Design and Industrial Applications of a Data-Driven PID Controller

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Introduction(1)

- Global competition in industrial world

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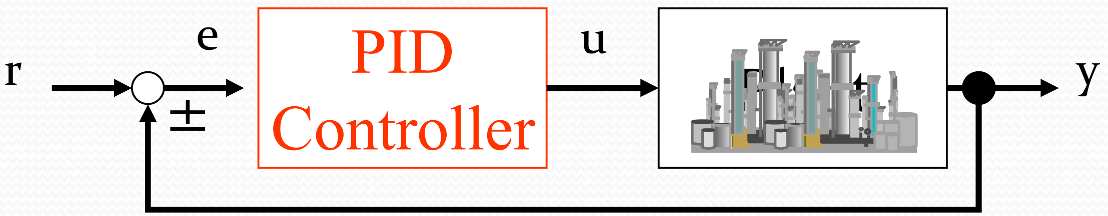
- Reduction of production costs
- Energy-saving and labor-saving
- Improvement of the quality of products

High-performance control systems are required in industries.

Introduction(2)

- **PID Controllers** ⟵ 80% or more in industrial systems
  - ✓ PID controllers have a simple structure.
  - ✓ PID controllers are simple to maintain and tune.
  - ✓ Physical meaning in sense of the control engineering is clear.



proportional (current) — integral (past) — derivative (future)

$$u(t) = k_c \left\{ e(t) + \frac{1}{T_I} \int_0^t e(\tau)\, d\tau + T_D \frac{de(t)}{dt} \right\}$$

Introduction(3)

- Systems have usually uncertainties.
  - ✓system changes
  - ✓nonlinearities

↑

In order to overcome these problems,

Data-Driven PID(DD-PID) Controller

(PID parameters are updated using a database)

This work was cooperated with OMRON Co. Ltd.

OMRON Sensing tomorrow™

Data-Driven PID(1)

Data-Driven PID Controller

Local control parameter tuning

Algorithm

[step 0] Create initial data-base by operating data

[step 1] Get an information request (query)

[step 2] Calculate distance between query & Information vectors

[step 3] Select neighbors with small distance

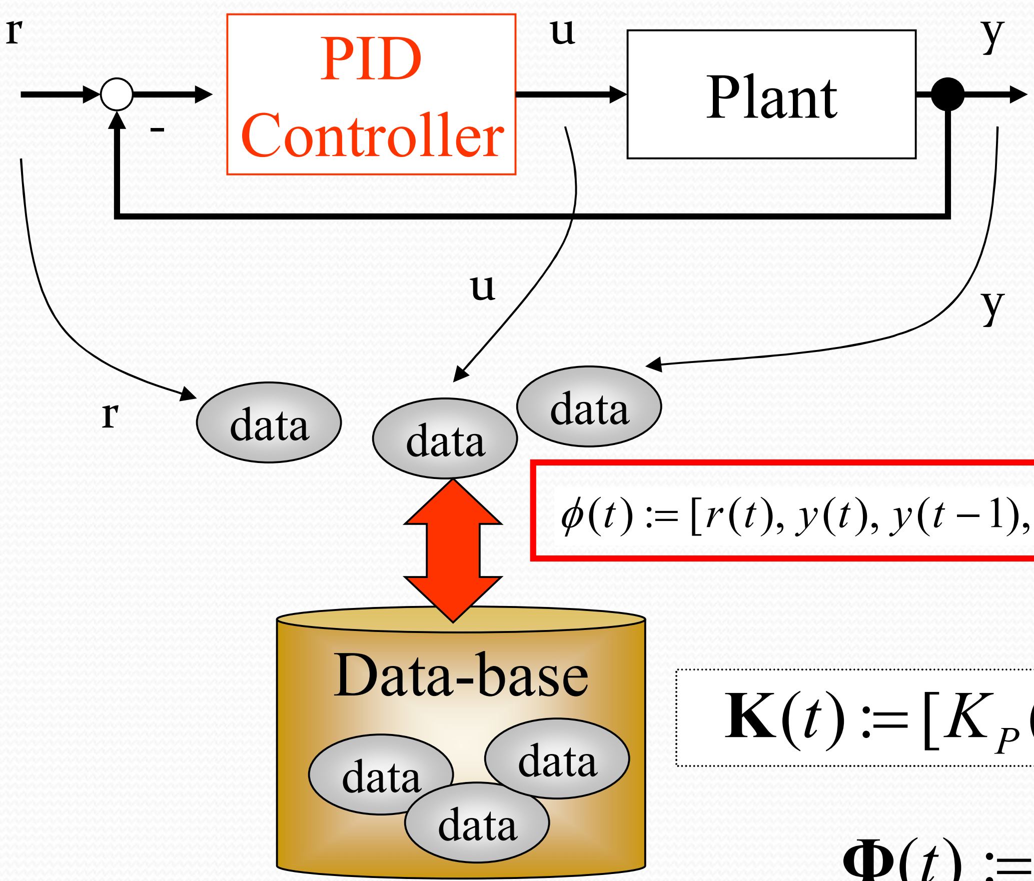
[step 4] Calculate PID parameters and generate control input

[step 5] Update PID parameters using gradient method

[step 6] Remove redundant data

Data-Driven PID(2)

[Step 0] Create initial data-base by operating data



information vector

$$\phi(t) := [r(t), y(t), y(t-1), y(t-2), u(t-1), u(t-2), \cdots, u(t-d-1)]'$$

+

PID parameter vector

$$\mathbf{K}(t) := [K_P(t),\ K_I(t),\ K_D(t)]'$$

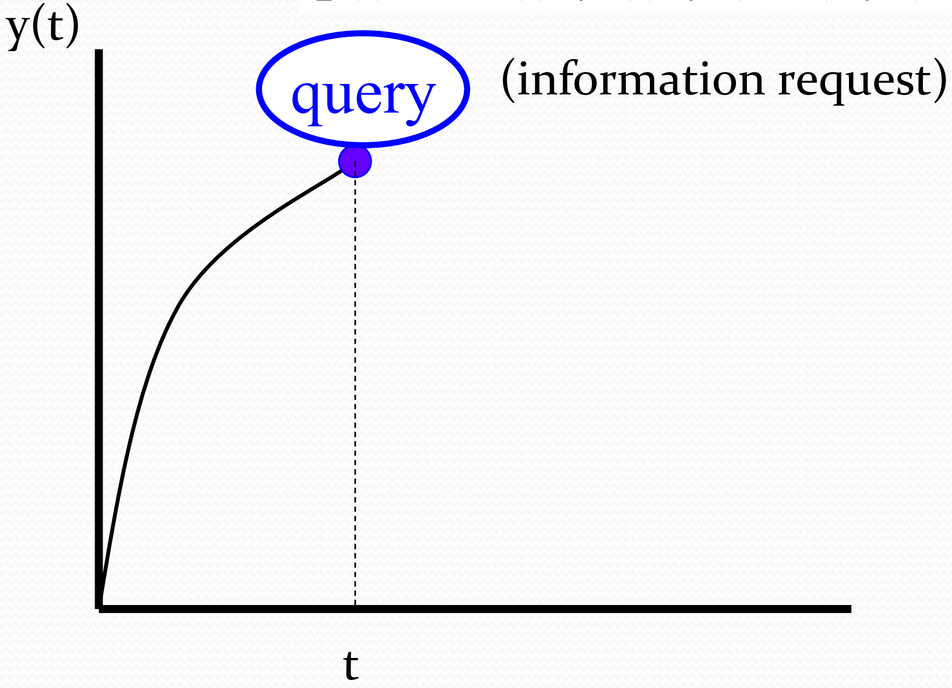
$$\downarrow$$

$$\mathbf{\Phi}(t) := [\phi(t)', K(t)']'$$

Data-Driven PID(3)

[Step 1] Given an information request (query)

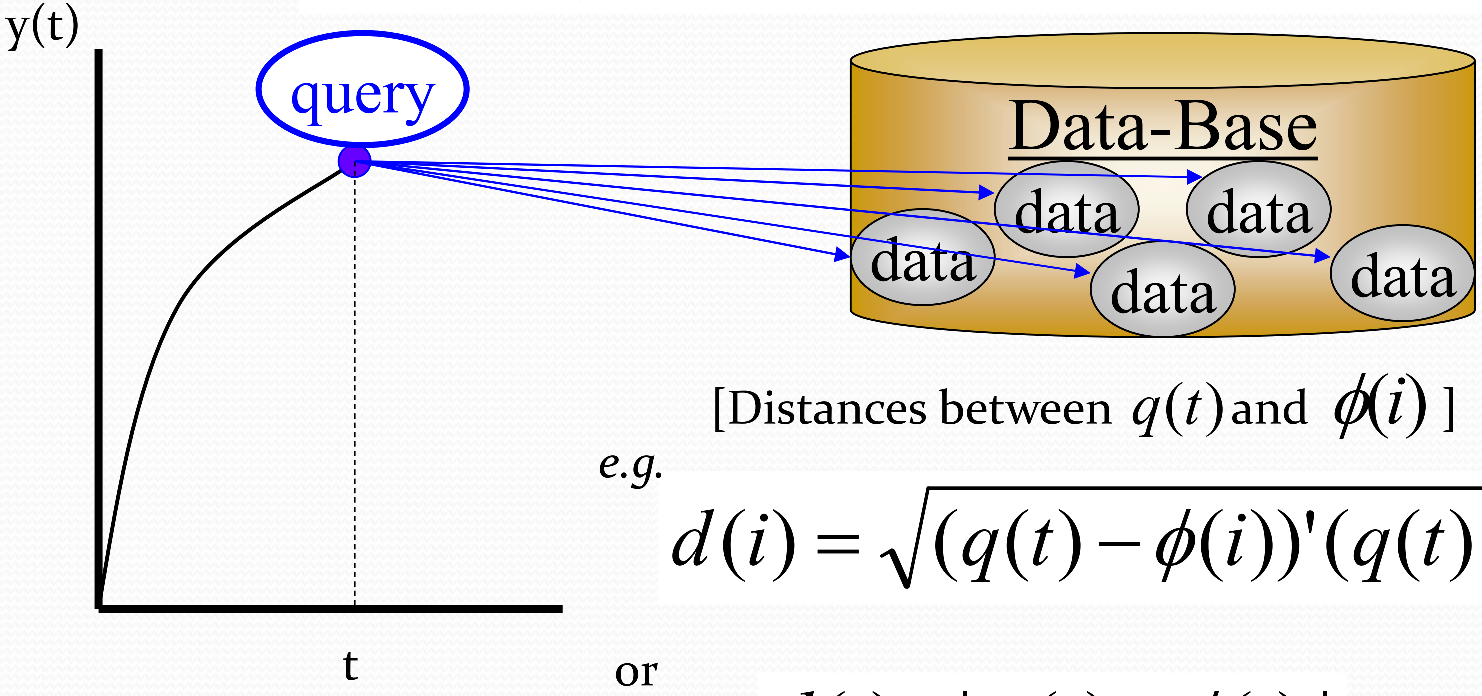
$$q(t) := [r(t), y(t), y(t-1), y(t-2), u(t-1), u(t-2), \cdots, u(t-d-1)]'$$



Data-Driven PID(4)

[Step 2] Calculate distance between query & information vectors

$$q(t) := [r(t), y(t), y(t-1), y(t-2), u(t-1), u(t-2), \cdots, u(t-d-1)]'$$



[Distances between $q(t)$ and $\phi(i)$]

e.g.

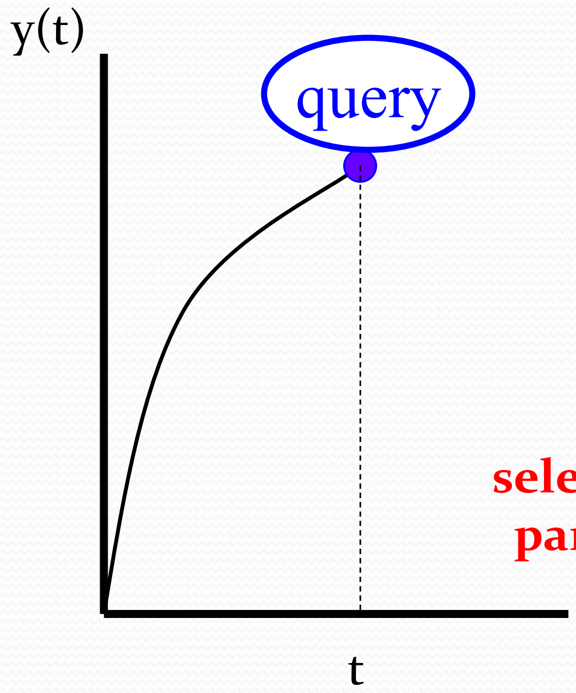
$$d(i) = \sqrt{(q(t)-\phi(i))'(q(t)-\phi(i))}$$

or

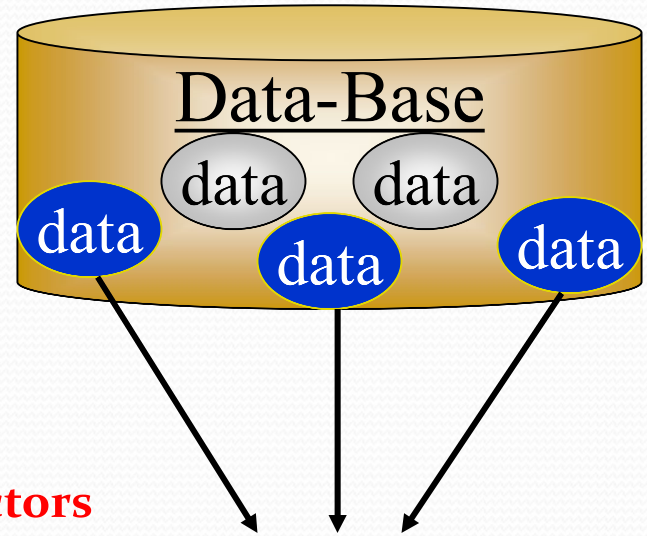
$$d(i) = | q(t) - \phi(i) |$$

Data-Driven PID(5)

[Step 3] Select neighbors with small distance



selected PID parameter vectors



$$\mathbf{K}(j) := [K_P(j),\ K_I(j),\ K_D(j)]$$

$$j = 1,2,\ldots\ldots,k$$

Review

Data-base

Distance

$\phi(1) := [r(1), y(1), \cdots, u(0), \cdots]'$	$\mathbf{K}(1) = [K_P(1), K_I(1), K_D(1)]'$	0.36
$\phi(2) := [r(2), y(2), \cdots, u(1), \cdots]'$	$\mathbf{K}(2) = [K_P(2), K_I(2), K_D(2)]'$	0.11
$\phi(3) := [r(3), y(3), \cdots, u(2), \cdots]'$	$\mathbf{K}(3) = [K_P(3), K_I(3), K_D(3)]'$	0.18
$\vdots$	$\vdots$	
$\phi(N) := [r(N), y(N), \cdots, u(N-1), \cdots]'$	$\mathbf{K}(N) = [K_P(N), K_I(N), K_D(N)]'$	0.22

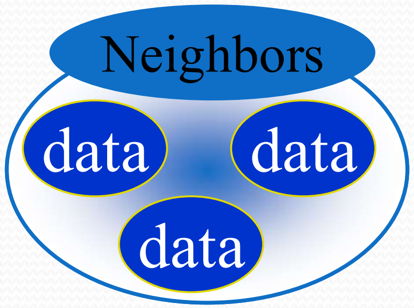
PID parameter vectors are selected

query

$$q(t) := [r(t), y(t), \cdots, u(t-1), \cdots]'$$

Data-Driven PID(6)

[Step 4]　Calculate PID parameters and generate control input



$$\mathbf{K}(t) \leftarrow \sum_{i=1}^{k} w_i \mathbf{K}(i), \qquad \sum_{i=1}^{k} w_i = 1$$

e.g.

$$v_i \leftarrow 1/d_i, \qquad w_i \leftarrow v_i \Big/ \sum_{i=1}^{k} v_i$$

[PID control]

$$\Delta u(t) = (\underline{K_P(t)}\Delta + \underline{K_I(t)} + \underline{K_D(t)}\Delta^2)e(t)$$

system

Review(*cont.*)

Data-base

		Distance	Weight
$\phi(1) := [r(1), y(1), \cdots, u(0), \cdots]'$	$\mathbf{K}(1) = [K_P(1), K_I(1), K_D(1)]'$	0.36	
$\phi(2) := [r(2), y(2), \cdots, u(1), \cdots]'$	$\mathbf{K}(2) = [K_P(2), K_I(2), K_D(2)]'$	0.11	0.473
$\phi(3) := [r(3), y(3), \cdots, u(2), \cdots]'$	$\mathbf{K}(3) = [K_P(3), K_I(3), K_D(3)]'$	0.18	0.290
$\vdots$	$\vdots$		
$\phi(N) := [r(N), y(N), \cdots, u(N-1), \cdots]'$	$\mathbf{K}(N) = [K_P(N), K_I(N), K_D(N)]'$	0.22	0.237

PID parameter vectors selected

query

$$q(t) := [r(t), y(t), \cdots, u(t-1), \cdots]'$$

$$K_P(t) \leftarrow 0.473 * K_P(2) + 0.290 * K_P(3) + 0.237 * K_P(N)$$

$$K_I(t) \leftarrow 0.473 * K_I(2) + 0.290 * K_I(3) + 0.237 * K_I(N)$$

$$K_D(t) \leftarrow 0.473 * K_D(2) + 0.290 * K_D(3) + 0.237 * K_D(N)$$

$$u(t)$$

Data-Driven PID(7)

[Step 5] Update PID parameters

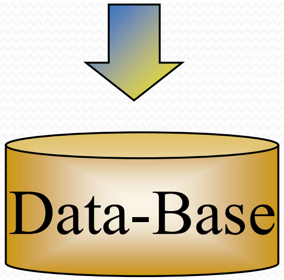
[Steepest descent method]

$$q(t) \quad + \quad \boxed{\mathbf{K}^{new}(t)} \leftarrow \mathbf{K}^{old}(t) - \boldsymbol{\eta} \frac{\partial J(t+1)}{\partial \mathbf{K}^{old}(t)}$$

new data vector

$$\boldsymbol{\Phi}(t) := [q(t)', \mathbf{K}^{new}(t)']'$$

$$J(t+1) = \frac{1}{2}(y_r(t+1) - y(t+1))^2$$



$\boldsymbol{\eta} := [\eta_P, \eta_I, \eta_D]$: leaning rate

$y_r(t) := \dfrac{z^{-1}T(1)}{T(z^{-1})} r(t)$: desied reference model

$T(z^{-1}) := 1 + t_1 z^{-1} + t_2 z^{-1}$

Data-Driven PID(8)

[Step 6] Remove redundant data

In order to avoid excessive increase of stored data

[First condition]

$$d(i) \leq \alpha_1$$

$$(\because \quad d(i) = \sqrt{(q(t)-\phi(i))'(q(t)-\phi(i))} \quad)$$

[Second condition]

$$\sum_{l=1}^{3} \left\{ \frac{\mathbf{K}_l(i) - \mathbf{K}^{new}{}_l(t)}{\mathbf{K}^{new}{}_l(t)} \right\}^2 \leq \alpha_2$$

$$\mathbf{K}_1(i) = K_P(i), \quad \mathbf{K}_2(i) = K_I(i), \quad \mathbf{K}_3(i) = K_D(i)$$

Simulation Example 1 (1)

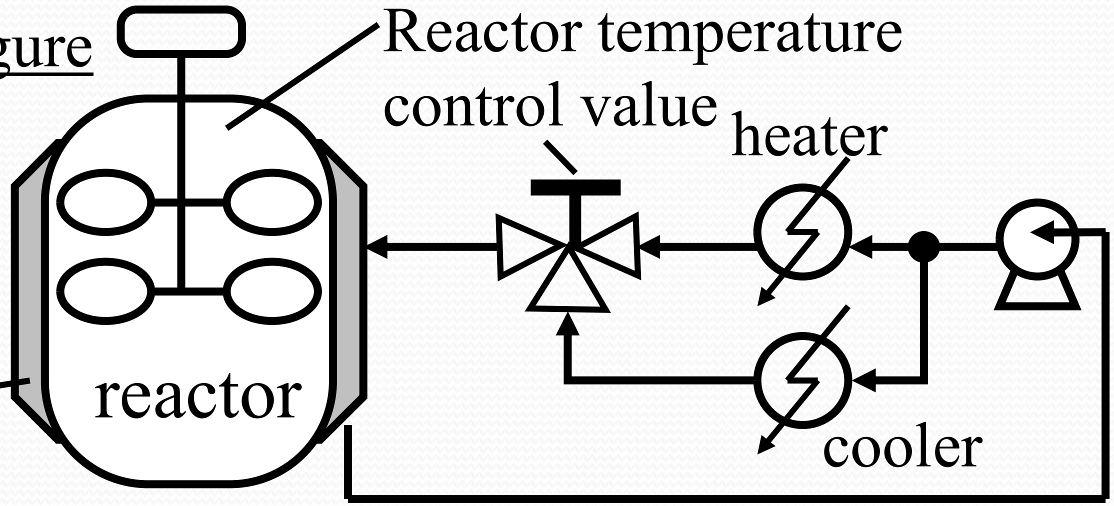
Polystyrene polymerization reactor model

$$y(t) = 0.804\,y(t-1) + 5.739 \times 10^{15} \cdot \exp\{-E_a / R(y(t-1)+273)\} + 0.148u(t-1) + \xi(t)$$

$\xi(t)$: white Gaussian noise with *zero* mean and variance 0.01

$E_a = 240$, $R = 0.01986$

Outline Figure

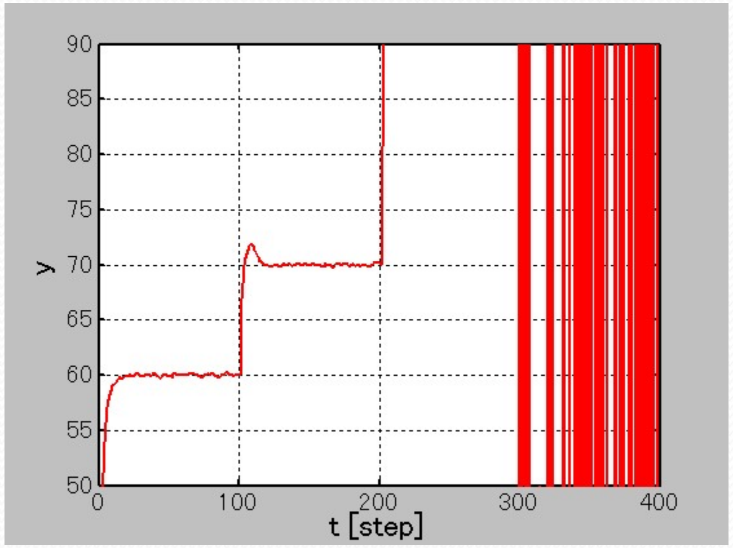


Strong nonlinear property

$y \geq 70$

Simulation Example 1 (2)

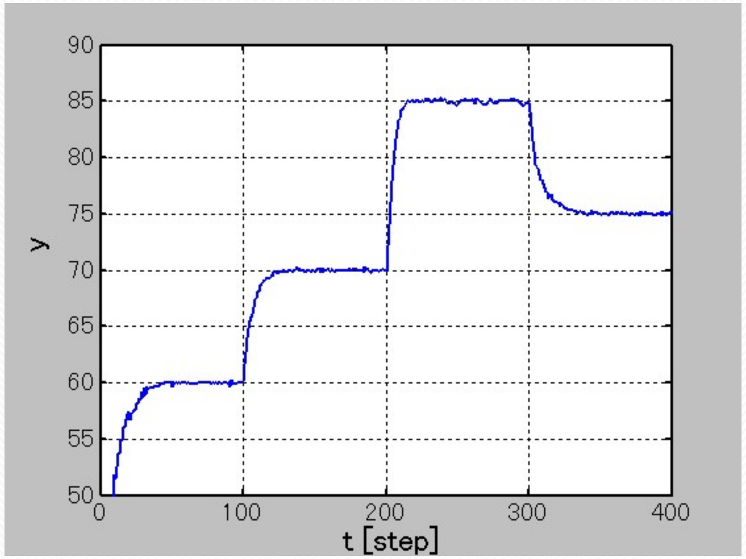
[Fixed PID controller]



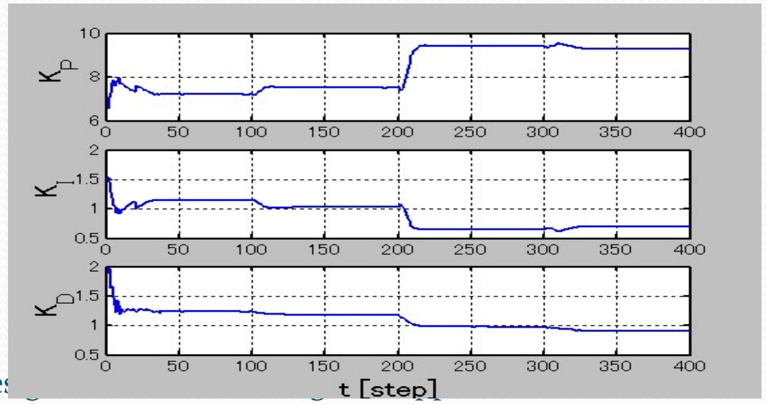
$$K_P = 6.5422\ ,\ K_I = 1.5522\ ,\ K_D = 1.8856$$

CHR tuning scheme

[Proposed method]



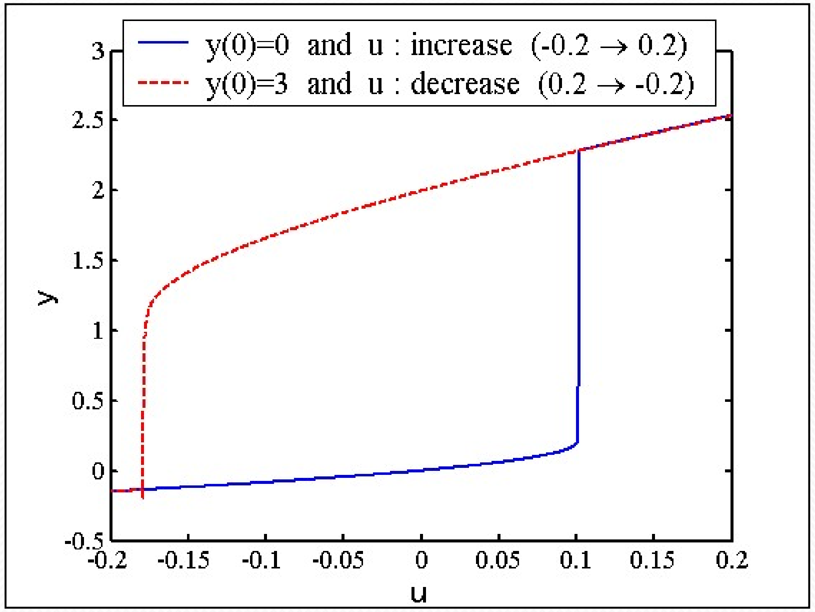
Trajectories of PID parameters



Simulation Example 2 (1)

$$y(t+1)=\frac{y(t)\,y(t-1)[y(t)+2.5]}{1+y^2(t)+y^2(t-1)}+u(t)+\xi(t)$$

$\xi(t)$: white Gaussian noise with *zero* mean and variance 0.0001



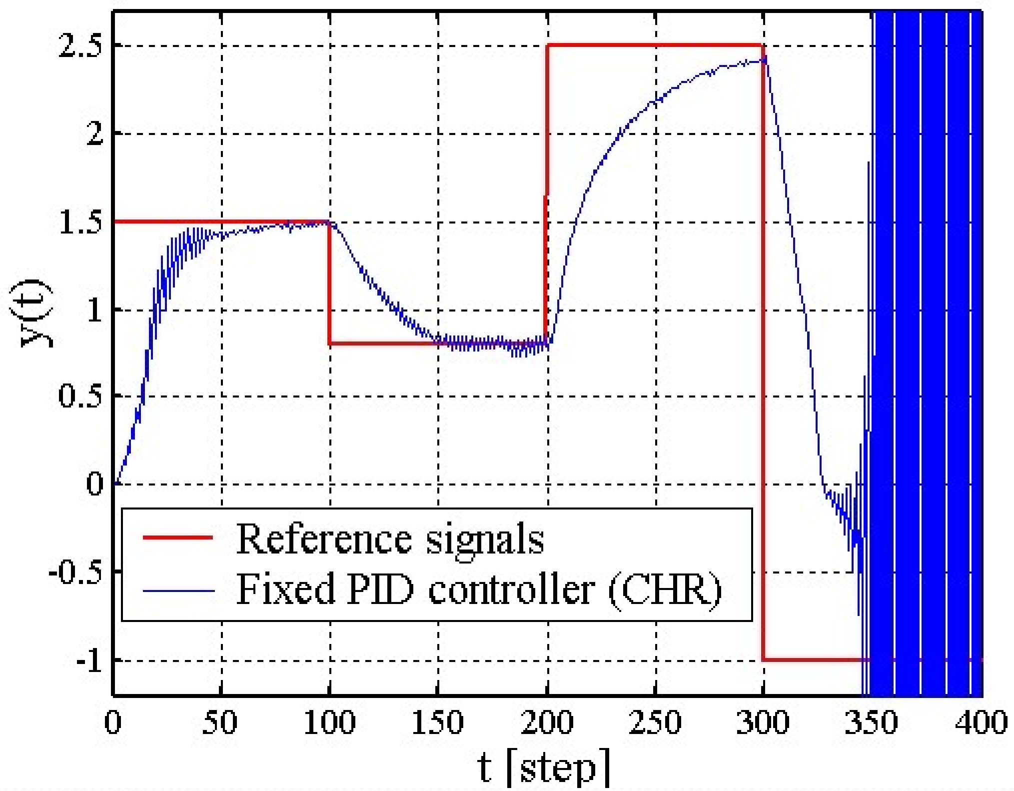
[Static property]

This system has Hysteresis between *y=0* and *y=2.0* (by K.S.Narendra)

Simulation Example 2 (2)

Using fixed PID parameters (CHR)

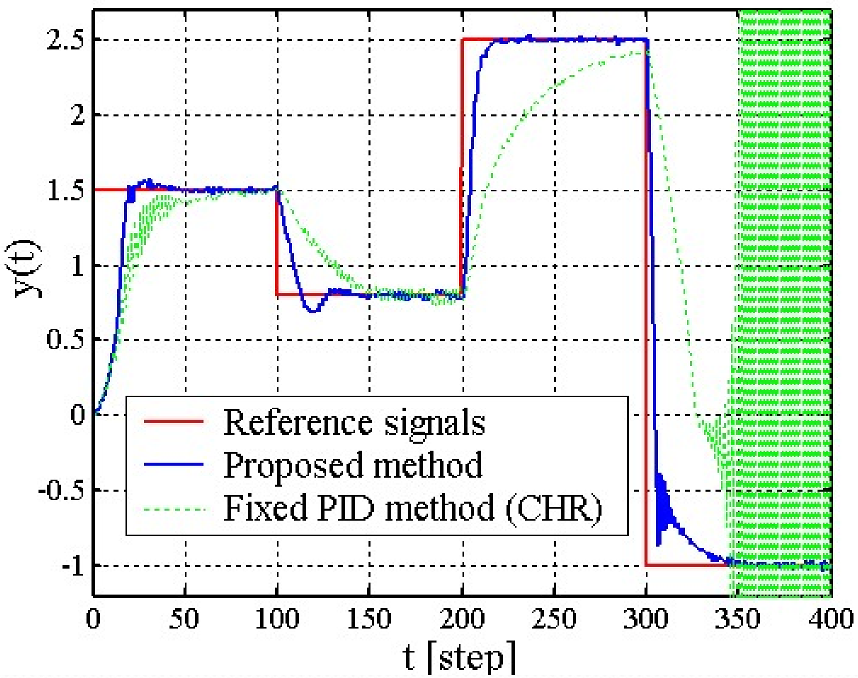
$$K_P = 0.654,\ K_I = 0.028,\ K_D = 0.327$$



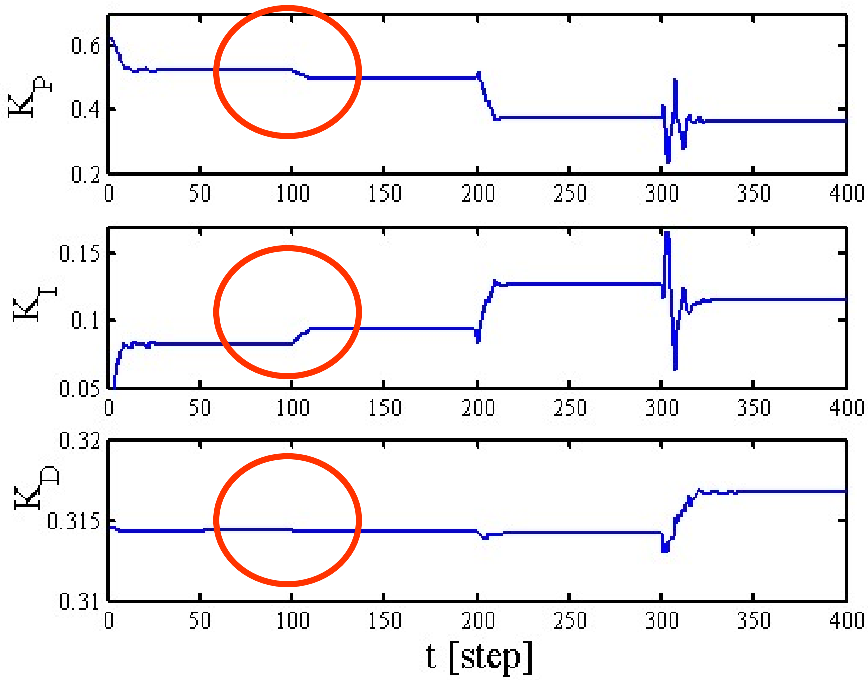
Simulation Example 2 (3)

[Proposed method]

Control result

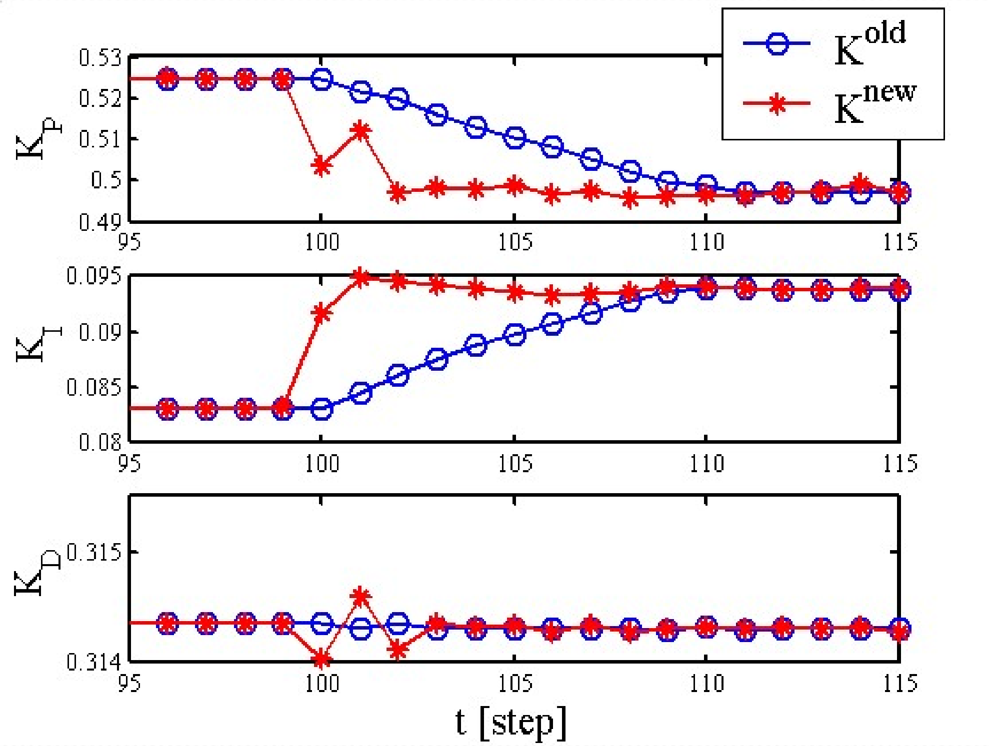


Trajectories of PID parameters

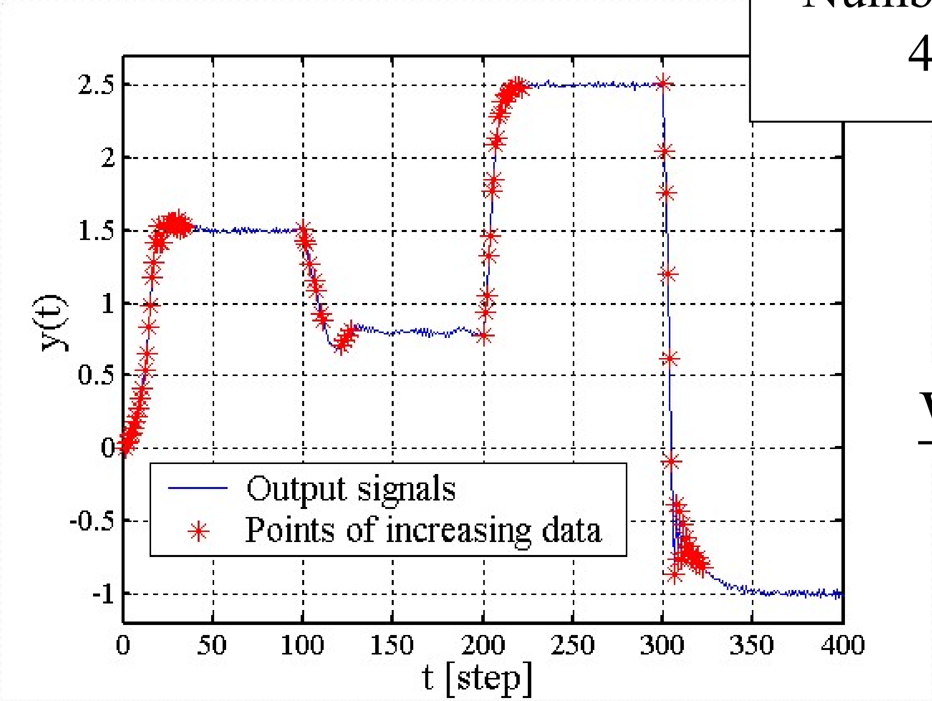


Simulation Example 2 (4)

Trajectories of $\mathbf{K}^{old}$ and $\mathbf{K}^{new}$



Simulation Example 2 (5)



<u>Without STEP 6</u>

Number of data = initial data + Control interval

406 = $N(0) = 6$ + 400[step]

<u>With STEP 6</u>

Number of data

406 → **89**

The number of data is decreased drastically

Simulation Example 2 (6)

Evaluation of control performances

$$\varepsilon_{ep}(epoc) := \frac{1}{N}\sum_{t=1}^{N}\left\{\frac{\varepsilon(t)}{r(t)}\right\}^2$$

In this case

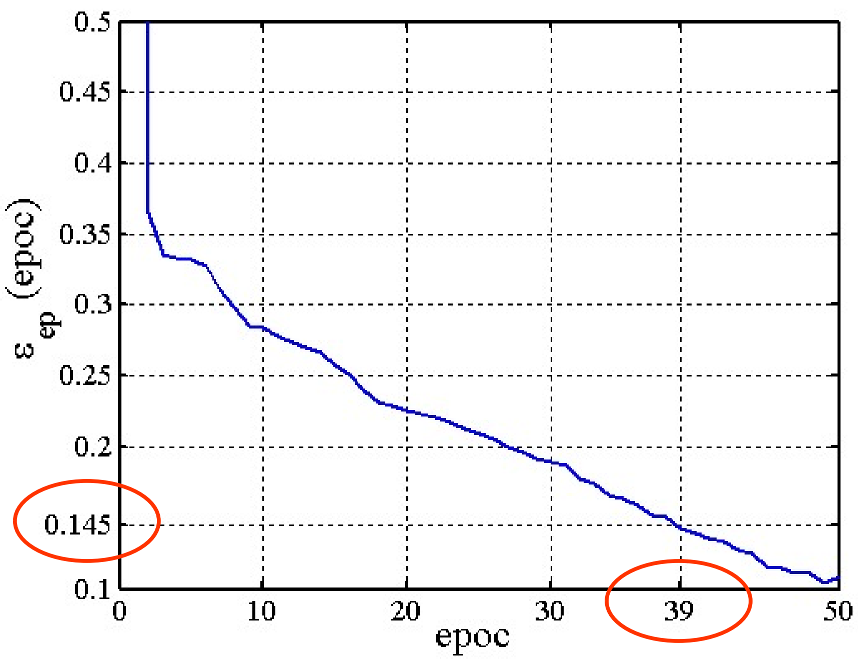
$$1[epoc] = 400\ [step]$$

DD-PID method

$$\varepsilon_{ep}(1) = 0.145$$

NN-PID method

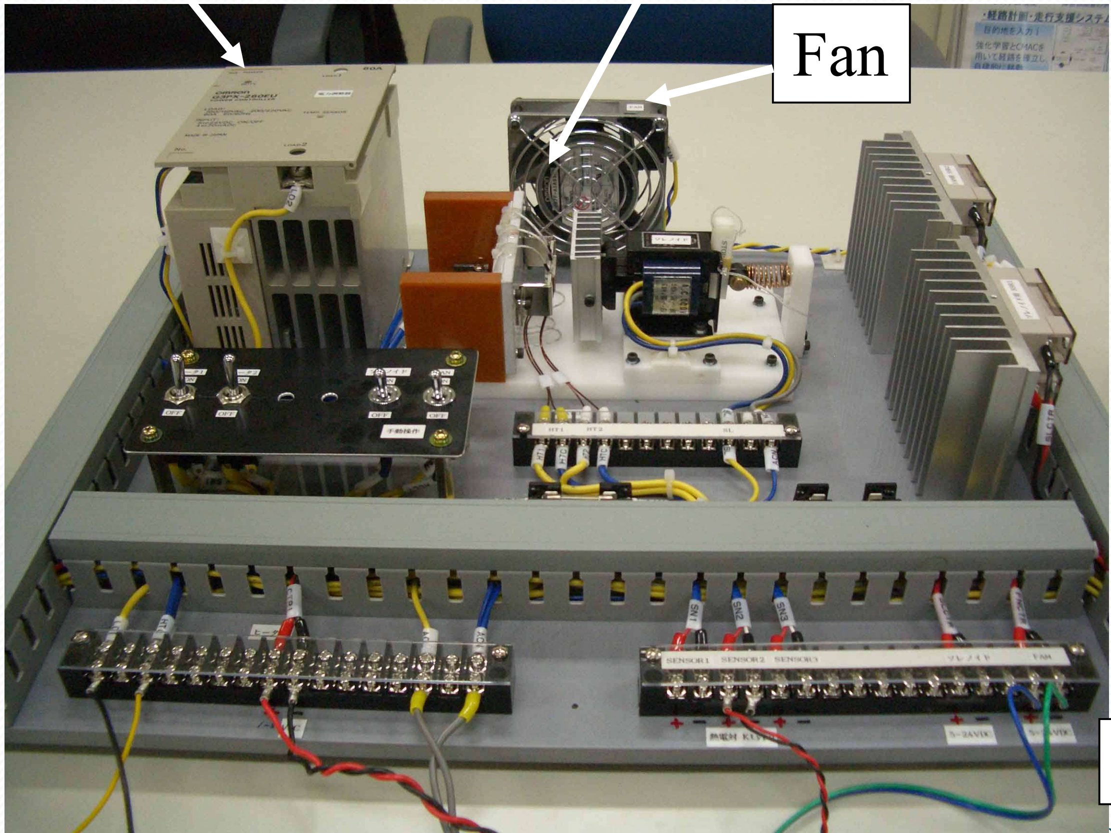
$$\varepsilon_{ep}(39) = 0.145$$

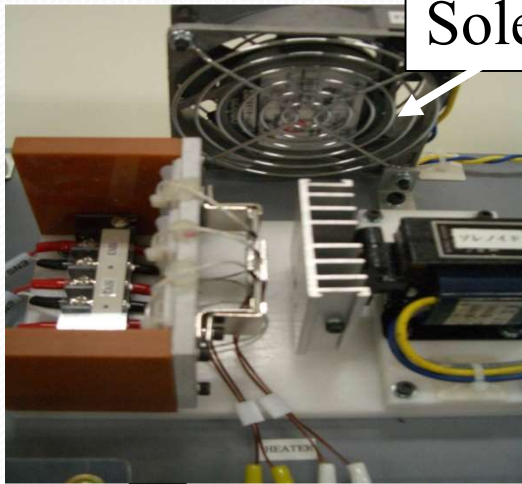


The learning speed of the DD-PID control scheme is very fast

Experimental Example (1)

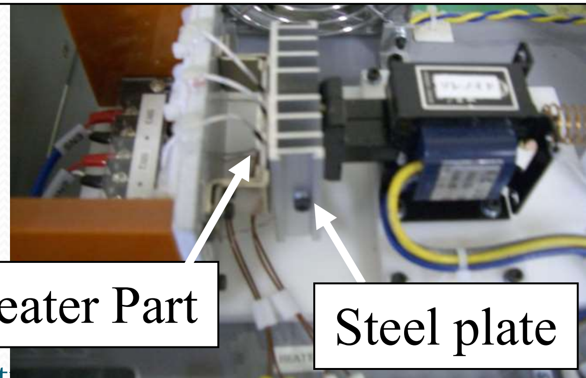
Temperature Control System





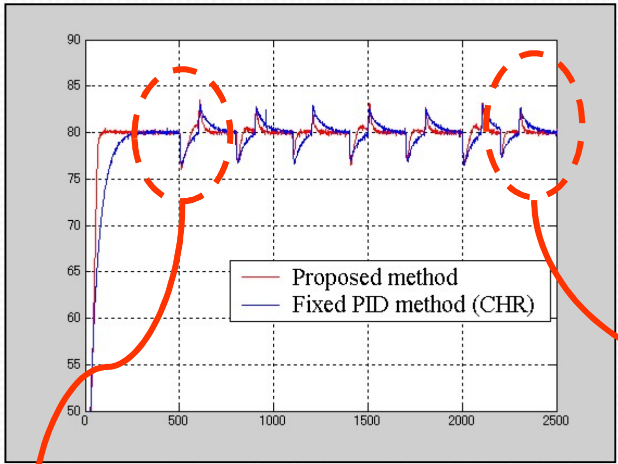
Solenoid: On

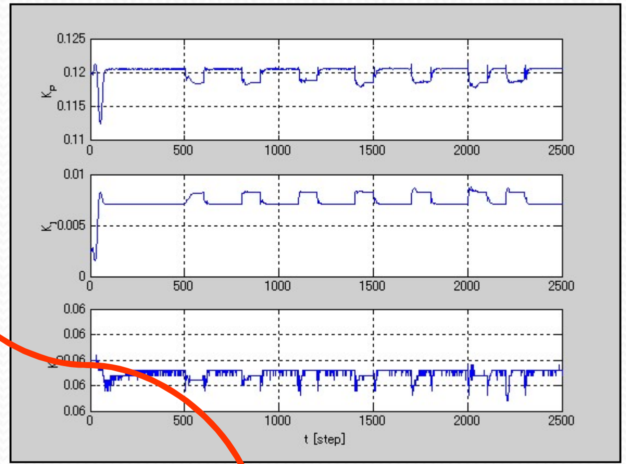
Generate periodic disturbances

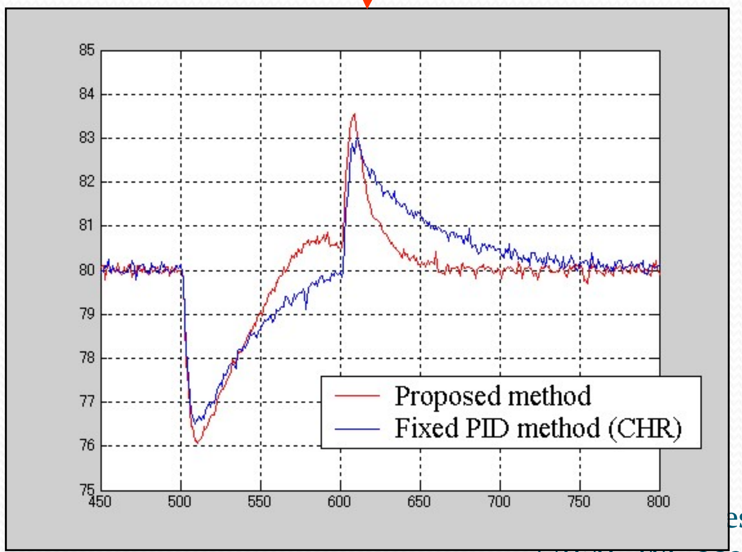


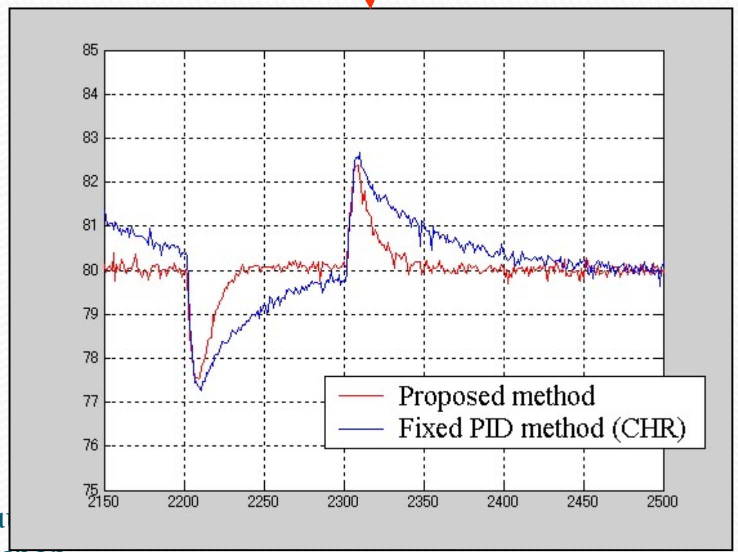
Experimental Example (2)

$$D(t) = \begin{cases} On & (500 \le t < 600) \\ On & (800 \le t < 900) \\ On & (1100 \le t < 1200) \\ On & (1400 \le t < 1500) \\ On & (1700 \le t < 1800) \\ On & (2000 \le t < 2100) \\ On & (2200 \le t < 2300) \\ Off & (\ otherwise\ ) \end{cases}$$





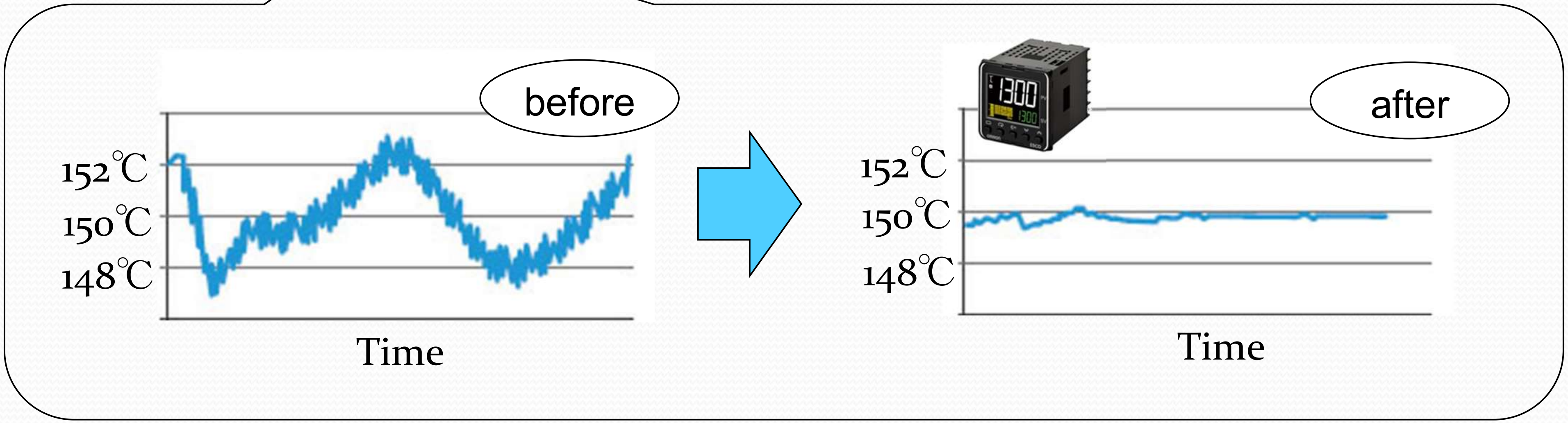




Implementation 1

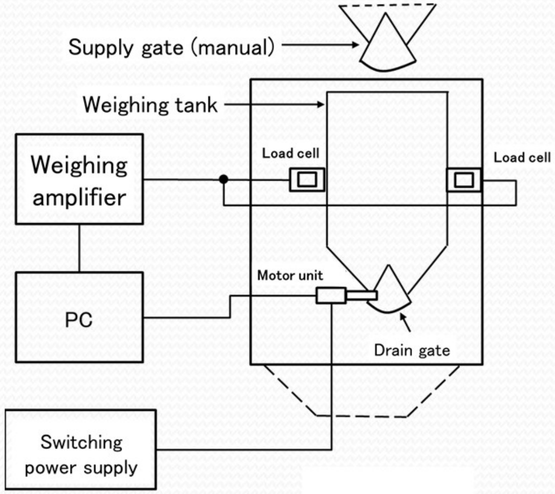
OMRON × HIROSHIMA UNIVERSITY

Electronic Thermal Regulator（E5CD）
Release date: 2017. 4. 3



OMRONHP: http://www.fa.omron.co.jp/products/family/3668/

Implementation 2

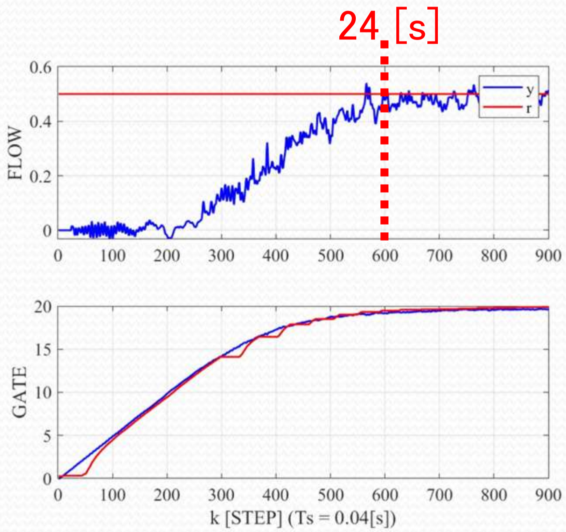


SATAKE × HIROSHIMA UNIVERSITY

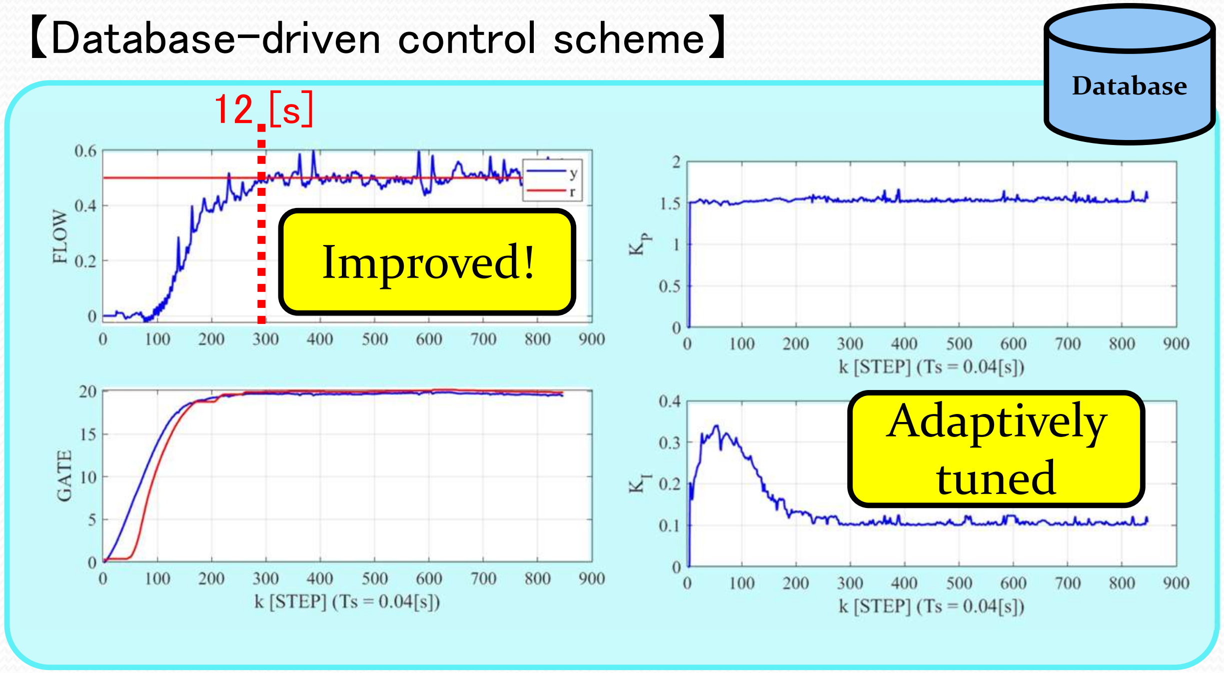
Purpose

Flow rate of rice follows
the reference signal
"accurately" and "quickly"

【Conventional Scheme】



【Database-driven control scheme】



Implementation 3

KOBELCO × HIROSHIMA UNIVERSITY

- DD-PID algorithm has been mounted on a hydraulic excavator in joint project with KOBELCO Construction Machinery.

  System properties change by the attachment and/or the temperature.

Summary of DD-PID Controller（1/2）

New Design of a PID Controller
Based on Database

[Features]

- Deal with nonlinear systems
- Robustness by knowledge stored in data-base
- Adaptability by adjusting PID parameters

Summary of DD-PID Controller（2/2）

[Reference]

T.Yamamoto, K.Takao and T.Yamada :
Design of a Data-Driven PID Controller,
IEEE Trans. on Control Systems Technology,
Vol.17, No.1, pp.29 -39 (2009)

Off-line leaning

S.Wakitani, T.Yamamoto and B.Gopaluni：
Design and Application of a Data-driven PID Control
with Data-Driven Updating Algorithm,
Industry & Engineering Chemistry Research,
Vol.58, No.26, pp.11419-11429 (2019)

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