927-1938.

Mutual Information: $I(X;Y)$

- **Given two random variables X, Y**

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

$$H(X) = -\int p(x)\log(p(x))\,\mathrm{d}x$$

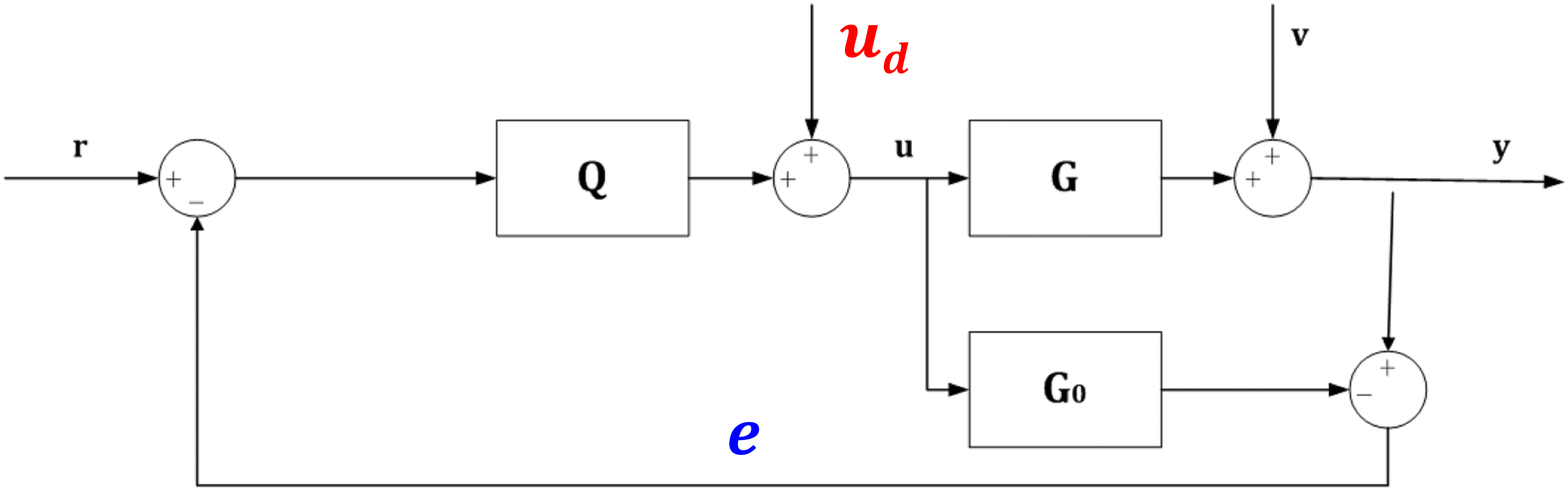
$$H(Y) = -\int p(y)\log(p(y))\,\mathrm{d}y$$

$$H(X,Y) = -\int p(x,y)\log(p(x,y))\,\mathrm{d}x\,\mathrm{d}y$$

MI quantify the information shared by X and Y

$I(X;Y) = 0$ iff X and Y are independent

MPM detection using MI



No MPM: $e = \mathrm{v}$ **independent of** u_d

$I(e; u_d) = 0$

MPM: $I(e; ud) \neq 0$

MI Estimation

- **MI Estimation**
  - **K-nearest neighbor approach**

$$\hat{I}(X;Y) = \psi(k) - \frac{1}{k} - \frac{1}{N}\sum_{i=1}^{N}[\psi(n_x(i)) + \psi(n_y(i))] + \psi(N)$$

- **MI Statistic Confidence Limit**
  - **Surrogate data approach**

    iAAFT: iterative amplitude adjusted Fourier Transform

MPM Localization using MI

MIMO System

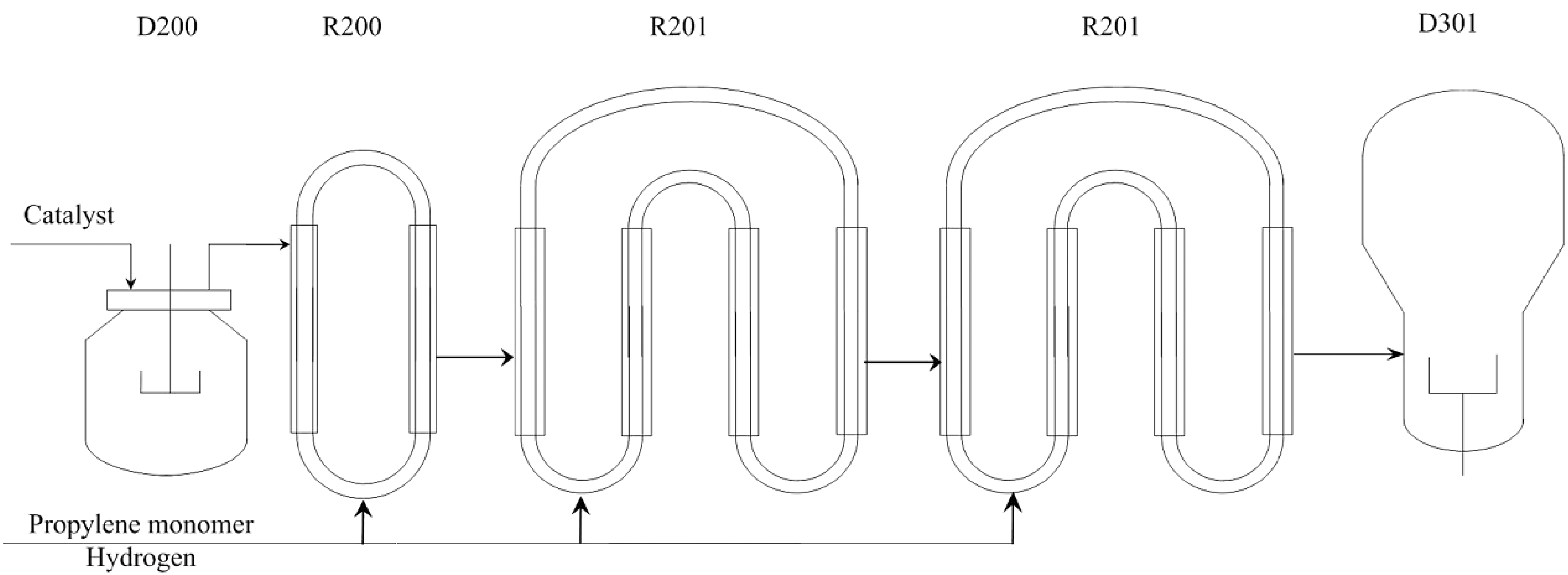
$$
\begin{matrix}
u_{d_1} & u_{d_2} & \cdots & u_{d_n} \\
, & , & \cdots & , \\
u_{c_1} & u_{c_2} & \cdots & u_{c_n} \\
\downarrow & \downarrow & \downarrow & \downarrow
\end{matrix}
$$

$$
\begin{bmatrix}
\Delta g_{11} & \Delta g_{12} & \cdots & \Delta g_{1n} \\
0 & 0 & \cdots & 0 \\
\vdots & & & \vdots \\
\Delta g_{m1} & \Delta g_{m2} & \cdots & \Delta g_{mn}
\end{bmatrix}
\begin{matrix}
\rightarrow e_1 \\
\rightarrow e_2 \\
\vdots \\
\rightarrow e_m
\end{matrix}
$$

If $I(e_i; ud_j) \neq 0$, then the jth column of $\Delta G(:, j) \neq 0$,

Industrial Application: Polypropylene Process

Polypropylene: General Purpose Plastic



Double-loop liquid propylene polymerization plant of SINOPEC Co. Ltd. (Zhenghai)

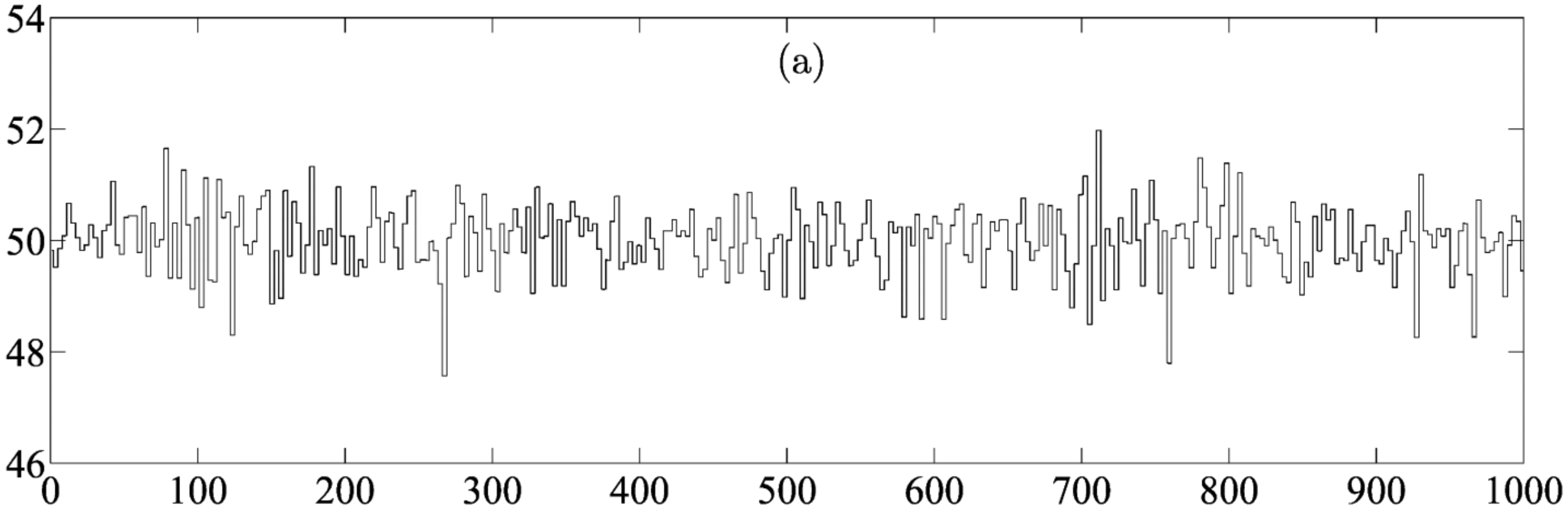
MPC for R201, R202

Table 1. MVs and CVs of the MPC for Tubular Reactors

variable	description
MVs	
MV1	flow of hydrogen
MV2	flow of propylene monomer
CVs	
CV1	concentration of hydrogen
CV2	density of slurry

MPC Performance

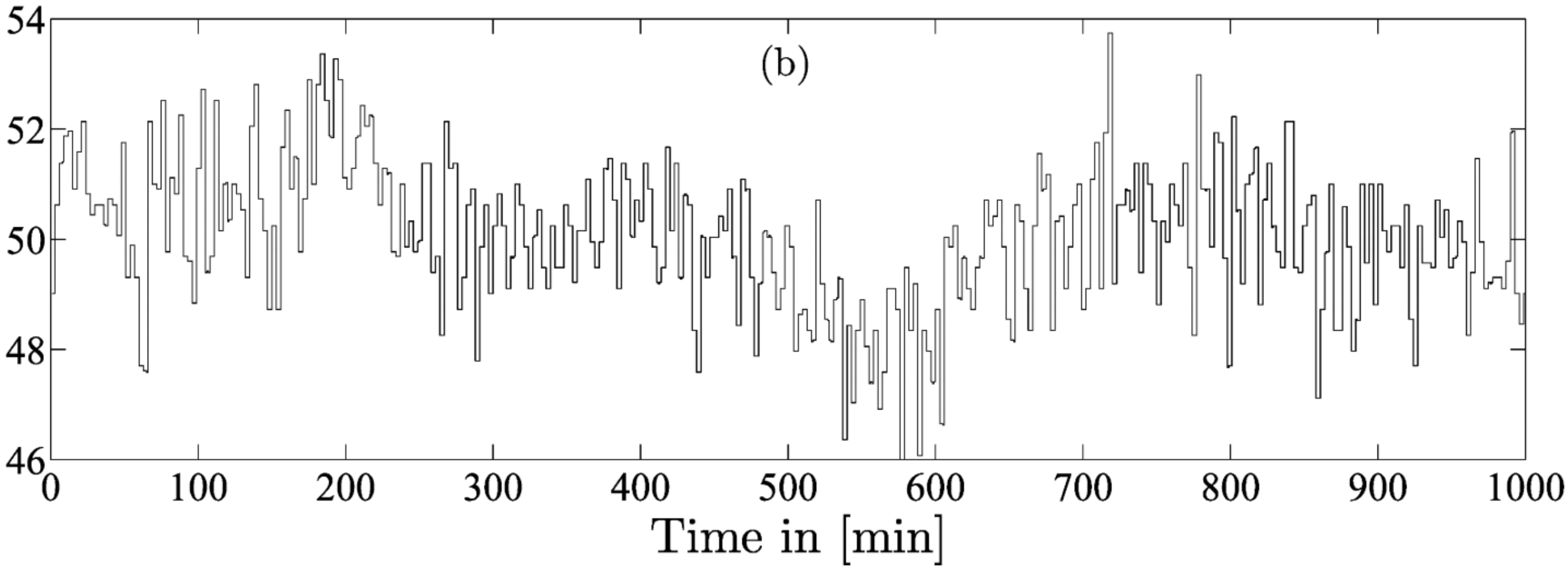
Slurry density: Important quality Index



Control results of MPC at early commissioning stage

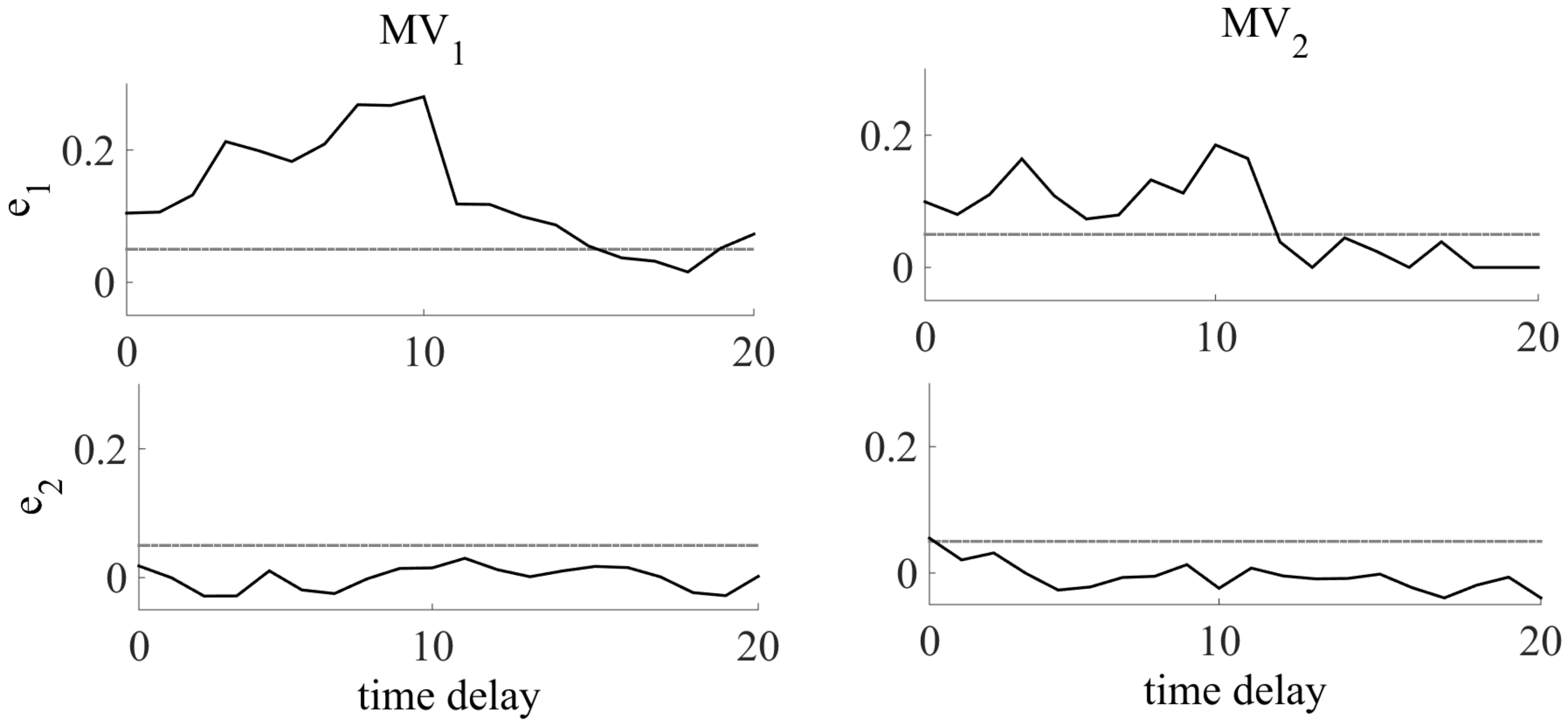
MPC Performance

Slurry density: Important quality Index



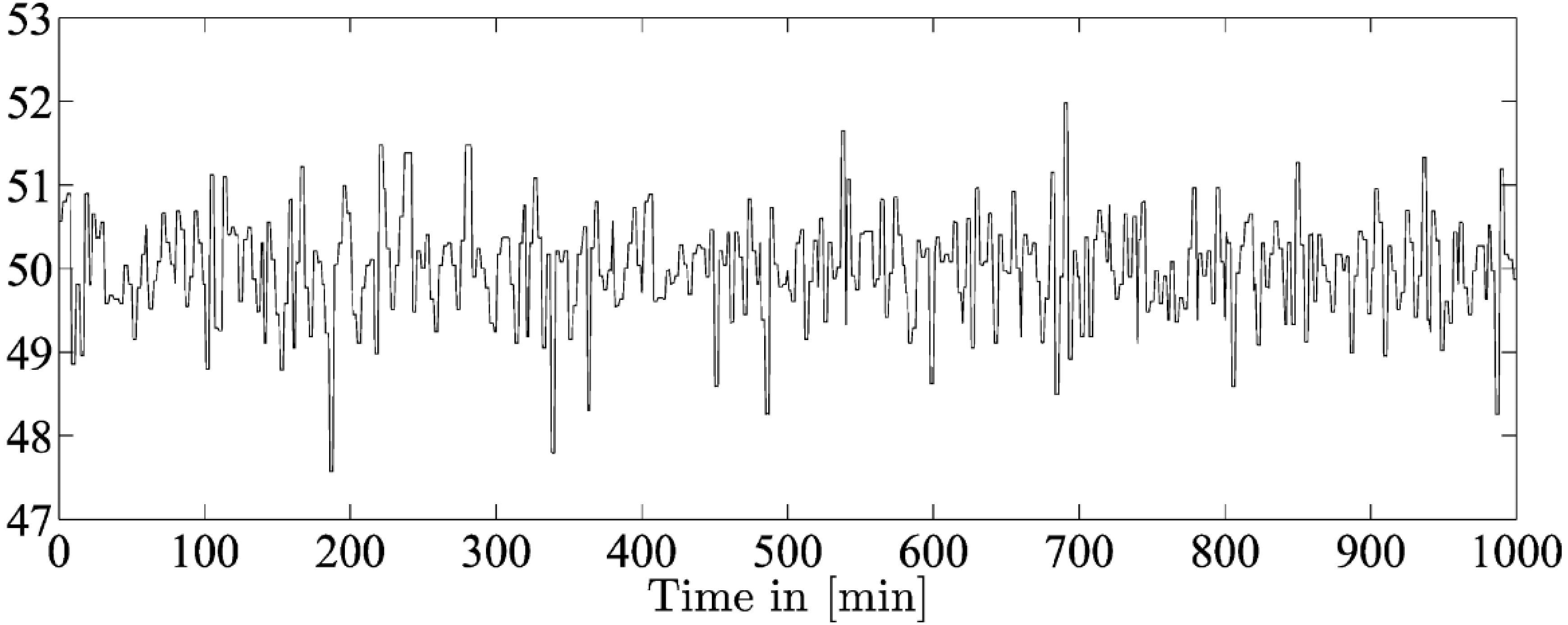
Control results of MPC after commissioning for 7 months

MPM Detection of R201



MPM exist in the channels of
$MV_1 \rightarrow e_1$ and $MV_2 \rightarrow e_1$

MPC Performance after Maintenance



Control results of MPC after model re-identification

Thank You!