PID Controller Design Based on Minimizing Generalized Output Errors

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***Abstract*— PID control systems have been widely employed in industrial processes. Recently, some data-oriented PID control systems have been proposed because it is difficult to adjust a set of suitable PID gains. In this paper, one of data-oriented PID control schemes, which is designed by using the generalized output errors, is proposed. The generalized output is defined from a PID control law. Moreover, PID gains are determined based on minimizing the errors between an operating data and the generalized output errors. The proposed scheme has been designed for single-input/single-output linear systems and multivariable systems, and the effectiveness of the scheme is verified by these numerical simulation examples.**

I. INTRODUCTION

PID control systems have been effectiveness control methods for industrial processes, such as petrochemical and chemical plants. They are implemented in more than 80% of the control loops in industrial processes[1] due to their simplicity. Lots of methods which tune PID gains as the control parameters have been proposed[2], [3], [4], [5]. Most tuning methods determine PID gains based on the system model. The system model is constructed using an operating data through system identification. Thus, the system model influences the control performance of obtained PID gains by it. However, it is difficult to obtain high-accuracy system models for the following reasons: Systems often have nonlinearity and uncertainness. System identification needs input signals including a comfortable Persistently Exciting (PE), however, the excitation for plants or machines incurs its instability. The cost of system identification is economical for strict due date and schedule. In addition, the obtained PID gains are required to adjust by several experiments until it satisfies the desired performance.

To overcome these problems, data-oriented control design methods have been proposed in recent years. These methods can determine control parameters without a system model, for example, the IFT (Iterative Feedback Tuning) method[6], the VRFT (Virtual Reference Feedback Tuning) method[7] and the FRIT (Fictitious Reference Iterative Tuning) method[8] have been proposed. These schemes adjust PID gains using the fictitious reference signal so that the property of closed-loop becomes close to it of the reference model system. On the other hand, authors have proposed a scheme based upon minimizing generalized output errors as one of data-oriented control design schemes. The generalized output is developed from a PID control law, and the generalized output errors are computed by the difference between system output of an operating data and the generalized output. According to the proposed scheme, PID gains can be obtained by only control specification and an operating data. Moreover, the concept is clear because the generalized output is defined as equivalent to the reference signal.

In this paper, a data-oriented PID control system based on minimizing generalized output is proposed. Section 2 presents the definition of the generalized output, and the effectiveness of the proposed scheme is verified by a simulation example in section 3. Section 4 discusses a multivariable PID control scheme for decoupling. Because real processes use multivariable systems with interference. These control schemes are demonstrated through some numerical examples, and the its effectiveness is illustrated.

II. THE DESIGN OF THE PROPOSED CONTROLLER

A. *The description of a system*

A single-input/single-output linear system is considered. The discrete-time PID controller is given by the following equation:

$$\begin{aligned} u(k) = u(k-1) &+ K_P\{y(k-1) - y(k)\} \\ &+ K_I\{r(k) - y(k)\} \\ &+ K_D\{2y(k-1) - y(k-2) - y(k)\}. \end{aligned} \quad (1)$$

where $u(k)$, $y(k)$ and $r(k)$ denote the control input, the corresponding output signal and the reference signal, respectively. K_P, K_I and K_D are the proportional, the integral and derivative gains, respectively. As previously noted, it is important to determine PID gains because they relate to the control performance. In this paper, the PID gains are determined by the generalized output error. Thus, the how to define the generalized output in detail is discussed.

B. *The design of the proposed PID controller*

First, equation (1) can be rewritten as

$$\begin{aligned} \Delta u(k) + (K_P + K_I + K_D)y(k) & \\ -(K_P + 2K_D)y(k-1) & \\ +K_D y(k-2) - K_I r(k) &= 0 \end{aligned} \quad (2)$$

where Δ denotes the differencing operator defined by $\Delta := 1 - z^{-1}$. Next, the both side of equation (2) is multiplied by

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$1/K_I$, the equation is obtained as follows:

$$\frac{\Delta u(k)}{K_I} + \frac{K_P + K_I + K_D}{K_I} y(k) - \frac{K_P + 2K_D}{K_I} y(k-1) + \frac{K_D}{K_I} y(k-2) - r(k) = 0. \quad (3)$$

Next, the generalized output $\Phi(k)$ is defined by the following equation:

$$\Phi(k) := a_1 \Delta u(k) + a_2 y(k) + a_3 y(k-1) + a_4 y(k-2) \quad (4)$$

where $a_i (i = 1, \cdots, 4)$ are

$$\left.\begin{aligned} a_1 &= \frac{1}{K_I} \\ a_2 &= \frac{K_P + K_I + K_D}{K_I} \\ a_3 &= -\frac{K_P + 2K_D}{K_I} \\ a_4 &= \frac{K_D}{K_I}. \end{aligned}\right\} \quad (5)$$

From equation (4) and (5), equation (3) can be replaced as follows:

$$\Phi(k) - r(k) = 0. \quad (6)$$

Thus, the relationship $\Phi(k) = r(k)$ is obtained.

The control objective is to obtain a set of suitable PID gains so that the system output $y(k)$ tracks the desired reference model output $y_m(k)$ is defined as

$$y_m(k) = G_m(z^{-1}) r(k). \quad (7)$$

where $G_m(z^{-1})$ denotes the reference model, and operators can design initial rise to the desired output shape using it. $G_m(z^{-1})$ is given by the following equations.

$$G_m(z^{-1}) = \frac{z^{-1} P(1)}{P(z^{-1})} = \frac{1 + p_1 + p_2}{1 + p_1 z^{-1} + p_2 z^{-2}} \quad (8)$$

where the coefficients p_1 and p_2 are determined by [10]

$$\left.\begin{aligned} p_1 &= -2e^{-\frac{\rho}{2\mu}} \cos\left(\frac{\sqrt{4\mu - 1}}{2\mu}\rho\right) \\ p_2 &= e^{-\frac{\rho}{\mu}} \\ \rho :&= \frac{T_s}{\sigma} \\ \mu :&= 0.25(1 - \delta) + 0.51\delta. \end{aligned}\right\} \quad (9)$$

T_s is the sampling interval, and σ and μ are parameters about the rise-time and the damping index, respectively. The reference output shape is changed by choosing σ and μ, which is adjusted by δ. σ corresponding to the rise-time can be set between $1/3 \sim 1/2$ of the time constant. Moreover, the step shape is shown as Binomial model response when δ is set to 0. and the response is shown as Butterworth model response when $\delta = 1$. If the desired output is determined in a practical way, δ should be set to 0.0 throws 2.0. Furthermore, these parameters need to be determined based on system property.

In the proposed scheme, the parameters a_i $(i = 1, \cdots, 4)$ is adjusted so that the following relation is satisfied:

$$G_m(z^{-1}) \Phi(k) \to y(k). \quad (10)$$

And then, from equation (6) and equation (10), the relationship can be obtained as follows:

$$y(k) \to G_m(z^{-1}) r(k). \quad (11)$$

Therefore, the PID controller is designed as the system output tracks the reference model output, In other words, the control objective can be achieved. By optimizing the following function, the relationship equation (11) can be obtained:

$$J = \frac{1}{N} \sum_{k=1}^{N} \varepsilon^2(k) \quad (12)$$

$$\varepsilon(k) = G_m(z^{-1}) \Phi(k) - y(k) \quad (13)$$

where N is step number of the operating data, and these equations are the generalized output errors. In order to minimize equation (12), for example, the optimization toolbox in Matlab can be utilized.

Moreover, if a system has an unknown time-delay, the time-delay can be estimated, and the corresponding PID gains can be adjusted. When a time-delay system is considered, equation (13) of the evaluated function is replaced as follows.

$$\varepsilon_d(k) = G_m(z^{-1}) \Phi(k - d) - y(k) \quad (14)$$

where d is a time-delay of the system. In detail, the time-delay is found by using the values of the evaluate function with changing d.

Therefore, it is the concept of the proposed scheme, and the proposed scheme can be designed PID controller to track the reference model output.

III. Simulation Example

To verify the effectiveness of the proposed scheme, the following system is considered[11].

$$G(s) = \frac{1}{s^3 + 2s^2 + 6s + 2} e^{-4s} \quad (15)$$

The system is discretized with $T_s = 1.0$ [s], the following equation is given:

$$\begin{aligned} y(k) = &\ 0.187y(k-1) + 0.151y(k-2) \\ &+ 0.135y(k-3) + 0.083u(k-d-1) \\ &+ 0.152u(k-d-2) + 0.0289u(k-d-3) \\ &+ \xi(k) \end{aligned} \quad (16)$$

where $\xi(k)$ denotes a Gaussian white noise with zero mean and covariance 0.01, and the time-delay is given as $d = 4$. Obviously, the operator does not know the true time-delay.

First, the following PID gains are determined by the Chien, Hrones and Reswick (CHR) method[3], and these gains are employed,

$$K_P = 1.5, K_I = 0.3, K_D = 3.0, \tag{17}$$

when the reference signal is given as:

$$r(k) = \begin{cases} 2.0\,(0 < k \leq 100) \\ 3.0\,(100 < k \leq 200) \\ 4.0\,(200 < k \leq 300). \end{cases} \tag{18}$$

Then, the control result is shown in Fig. 1. The results is

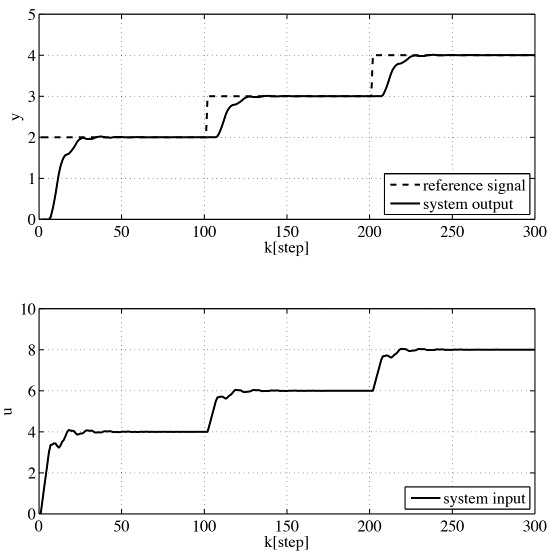

Fig. 1. The control result when $K_P = 1.5$, $K_I = 0.3$, $K_D = 3.0$ for a time-delay system

Next, in order to employ the proposed scheme, the reference model is given by $\sigma = 6.0$ [s] and $\delta = 0.0$, and $G_m(z^{-1})$ is designed as following equation:

$$G_m(z^{-1}) = \frac{0.08z^{-1}}{1 - 1.43z^{-1} + 0.51z^{-2}}. \tag{19}$$

The proposed scheme computes PID gains by changing d of equation (14), then Table I shows sets of PID gains and the corresponding errors. According to Table I, the error is smallest at $d = 4$, and this is the true time-delay. Thus, the PID gains of $d = 4$ are employed the system, and the control result is shown in Fig. 2,

Therefore, the time-delay can be estimated and whose system is controlled as the desired control performance by using the generalized output error even if a system has an unknown time-delay.

TABLE I
PID GAINS AND THE ERROR BY EACH TIME-DELAY.

d	K_P	K_I	K_D	generalized output error
1	4.065	0.753	10.000	0.350
2	2.492	0.496	6.083	0.236
3	1.647	0.362	3.516	0.027
4	1.152	0.286	1.729	0.019
5	0.851	0.241	0.429	0.030
6	0.781	0.227	0.301	0.052
7	0.698	0.218	0.001	0.152
8	0.554	0.185	0.001	0.821
9	0.506	0.162	0.001	2.021
10	0.524	0.144	0.001	3.587

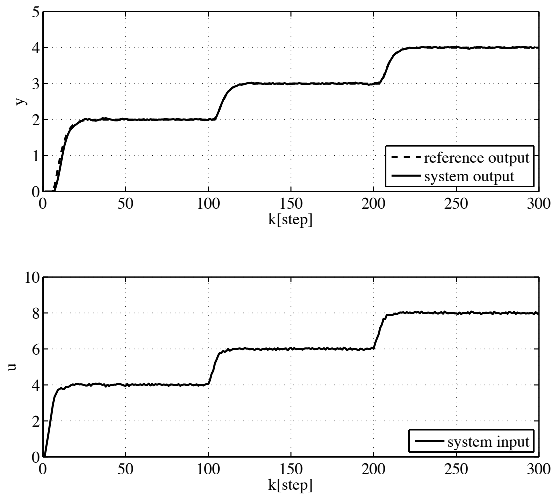

Fig. 2. The control result by using the proposed scheme for a time-delay system

IV. DESIGN OF A MULTIVARIABLE PID CONTROLLER

A. The description of a multivariable system

For a step toward the practical use of the method, multi-input/multi-output systems are considered, because most real systems are multivariate systems. Therefore, it is necessary that the scheme is extended to multi-input/multi-output(MIMO) cases. In addition, if systems are given as MIMO, the influence of mutual interference between the input and output need to be considered. Usually, in the case of a controlled multivariable system such that the interference, the system is controlled by a method based on the modern control theory or a method by using a pre-compensator. However, in order to use these methods, it is necessary to identify the system parameters. Therefore, the proposed scheme optimizes non-diagonal elements in the PID gains matrix so as to solve the problem.

A multivariable control law is given by

$$\begin{aligned} \boldsymbol{u}(k) = \boldsymbol{u}(k-1) &+ \boldsymbol{K_P}\{\boldsymbol{y}(k-1) - \boldsymbol{y}(k)\} \\ &+ \boldsymbol{K_I}\{\boldsymbol{r}(k) - \boldsymbol{y}(k)\} \\ &+ \boldsymbol{K_D}\{2\boldsymbol{y}(k-1) - \boldsymbol{y}(k-2) - \boldsymbol{y}(k)\}, \end{aligned} \tag{20}$$

where $\boldsymbol{K_P}$, $\boldsymbol{K_I}$ and $\boldsymbol{K_D}$ are the proportional gain matrix, the integral gain matrix and derivative gain matrix, respectively. Each matrix is $\boldsymbol{K_P} \in \boldsymbol{R}^{p\times p}$, $\boldsymbol{K_I} \in \boldsymbol{R}^{p\times p}$ and $\boldsymbol{K_D} \in \boldsymbol{R}^{p\times p}$. $\boldsymbol{u}(k)$, $\boldsymbol{y}(k)$ and $\boldsymbol{r}(k)$ denote the control input signal, the corresponding output signal and the reference signal, respectively. They are given by p-dim vectors, which are as follows:

$$\left.\begin{array}{l} \boldsymbol{u}(k) = [\ u_1(k),\ u_2(k),\ \cdots,\ u_p(k)\ ]^T \\ \boldsymbol{y}(k) = [\ y_1(k),\ y_2(k),\ \cdots,\ y_p(k)\ ]^T \\ \boldsymbol{r}(k) = [\ r_1(k),\ r_2(k),\ \cdots,\ r_p(k)\ ]^T. \end{array}\right\} \tag{21}$$

In addition, the mutual interference in multivariable system is alleviated by non-diagonal elements in each gains matrix.

B. The design of the proposed multivariable PID controller

In the proposed scheme, the generalized output is developed so that the generalized output is equivalent to the reference signal. Therefore, in multivariable systems, the generalized output vector $\boldsymbol{\Phi}(k)$ is defined as follows:

$$\begin{aligned} \boldsymbol{\Phi}(k) := \quad & \boldsymbol{C_1}\tilde{\boldsymbol{u}}(k) + \boldsymbol{C_2}\boldsymbol{y}(k) \\ & + \boldsymbol{C_3}\boldsymbol{y}(k-1) \\ & + (\boldsymbol{I} - \boldsymbol{C_2} - \boldsymbol{C_3})\boldsymbol{y}(k-2) \end{aligned} \tag{22}$$

$$\boldsymbol{\Phi}(k) = \quad [\ \Phi_1(k),\ \Phi_2(k),\ \cdots,\ \Phi_p(k)\ ]^T. \tag{23}$$

where $\tilde{\boldsymbol{u}}$ is given by the following equation.

$$\tilde{\boldsymbol{u}}(k) = \quad [\ \Delta u_1(k)\ \ \Delta u_2(k)\ \ \cdots\ \ \Delta u_p(k)\ ]^T \tag{24}$$

Moreover, $\boldsymbol{C_i} \in \boldsymbol{R}^{p\times p}$ $(i = 1, 2, 3)$ are given by

$$\left.\begin{array}{l} \boldsymbol{C_1} = \boldsymbol{K_I}^{-1} \\ \boldsymbol{C_2} = \boldsymbol{K_I}^{-1}\big(\boldsymbol{K_P} + \boldsymbol{K_I} + \boldsymbol{K_D}\big) \\ \boldsymbol{C_3} = -\boldsymbol{K_I}^{-1}\big(\boldsymbol{K_P} + 2\boldsymbol{K_D}\big). \end{array}\right\} \tag{25}$$

In the same way as section II, the parameter matrix $\boldsymbol{C_i}(i = 1, 2, 3)$ of $\boldsymbol{\Phi}(k)$ is optimized so that $\boldsymbol{G_m}(z^{-1})\boldsymbol{\Phi}(k)$ becomes to equal to $\boldsymbol{y}(k)$. The reference model $\boldsymbol{G_m(z^{-1})}$ are introduced as follows:

$$\begin{aligned} \boldsymbol{G_m}(z^{-1}) = \mathrm{diag}\big\{&G_{m_1}(z^{-1}), G_{m_2}(z^{-1}), \\ &\cdots, G_{m_p}(z^{-1})\big\} \end{aligned} \tag{26}$$

$$G_{m_j}(z^{-1}) = \frac{z^{-1}P(1)}{P_j(z^{-1})} \tag{27}$$

$$P_j(z^{-1}) = 1 + p_{1_j}z^{-1} + p_{2_j}z^{-2} \tag{28}$$

where p_{1_j} and $p_{2_j}(j = 1, 2, \cdots, p)$ are determined by

$$\left.\begin{array}{l} p_{1j} = -2e^{-\frac{\rho_j}{2\mu_j}}\cos\big(\frac{\sqrt{4\mu_j - 1}}{2\mu_j}\rho_j\big) \\ p_{2j} = e^{-\frac{\rho_j}{\mu_j}} \\ \rho_j := \dfrac{T_s}{\sigma_j} \\ \mu_j := 0.25(1 - \delta_j) + 0.51\delta_j. \end{array}\right\} \tag{29}$$

σ_j is a parameter is related to the rise-time, and μ_j is the damping index and it is adjusted by δ_j.

Therefore, to optimize $\boldsymbol{C_i}$ $(i = 1, 2, 3)$, the following evaluated function J is considered:

$$J = \sum_{j=1}^{p}\lambda_j\Big\{\sum_{k=1}^{N}\varepsilon_j^2(k)\Big\} \tag{30}$$

$$\boldsymbol{\varepsilon}(k) = \boldsymbol{y}(k) - \boldsymbol{y_m}(k) \tag{31}$$

$$\boldsymbol{\varepsilon}(k) = [\ \varepsilon_1(k),\ \varepsilon_2(k),\ \cdots,\ \varepsilon_p(k)\ ]^T \tag{32}$$

where N is the step of an operating data. $\lambda_j(j = 1, 2, \cdots, p)$ is the weight parameter for each controller. λ_j should be designed according to operating conditions, to simplify $\lambda_j = 1$ in this paper. Moreover, $\boldsymbol{C_i}(i = 1, 2, 3)$ is calculated by a suitable optimization algorithm as be a regular matrix.

If $\boldsymbol{C_i}$ is calculated, PID gains matrix can be obtained as follows:

$$\left.\begin{array}{l} \boldsymbol{K_P} = \boldsymbol{C_1}^{-1}\big(2\boldsymbol{C_2} + \boldsymbol{C_3} - 2\boldsymbol{I}\big) \\ \boldsymbol{K_I} = \boldsymbol{C_1}^{-1} \\ \boldsymbol{K_D} = \boldsymbol{C_1}^{-1}\big(\boldsymbol{I} - \boldsymbol{C_2} - \boldsymbol{C_3}\big). \end{array}\right\} \tag{33}$$

Therefore, the control system is constructed using obtained PID gains matrix.

V. SIMULATION EXAMPLES BY THE PROPOSED MULTIVARIABLE CONTROLLER

In order to verify the effectiveness of the proposed scheme, some numerical examples are simulated. The following 2-input/2-output system[12] is considered.

$$\begin{aligned} \boldsymbol{y}(k) = &\begin{bmatrix} 0.9 & 0 \\ 0 & 0.8 \end{bmatrix}\boldsymbol{y}(k-1) + \begin{bmatrix} 0.2 & 0 \\ 0 & 0.1 \end{bmatrix}\boldsymbol{y}(k-2) \\ &+ \begin{bmatrix} 0.6 & 0.5 \\ 0.4 & 0.8 \end{bmatrix}\boldsymbol{u}(k-1) + \begin{bmatrix} 0.3 & 0.4 \\ 0.3 & 0.3 \end{bmatrix}\boldsymbol{u}(k-2) \\ &+ \boldsymbol{\xi}(k) \end{aligned} \tag{34}$$

where $\boldsymbol{\xi}(k)$ is given by the following equation.

$$\boldsymbol{\xi}(k) = \big[\xi_1(k) \quad \xi_2(k)\big]^T \tag{35}$$

$\xi_j(k)$ $(j = 1, 2)$ is a white gaussian noise with zero mean and 0.01 variance. The reference signals are given as follows:

$$r_1(k) = \begin{cases} 1.0 & (0 \le k \le 200) \\ 2.0 & (200 < k \le 400) \\ 0.5 & (400 < k \le 600) \end{cases} \tag{36}$$

$$r_2(k) = \begin{cases} 3.0 & (0 \le k \le 250) \\ 1.0 & (250 < k \le 450) \\ 2.0 & (450 < k \le 600) \end{cases} \tag{37}$$

First, the following PID gains matrix are computed by the CHR method, and these gains matrix are employed.

$$\begin{aligned} &\boldsymbol{K_P} = \begin{bmatrix} 0.36 & 0 \\ 0 & 0.43 \end{bmatrix}, \boldsymbol{K_I} = \begin{bmatrix} 0.21 & 0 \\ 0 & 0.12 \end{bmatrix}, \\ &\boldsymbol{K_D} = \begin{bmatrix} 0.14 & 0 \\ 0 & 0.17 \end{bmatrix} \end{aligned} \tag{38}$$

The control results are shown in Fig. 3. From Fig. 3, the outputs nearly track the reference signals although y_1

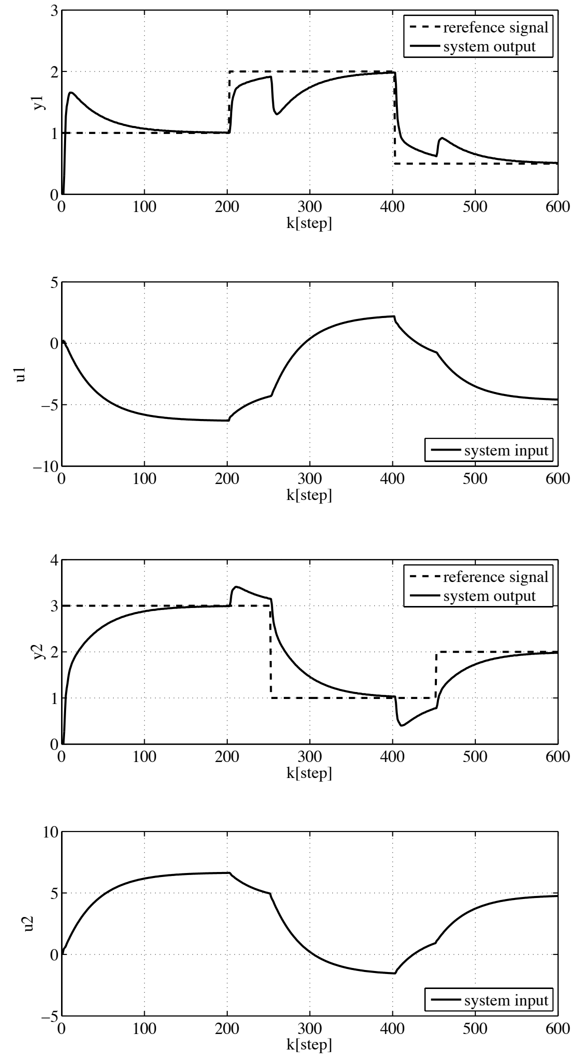

Fig. 3. Control result by using CHR method for 2-input/2-output system.

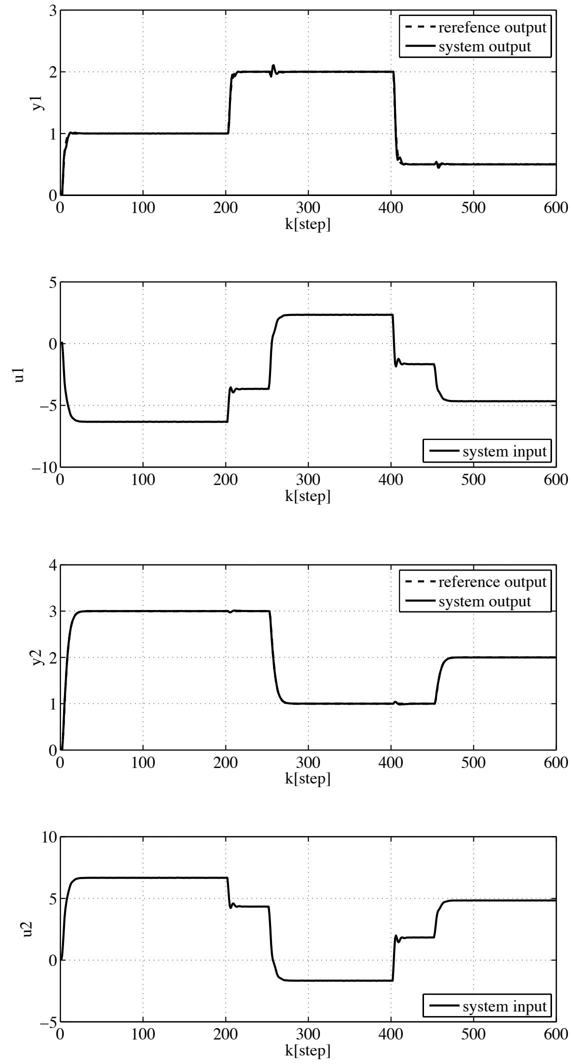

Fig. 4. Control result by using the proposed scheme when parameters are set $\lambda_1 = \lambda_2 = 1.00$ for 2-input/2-output system.

shows an overshoot. However, it is clear that each output is influenced a great deal by each other.

Next, the proposed scheme is employed using operating data about the control results in Fig. 3. The reference model is designed by setting $T_s = 1.0$[s], $\sigma_1 = 3.0$[s], $\sigma_2 = 6.0$[s] and $\delta_1 = \delta_2 = 0.0$, and the following polynomial is obtained:

$$G_{m_1}(z^{-1}) = \frac{0.24z^{-1}}{1 - 1.03z^{-1} + 0.26z^{-2}} \tag{39}$$

$$G_{m_2}(z^{-1}) = \frac{0.08z^{-1}}{1 - 1.43z^{-1} + 0.51z^{-2}} \tag{40}$$

The weight parameter λ_j to each output is $\lambda_1 = \lambda_2 = 1.00$. The control result is shown in Fig. 4, and the computed PID gains matrix are

$$\boldsymbol{K_P} = \begin{bmatrix} 0.20 & 0.68 \\ -0.29 & 0.04 \end{bmatrix}, \boldsymbol{K_I} = \begin{bmatrix} 0.70 & -0.38 \\ -0.64 & 0.50 \end{bmatrix},$$
$$\boldsymbol{K_D} = \begin{bmatrix} 1.21 & -2.44 \\ -0.89 & 1.26 \end{bmatrix} \tag{41}$$

By comparison of these results, it is clear that the proposed scheme can be decoupled about y_1 effectively.

Moreover, the effect of the weight parameter λ_j is considered. Then, the operating data is used results whose Fig. 3. Fig. 5 shows the control result by using the proposed scheme with $\lambda_1 = 1.00$ and $\lambda_2 = 0.01$.

As a result, when the weight of y_1 is set to be large, the interference of y_1 can be suppressed more. By contrast, the control performance of y_2 becomes depleted.

Table II shows integral square errors about each output computed by changing λ_j. Here, ε_j is error between the reference output and the control output, and is defined by the following equation.

$$\varepsilon_j = G_{m_j}(z^{-1})r_j(k) - y_j(k) \tag{42}$$

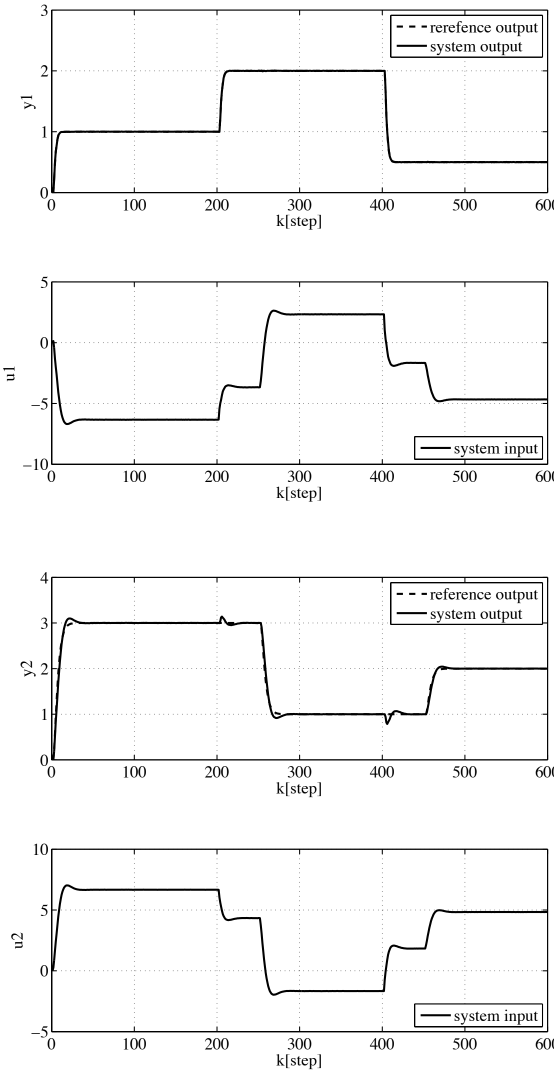

Fig. 5. Control result by using the proposed scheme when parameters are set $\lambda_1 = 1.00$ and $\lambda_2 = 0.01$.

TABLE II

THE SUM OF SQUARED CONTROL ERROR CORRESPONDING TO THE CHANGING λ_j.

λ	$\int \varepsilon_1$	$\int \varepsilon_2$
$\lambda_1 = 0.01, \lambda_2 = 1.00$	0.178	0.013
$\lambda_1 = 1.00, \lambda_2 = 1.00$	0.177	0.021
$\lambda_1 = 1.00, \lambda_2 = 0.01$	0.007	1.056

From Table II, it is clear that the proposed scheme obtain better performance by changing a weight rate, so that λ_j works properly. In particular, if operator sets to λ_j to match the operating conditions and system, the desired output can be obtained.

Therefore, the effectiveness of the proposed multivarible PID controller is verified.

VI. CONCLUSIONS

In this chapter, a data-oriented PID control systems have been proposed. First, the generalized output as key of the proposed scheme was discussed. According to the proposed scheme, the generalized output is defined from a discretized the discrete-time PID controller, PID gains included in the generalized output are adjusted by optimized so as to reduce generalized output error using the operation data previously obtained.

Secondly, the proposed scheme have been expanded to multivariable systems because real processes often are use multi-input/multi-output system. In the proposed scheme, non-diagonal elements of PID gains matrix are computed to reduce interferences while each input-output. Moreover, by adjusting the weight $\boldsymbol{\lambda}$, it is possible to obtain control performance to match the operating conditions.

The behaviors of the proposed controllers are examined by some numerical simulation examples, and the effectivenesses are shown. In the future, in order to illustrate the usefulness of the proposed scheme, the proposed controllers works in real systems.

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