# Design and Experimental Evaluation of a PID Controller Based on GPC*

Zhe Guan[1] Shin Wakitani[2] and Toru Yamamoto[3]

***Abstract*— PID control plays an important role in industrial system. As known that tuning PID parameters have strong effect on the control performance, therefore, many tuning PID parameters schemes have appeared, such as model based design methods which are still used in practical applications. However, in some sophisticated systems like thermal processes and chemical processes, experiments are required multiple times in order to calculate control parameters. As to overcome such problem, the data-oriented design scheme has received much attention in the last few years. In this study, the data-oriented PID controller design based on Generalized Predictive Control (GPC) is proposed. According to the proposed method, control parameters are obtained based on predictive values of system output, and a GPC-based PID controller is given by converting these parameters. Moreover, the control performance can be suitably adjusted by user specified parameters.The effectiveness of the proposed method is evaluated by a numerical example. And the proposed method is employed in the experiment.**

## I. Introduction

Proportional-integral-derivative(PID) controllers have been widely used in process industries for the last decades. The major reasons for their wide acceptance in industries are their ability to control most of the processes, well-understood control action and ease of implementation.[1] Aside from which, the control performance of a closed-loop system is strongly affected by tuning PID parameters. Therefore, deign and tuning of PID controllers have been the subject of many researchers working in this field. Over the years, considerable techniques have been provided for tuning of the PID parameters. And they are generally concerned in the system modeling which is referred as model-based and these schemes have remained as the most widely used schemes in industrial process control.[4] However, in process systems, such as a thermal processes or chemical processes, a long-period step response test is performed which will take a tremendous amount of time to obtain a system model. Moreover, the model is not satisfactory in terms of accuracy, therefore the computational cost is large so as to identify the model accurately. On the one hand, in recent years, some techniques which compute control parameters using only operating data have been proposed such as Virtual Reference Feedback Tuning (VRFT) [5] and Fictitious Reference Iterative Tuning (FRIT) [6] and these methods have attracted much attention as a data-oriented control design scheme in recent years. According to these methods, it is capable of calculating the PID parameters directly from a set of I/O data. Moreover, these schemes are referred to as the data-oriented development scheme.[10] Under this circumstances, the data-oriented PID controller design scheme based on the Generalized Minimum Variance Control (GMVC) has been proposed, and the effectiveness of the proposed method is evaluated by simulations and experiments[7]. However, in the GMV-PID control system design method, control parameters are designed based on only the predicted value of the time-delay ahead, thus sometimes the control system becomes unstable by an aggressive design when the time-delay of controlled object is large or unknown.

In this paper, a data-oriented Generalized Predictive Control GPC [8] system design method is considered. The GPC has a multi-step prediction structure of a system output. According to the above method, multi-step prediction can be performed by calculating one-step ahead of predictive output by a set of closed loop data and solving recursive formulas based on the value. Moreover, in the proposed method, the implicit method of the GMVC to calculate the initial value is introduced, and as a result of which the system parameters can be known. The stability of the control system is improved by using a multi-step prediction value, and it is expected to obtain more desirable control results compared to the GMV-PID control system with large time-delay. This paper presents the theoretical design method of the data-oriented GPC-PID control and the effectiveness of the method is evaluated by a simulation. The experiment is carried out to evaluate the usefulness of the proposed method. It is capable of adjusting the weighting factor $\lambda$ to obtain the satisfactory result.

## II. Design of a GPC-PID control system

### A. System description

A controlled object is assumed to be described as the following CARIMA (Controlled Auto Regressive Integrated Moving Average) model:

$$A(z^{-1})y(t) = z^{-1}B(z^{-1})u(t) + \frac{\xi(t)}{\Delta} \quad (1)$$

$$\left.\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + a_2 z^{-2} \\ B(z^{-1}) &= b_0 + \cdots + b_m z^{-m} \end{aligned}\right\} \quad (2)$$

where, $u(t)$ and $y(t)$ indicate the control input and the system output respectively and $\xi(t)$ is expressed as white Gaussian noise with a mean of zero and a variance of $\sigma^2$. $z^{-1}$ denotes

[1]Zhe Guan is with Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi Hiroshima, Hiroshima, Japan guan--zhe@hiroshima-u.ac.jp

[2]Shin Wakitani is with Department of Electrical and Electronics Engineering Tokyo University of Agriculture and Technology 2-24-16 Nakacho, Koganei-shi, Tokyo 184-8588, Japan wakitani@cc.tuat.ac.jp

[3]Toru Yamamoto is with Faculty of Electrical Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi Hiroshima, Hiroshima, Japan yama@hiroshima-u.ac.jp

the backward shift operator which implies $z^{-1}y(t)=y(t-1)$ and $\Delta$ represents the difference operator given by $\Delta := 1-z^{-1}$. Moreover, $m$ takes into consideration the order of polynomial $B(z^{-1})$ that is determined by considering the time-delay of the system. Additionally, in the above model, $A(z^{-1})$ and $B(z^{-1})$ are unknown.

### *B. Design of a generalized predictive control system*

The generalized predictive control law corresponding to the system (1) is derived based on the minimization of the criterion (3) in the following equation.

$$J = E\left[\sum_{j=1}^{N}\{y(t+j)-w(t+j)\}^2 + \sum_{j=1}^{N}\lambda(j)\{\Delta u(t+j-1)\}^2\right] \quad (3)$$

where, $[1,N]$ denotes the control horizon and prediction horizon. In addition, in (3), the target reference $w(t+j)$ is as follows:

$$w(t)=w(t+1)=\cdots=w(t+j) \quad (4)$$

In addition, $\lambda(j)$ is a control weighting sequence and can be set by user arbitrarily. Here, in order to minimize the expression (3), future predicted values of the system outputs $y$ and the control inputs $\Delta u$ are required. Therefore, the two Diophantine equations are introduced.

$$1=\Delta A(z^{-1})E_j(z^{-1})+z^{-j}F_j(z^{-1}) \quad (5)$$

$$E_j(z^{-1})B(z^{-1})=R(z^{-1})+z^{-j}S_j(z^{-1}) \quad (6)$$

where, $E_j(z^{-1})B_j(z^{-1})=G_j(z^{-1})$

$$\left.\begin{array}{l} E_j(z^{-1})=1+e_1z^{-1}\cdots+e_{j-1}z^{-(j-1)} \\ F_j(z^{-1})=f_0^j+f_1^jz^{-1}+f_2^jz^{-2} \\ R_j(z^{-1})=r_0+r_1z^{-1}+\cdots+r_{j-1}z^{-(j-1)} \\ S_j(z^{-1})=s_0^j+s_1^jz^{-1}+\cdots+s_{m-1}^jz^{-(m-1)} \end{array}\right\} \quad (7)$$

Combing the equation (1) with (5) gives:

$$y(t+j) = F_j(z^{-1})y(t)+E_j(z^{-1})B(z^{-1})\Delta u(t+j-1) + E_j(z^{-1})\xi(t+j) \quad (8)$$

Through the equation (6) and (8), the following equation yields:

$$y(t+j) = R_j(z^{-1})\Delta u(t+j-1)+h_j(t)+\varepsilon(t+j) \quad (9)$$

where,

$$h_j(t) := F_j(z^{-1})y(t)+S_j(z^{-1})\Delta u(t-1) \quad (10)$$

$$\varepsilon(t+j) := E_j(z^{-1})\xi(t+j) \quad (11)$$

The criterion (3) of formula can be written in the vector form.

$$J = E\left[\{\tilde{y}-w\}^T\{\tilde{y}-w\}+\tilde{u}^T\Lambda\tilde{u}\right] \quad (12)$$

where the vectors are all $N\times 1$

$$\tilde{y} := [y(t+1),\ldots,y(t+N)]^T \quad (13)$$

$$w := [w(t+1),\ldots,w(t+N)]^T \quad (14)$$

$$\tilde{u} := [\Delta u(t),\ldots,\Delta u(t+N-1)]^T \quad (15)$$

$$\Lambda := \mathrm{diag}[\lambda,\ldots,\lambda]^T \quad (16)$$

Then, the expression (9) in vector format is the prediction formula that is $j$ steps ahead and is described as follows:

$$\tilde{y}=R\tilde{u}+h+\varepsilon \quad (17)$$

where, $h$ and $\varepsilon$ are shown as follows,

$$h := [h_1(t),\ldots,h_N(t)]^T \quad (18)$$

$$\varepsilon := [\varepsilon_1(t+j),\ldots,\varepsilon_N(t+j)] \quad (19)$$

And $R$ is defined as,

$$R := \begin{bmatrix} r_0 & 0 & \mathbf{0} & \\ r_1 & r_0 & & \\ \vdots & \vdots & \ddots & \\ r_N & r_{N-1} & \cdots & r_0 \end{bmatrix} \quad (20)$$

The control law to minimize the cost function (12), can be obtained as the following equation by doing a partial differential of $\tilde{u}$ to both sides of the equation.

$$\tilde{u}=[R^TR+\Lambda]^{-1}R^T(h-w) \quad (21)$$

Please refer to [7] for more detailed explanations. In most predictive control schemes, such as GPC, the first element $u$ of the sequence is asserted, which is done using the receding horizon approach. Thus, the $\Delta u(t)$ in time $t$[step] can be obtained as follows:

$$\Delta u(t)=[1,0,\ldots,0][R^TR+\Lambda]^{-1}R^T(h-w) \quad (22)$$

### *C. The replacement of I-PD control law from generalized predictive control system*

Here from the equation (22), it is discussed how to replace the velocity type PID control law (I-PD) from the GPC law. First, the following equation's control law is obtained from (22).

$$\sum_{j=1}^{N}p_jF_j(z^{-1})y(t)+\{1+z^{-1}\sum_{j=1}^{N}p_js_0^j\}\Delta u(t) - \sum_{j=1}^{N}p_jw(t)=0 \quad (23)$$

However, $p_j$ is obtained by the following equation which is defined as the part of the right side of the equation (22).

$$[p_1,p_2,\cdots,p_N] := [1,0,\cdots,0](R^TR+\Lambda)^{-1}R^T \quad (24)$$

On the other hand, the velocity type PID control law is given as shown below.

$$\Delta u(t)=\frac{k_c\cdot T_s}{T_I}e(t)-k_c\{\Delta+\frac{T_D}{T_s}\Delta^2\}y(t) \quad (25)$$

where, $e(t)$ denotes the control error, and is defined by the following equation:

$$e(t) := w(t) - y(t) \tag{26}$$

Additionally, $k_c$, $T_I$ and $T_D$ are the proportional gain, the integral time, and the derivative time respectively. Meanwhile, $T_s$ expresses the sampling time. For simplicity, $L(z^{-1})$ is defined as the following equation,

$$L(z^{-1}) := k_c \left\{ \left(1 + \frac{T_s}{T_I} + \frac{T_D}{T_s}\right) - \left(1 + \frac{2T_D}{T_s}\right) z^{-1} + \frac{T_D}{T_s} z^{-2} \right\} \tag{27}$$

PID control law (25) can be rewritten as shown below.

$$L(z^{-1})y(t) + \Delta u(t) - L(1)w(t) = 0 \tag{28}$$

Here, the polynomial equation of $\Delta u(t)$ is replaced by a static gain with the emphasis on the steady-state characteristics. Meanwhile, with the formula (23), the following equation can be obtained.

$$\tilde{F}(z^{-1})y(t) + \Delta u(t) - \tilde{F}(1)w(t) = 0 \tag{29}$$

however,

$$\tilde{F}(z^{-1}) := \frac{1}{X} \sum_{j=1}^{N} p_j F_j(z^{-1}) \tag{30}$$

$$= \tilde{f}_0 + \tilde{f}_1 z^{-1} + \tilde{f}_2 z^{-2} \tag{31}$$

$$X := 1 + \sum_{j=1}^{N} p_j s_0^j \tag{32}$$

From the above relationship and by comparing the coefficients of the formula (25), I-PD control law based on the GPC law is derived approximately.

$$\left.\begin{aligned} k_c &= -(\tilde{f}_1 + 2\tilde{f}_2) \\ T_I &= -\frac{\tilde{f}_1 + 2\tilde{f}_2}{\tilde{f}_0 + \tilde{f}_1 + \tilde{f}_2} T_s \\ T_D &= -\frac{\tilde{f}_2}{(\tilde{f}_1 + 2\tilde{f}_2)} T_s \end{aligned}\right\} \tag{33}$$

## III. Calculation of the Control Parameters Based on the Closed Loop Data

As mentioned earlier, even though the structure of the target system has been known, the system parameters $A(z^{-1})$ and $B(z^{-1})$ are unknown, which is the feature of the data-oriented method. One effective scheme is to obtain $F_j(z^{-1})$ and $G_j(z^{-1})$ by using closed loop data. Particularly, the initial parameters $F_1(z^{-1})$ and $G_1(z^{-1})$ are directly calculated from a set of closed loop data, and then by solving the recursive formula, $F_j(z^{-1})$ and $G_j(z^{-1})$ are obtained. The Diophantine equations are considered for $t+j$[step] and $t+j+1$[step] ahead:

$$1 = E_j(z^{-1})\tilde{A}(z^{-1}) + z^{-j}F_j \tag{34}$$

$$1 = E_{j+1}(z^{-1})\tilde{A}(z^{-1}) + z^{-(j+1)}F_{j+1} \tag{35}$$

Note that $\tilde{A}(z^{-1}) := \Delta A(z^{-1})$. Subtracting (34) from (35) gives:

$$0 = \tilde{A}(z^{-1})\{E_{j+1}(z^{-1}) - E_j(z^{-1})\} + z^{-j}\{z^{-1}F_{j+1} - F_j(z^{-1})\} \tag{36}$$

It is considered to rewrite a component of (36) as follows,

$$E_{j+1}(z^{-1}) - E_j(z^{-1}) = \tilde{E}(z^{-1}) + e_j^{j+1} z^{-j} \tag{37}$$

and substituting $E_{j+1}(z^{-1}) - E_j(z^{-1})$ from the above equation gives:

$$0 = \tilde{A}(z^{-1})\tilde{E}(z^{-1}) + z^{-j}(z^{-1}F_{j+1}(z^{-1}) - F_j(z^{-1}) + \tilde{A}(z^{-1})e_j^{j+1}) \tag{38}$$

so that, equations hold identical to the expression (38). Clearly then

$$\tilde{E}(z^{-1}) = 0 \tag{39}$$

$$z^{-1}F_{j+1}(z^{-1}) - F_j(z^{-1}) + \tilde{A}(z^{-1})e_j^{j+1} = 0 \tag{40}$$

and, to rearrange equation (40) as the following equation.

$$F_j(z^{-1}) = z^{-1}F_{j+1}(z^{-1}) + \tilde{A}(z^{-1})e_j^{j+1} \tag{41}$$

From (39) and (40), the following relationships can be obtained.

$$\left.\begin{aligned} e_j^{j+1} &= f_0^j \\ f_0^{j+1} &= f_1^j - \tilde{a}_1 f_0^j \\ f_1^{j+1} &= f_2^j - \tilde{a}_2 f_0^j \\ f_2^{j+1} &= -\tilde{a}_3 f_0^j \end{aligned}\right\} \tag{42}$$

Now the Diophantine equations for $j = 1$ gives:

$$\Delta A(z^{-1}) = 1 - z^{-1}F_1(z^{-1}) \tag{43}$$

From above equation, (42) can be rewritten as follows.

$$\left.\begin{aligned} e_j^{j+1} &= f_0^j \\ f_0^{j+1} &= f_1^j - f_0^1 f_0^j \\ f_1^{j+1} &= f_2^j - f_1^1 f_0^j \\ f_2^{j+1} &= -f_2^1 f_0^j \end{aligned}\right\} \tag{44}$$

Moreover, recall the equation (37) and equation (39) and the following equation is obtained.

$$E_{j+1}(z^{-1}) = E_j(z^{-1}) + z^{-j}e_j^{j+1} \tag{45}$$

And then $G_j(z^{-1})$ becomes,

$$G_{j+1}(z^{-1}) = \{E_j(z^{-1}) + z^{-j}e_j^{j+1}\}B(z^{-1}) \tag{46}$$

Here, in order to obtain the $S(z^{-1})$ and $R(z^{-1})$ from Diophantine equation (6), system parameter $B(z^{-1})$ is necessary, however, considering that $E_1(z^{-1}) = 1$,

$$G_1(z^{-1}) = E_1(z^{-1})B(z^{-1}) = B(z^{-1}) \tag{47}$$

Therefore, from the relationship between (46) and (47),

$$G_{j+1}(z^{-1}) = \{E_j(z^{-1}) + z^{-j}e_j^{j+1}\}G_1(z^{-1}) \tag{48}$$

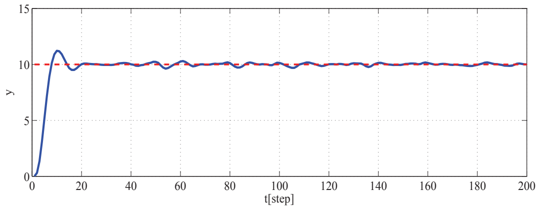


Fig. 1. Control result by the the fixed PID controller.

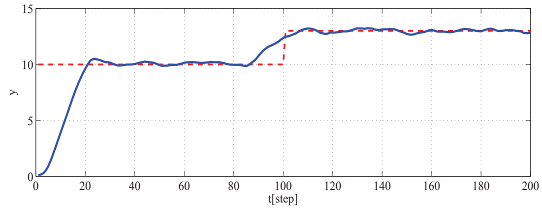


Fig. 2. Control result by the proposed method.

From the above, when the initial parameters $F_1(z^{-1})$ and $G_1(z^{-1})$ are known, subsequent parameters are obtained by solving the recursive formula in the multi-step prediction in GPC. In addition, the initial $F_1(z^{-1})$ and $G_1(z^{-1})$ are capable of computing based on the implicit method of GMVC. Please refer to references [7] for more information.

## IV. Simulation Example

To evaluate the effectiveness of the proposed method, it is applied to the following system which is a 4th-order system shown as equation (49) with the time-delay. Maximum overshoot is used as a quantitative criteria.

$$G(s) = \frac{12s+8}{20s^4+113s^3+147s^2+62s+8}e^{-10s} \tag{49}$$

After the discretization of the above equation by $T_s = 1[\mathrm{s}]$,the following equation is obtained. Moreover, in (50), $\xi(t)/\Delta$ is added as a modeling error, and $\sigma^2$ is set to $1.0\times10^{-5}$.

$$\begin{aligned} y(t) &= 1.835y(t-1) - 1.088y(t-2) + 0.211y(t-3) \\ &\quad -0.004y(t-4) + 0.036u(t-11) + 0.036u(t-12) \\ &\quad -0.024u(t-13) - 0.002u(t-14) + \xi(t)/\Delta \end{aligned} \tag{50}$$

In this paper, the control method is done by designing the control system to discretized equation (50). The control result is shown in Fig.1 by using Chien-Hrones-Reswich(CHR) method in which maximum overshoot is 15%. According to this strategy, PID parameters are as follows:

$$k_c = 0.338, \quad T_i = 6.12, \quad T_d = 5.38 \tag{51}$$

The control result shows that desired performance is obtained. However, a little long time is taken to reach the stability. Next the proposed method is applied by using I/O data from Fig. 1. The control result are shown in Figure 2 in which the design parameters are set as $m = 12, N = 15, \lambda = 90$. The maximum overshoot in this strategy is 0.36%. The PID parameters are shown as follows:

$$k_c = 0.0508, \quad T_i = 2.13, \quad T_d = 0.2486 \tag{52}$$

Although the settling time of the result by the proposed method is a little different from that by using CHR method which finds suppression of the overshoot. The reasons are considered that proportional gain becomes smaller due to the increase in stability of the the closed loop by introducing the prediction interval and $\lambda$ as well as the integral time becomes shorter to keep a quick response. Finally, to illustrate the superiority of the proposed method, another more research is needed. The Fig.3 shows the result with using designing method of PID controller based on GMVC ,say GMV-PID. When design parameters are set to $P(z^{-1}) = 1, m = 12, \lambda = 90$,the following PID parameters are calculated. And the maximum overshoot is about 29.6%.

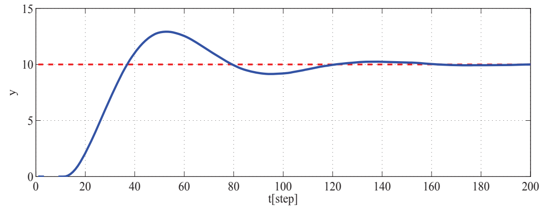


Fig. 3. Control result by the data-oriented GMV-PID controller.

$$k_c = 0.01, \quad T_i = 0.9043, \quad T_d = 0.5541 \tag{53}$$

And the result shows that the overshoot exists highly when the parameters are set as the same with previous one. In GMV-PID control system, the control input is determined just only based on the predicted value of the time-delay ahead. Whereas the calculation with respect to the control action in GPC-PID proceeds with much more steps. Therefore, the result with GMV-PID is liable to become oscillatory than that with GPC-PID. In other words, the GPC-PID designs are conservation so that the control results are better than GMV-PID.

## V. Experimental Application

Experimental studies were carried out in a temperature control system. The figure and schematic diagram of the process system is shown in Fig. 4 and Fig. 5, receptively .

The system consists of a tank with 65 *cm* high with an inside diameter of 30 *cm*. Hot water, which is heated by the boiler beforehand, enters the tank. And the water leaving the tank passes through the pipe with 3 thermocouples placed along its length. The temperatures are measured and are displayed as Temp.1, Temp.2 and Temp.3. The Temp.2 is considered as the output variable. The computer performs the control calculation after inputting the signal using A/D and D/A conversions.

The values of the temperature are as the initial value of estimation of the system. Moreover, CHR method is applied considering the stability of the system when the system parameters are identified.

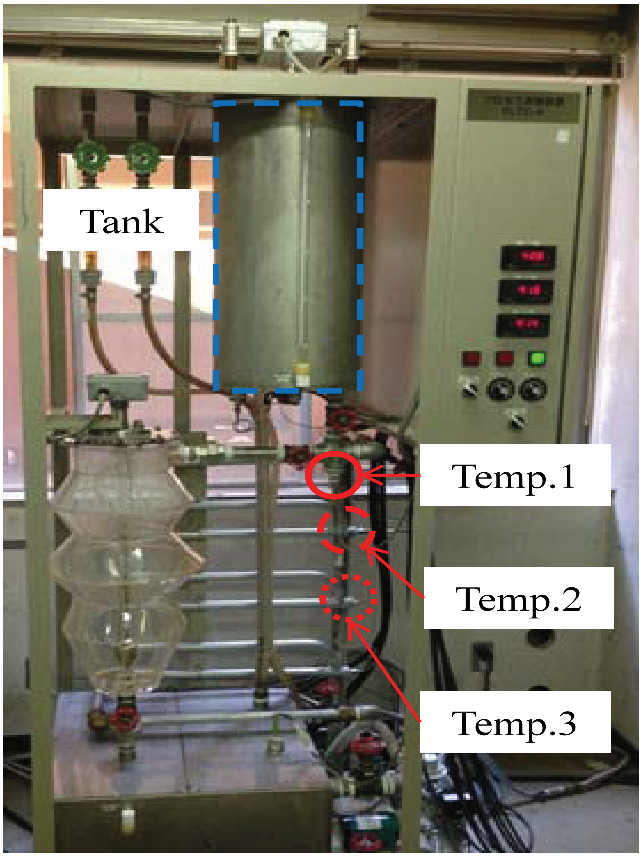


Fig. 4. Photo of the temperature control system.

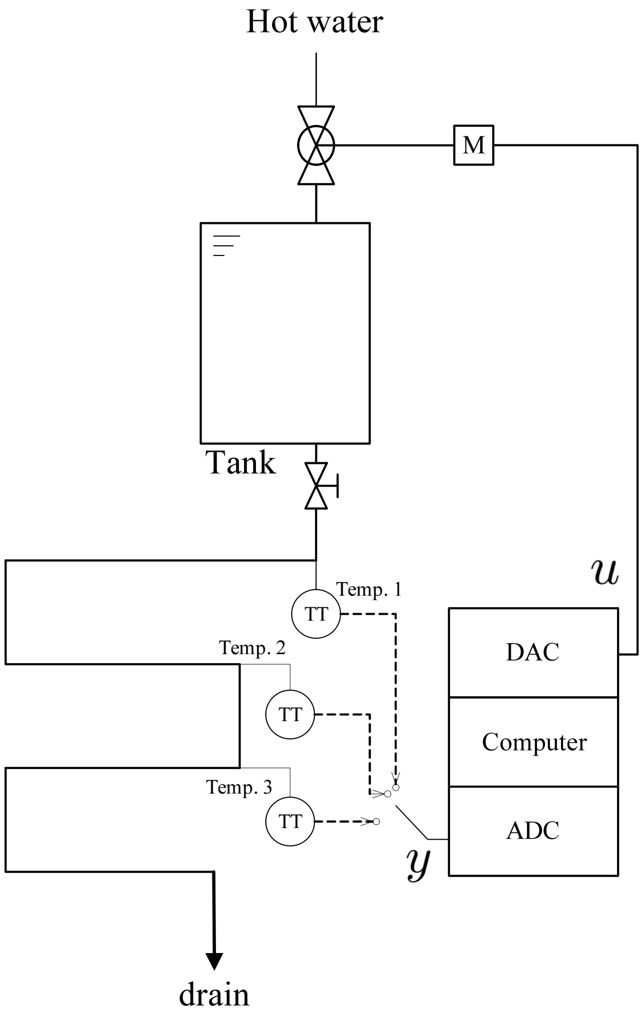


Fig. 5. Schematic diagram of the temperature control system.

Additionally, the control system is constructed as a digital control system, thus the form of digital control law is displayed below.

$$u(k) = u(k-1)+K_I e(k)-K_P\{y(k)-y(k-1)\} -K_D\{y(k)-2y(k-1)+y(k-2)\}, \quad (54)$$

$$e(k) := w(k)-y(k). \quad (55)$$

where, $k$ is a number of step, $w(k)$ and $y(k)$ indicate the reference value and the controlled value, respectively. Therefore, PID gains $K_P$,$K_I$ and $K_D$ are defined as follows:

$$K_P = k_c, \quad K_I = k_c T_s/T_I, \quad K_D = k_c T_D/T_s \quad (56)$$

where, $T_s$, the sampling time, is set as $T_s = 5[s]$ in this experiment. Consider the first order system with time-delay as the controlled object. As a result of the step response, the system parameters are estimated. Meanwhile, the PID parameters can be obtained. The system parameters are shown as follows:

$$K = 0.5121, \quad T = 99.9854[s], \quad L = 22.3040[s] \quad (57)$$

After doing the previous step, the closed-loop data is obtained by applying the CHR method whose parameters are shown as following.

$$k_c = 5.2525, \quad T_i = 0.2627, \quad T_d = 11.7152 \quad (58)$$

Since the closed loop data which is from Fig.6 has already been obtained, and with the least square method, the initial value $F_1$ and $G_1$ are identified which means the key point of the proposed method. After identification, the proposed method in which the prediction horizons are set to constant values of 1 and 15 is employed. The parameter $\lambda$ equals to 45. Fig.7 gives you the result. The manipulated variable is stable. According to the method, PID parameters are calculated as following:

$$k_c = 0.1617, \quad T_i = 34.3281, \quad T_d = 0.4001 \quad (59)$$

The user-specified parameter $\lambda$ plays an important role in the experiment. Therefore, in the experiment, the different value of $\lambda$ is applied. Figure 8 shows the result by setting $\lambda = 15$. Compared with both two results, the overshoot exists when the $\lambda$ is set as a smaller value. The reason is the manipulated variable will take action towards avoiding the overshoot. That leads to obvious variations shown in Fig.8.

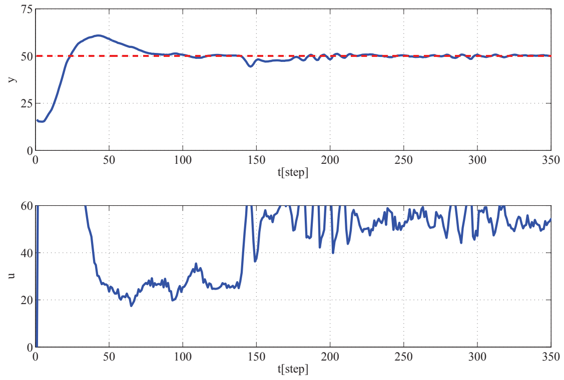


Fig. 6. Control result by the CHR method

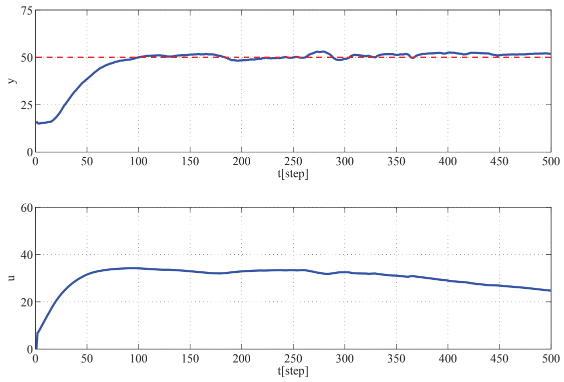


Fig. 7. Control result by the proposed method($\lambda = 45$)

## VI. Conclusions

In this paper, the design method of a data-oriented PID control system based on Generalized Predictive Control is considered. According to the proposed method, by using a set of closed loop data, the initial parameters of the Diophantine equation is identified, and multi-step output signals are obtained by solving a recursive formula. Those have broken the limitations of having prior knowledge of model. Moreover, the effectiveness of this method is verified by an numerical example as well as experimental result. In the simulation, it is confirmed that a desired control result can be obtained using the proposed method even if an initial closed loop data is not satisfactory. By comparing the conventional data-oriented GMV-PID control, the proposed method can obtain better control result when the time-delay is large or can not be estimated accurately. In the experiment, the PID gains obtained from the proposed method are applied to the temperature equipment, as shown in the paper, the control result is desirable. Through the comparison with different value of $\lambda$ , the stability of the systems is different.

In the future work, more experiments will be performed with various methods so as to compare with the proposed method. How to decide the value of $\lambda$ will become an

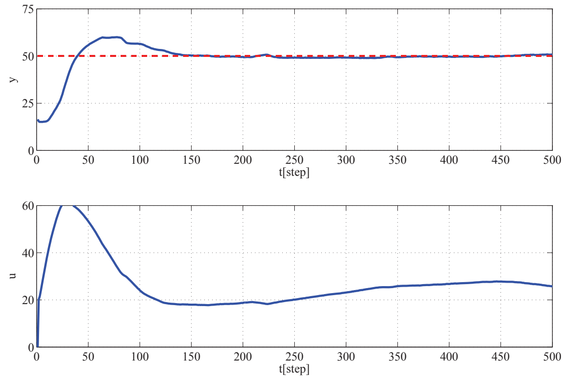


Fig. 8. Control result by the proposed method($\lambda = 15$)

important topic. And the proposed method will be extended to the MIMO system and be evaluated in the simulation. Furthermore, applying the extended proposed method to the experiment will be more important work.

## References

[1] M.Ramasamy, S.Sundaramoorthy:"PID control tuning for desired closed-loop responses for SISO systems using impulse response", Computers and Chemical Engineering 32,1773–1788(2008).
[2] J.G.Zieglar and N.B.Nichols:"Optimum settings for automatic controllers",Trans. ASME, Vol.64,No.8,pp.759–768(1942).
[3] K.L.Chien, J.A.Hrones, and J.B.Reswick:"On the Automatic Control of Generalized Passive Systems",Trans. ASME,Vol.74,pp.175–185(1972).
[4] K.K.Tan, T.H.Lee, S.N.Huang, and F.M.Leu:"PID Control Design Based on a GPC Approach", Ind.Eng.Chem.Res.2002,41(2013-2022).
[5] M.C.Campi:"Virtual reference feedback tuning (VRFT) : A direct method for the design of feedback controllers", Automatica,Vol.38,No.8, pp.1337–1346(2002).
[6] S.Soma,O.Kaneko and T.Fujii:"A New Approach to Parameter Tuning of Controllers by Using One-Shot Experimental Data : A Proposal of Fictitious Reference Iterative Tuning" Trans. Institute of Systems Control and Information Engineers,Vol.17,No.12,pp.528-536(2004).
[7] S.Wakitani, K.Hosokawa and T.Yamamoto:"Design of an Implicit GMV-PID Controller Using Closed Loop Data", EEJ Transactions on Electronics, Information and Systems,Vol.132,No.6, pp.873-878(2012).
[8] D.W.clarke, C.Mohtadi and P.S.Tuffs:"Generalized Predictive Control - Part I. The Basis Algorithm", Automatica, Vol.23, No.2, pp.137–148(1987).
[9] S.Wakitani, Y.B.Zhao and T.Yamamoto:"Design of a Partial Model Matching based PID Controller for a Temperature Control System", Proc. the 2013 International Conference on Advanced Mechatronic Systems, pp.559-564(2013).
[10] Z.Guan, S.Wakitani, and T.Yamamoto:"Design of a Data-Oriented GPC", Proc. the 2013 International Conference on Advanced Mechatronic Systems, pp.555-558(2013).
[11] S,Masuda, T.Yamamoto and M.Ohshima:"Model Predictive Control-III : Generalized Predictive Control (GPC) and the Relevant Topics", Trans. Institute of Systems Control and Information Engineers, Vol.46, No.9,pp.578-584(2002).
[12] D.W.Clarke and P.J.Gawthrop:"Self-Tuning Control", Proc.IEE, 126D-6,pp.633–640(1979).
[13] David S. Shok, Coorous Mohtadi, and Sirish L. Shah:"Special Issue Technical Notes : A control-Relevant Identification Strategy for GPC", IEEE Transactions on Automatic Control, Vol.37, No.7,pp.975–979(1992).