A Systematic Gain Tuning of PID Controller Based on the Concept of Time Delay Control

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In this paper, through the study of discrete implementation of time delay control (TDC) and PID control algorithm, a new systematic gain selection method for PID controller is proposed. An important advantage of this method is that it may be applied to real systems with very simple and systematic procedure. The proposed method is derived for SISO systems and then extended to MIMO system. Through simulation for the second order non-linear plant and experiment on 2-DOF robot, the effectiveness of the proposed method is confirmed. The proposed method could solve the problem of difficulty in gain tuning of existing PID controller.

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1. Introduction

PID controllers are found in large numbers in nearly all industrial applications.[1,2] For the systems where the dominant dynamics are of the second order, the PID controller or minor variation of it controls most systems. PID controllers are implemented in different forms and are widely known for their effectiveness, simplicity, and applicability. The PID control algorithm has been approached from many different points of view. It can be viewed as a device which can be operated with a few rules of thumb, and it can also be approached analytically.[1-7] Moreover, related research areas include anti-windup schemes for saturation windup, and discretization and pre-filtering schemes for digital implementation.[1]

In order to get a satisfied performance from a PID controller, the parameters of the PID controller must be suitably tuned. In literature, there exist several different methods to select the parameters of the PID controller.[1-5] These methods differ mainly with respect to the knowledge of the plant dynamics they require. In the classical Ziegler-Nichols methods, the dynamics are characterized by two parameters. In the step response method, they are taken from the open loop step response. In the frequency response methods, the parameters are the frequency and gain where the open loop dynamics have a phase shift of 180 degrees. Another way to obtain a characterization of plant dynamics with few parameters is to use the approximated first or second order plant model. These methods include the dominant pole design method and the closed loop pole placement method.

PID controllers are designed based on on-quarter decay ration using Ziegler-Nichols method and several others. Hence, overshoot is obviously expected of those controllers. This unexpected phenomenon is due to the effects of the uncertainties in the plant model or the non-optimality in the selected controller parameters. Furthermore, for the above methods to be successful in real implementation, some tuning procedures with trials and errors are required for the optimal performance. From our experiences on real applications, these tuning procedures are very time-consuming and require significant costs. Especially in the case of MIMO plants, since there are larger number of parameters, the overall tuning of parameters can be more complex.

The time delay control (TDC) has been proposed as a robust control algorithm for nonlinear plants.[8-12] By using the time-delayed informations (the values of control input and derivatives of state variables at the previous step), TDC estimates both the plant dynamics and the uncertainties. Therefore, the resulting TDC can be designed without an exact knowledge of the plant model. In addition, the TDC, which has a similar structure with a disturbance observer,[13] has been shown to give robust control performances against unmodeled nonlinear dynamics and unexpected disturbances.

Through the study of discrete implementation of TDC and PID control algorithm, it is found that the two control systems have the same structure. There are differences in the basic concept of the controller and the procedure in selecting parameters. Motivated by this finding, in this paper, a new systematic gain selection method for the PID controller is proposed. The method is based on the concept of the TDC. By the proposed gain tuning method, the conventional PID controller can be visualized in another different angle. In other words, the characteristics of the PID control system can be analyzed in terms of the TDC theory. An important advantage of this method over other method previously suggested is that it may be applied to real systems with very simple and systematic procedure, and thereby it can solve the problems of difficulties in the tuning of PID parameters.

In the following section, the discrete PID and TDC controllers will be derived, and their similarity and differences will be investigated. In Section 3, after reviewing the known gain selection methods for PID controller, the new gain selection method using the concept of TDC will be proposed for SISO systems. In Section 4, the proposed method will be extended to MIMO systems. Section 5 will present the simulation results and Section 6 will present the experimental results, followed by the conclusion in Section 7.

2. Discrete PID Controller and Discrete TDC Law

In this section, we will briefly review two controllers – the discrete PID controller and the discrete TDC controller; after which, the similarities and differences will be investigated. The plant considered is the following second order nonlinear plant.

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}) + \mathbf{B}(\mathbf{x})u \\ y &= \mathbf{C}\mathbf{x} \end{aligned} \tag{1}$$

where $\mathbf{x} \in \Re^2$, $y \in \Re^1$, and $u \in \Re^1$ denote the state vector, the plant output, and the plant input, respectively. Here, $\mathbf{f}(\mathbf{x})$ is the nonlinear function, $\mathbf{B}(\mathbf{x})$ the nonlinear input distribution vector, and $\mathbf{C}$ the output distribution matrix.

For the design of PID controller, we assume that the dominant dynamics of (1) are of the following second order linear system.

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= p_1 x_1 + p_2 x_2 + bu \\ y &= x_1 \end{aligned} \tag{2}$$

where x_1 and x_2 denote state variables in phase variable form, respectively, and p_1, p_2, and b are the parameters of the system.

2.1 Discrete PID controller

While there are no industrial or scientific standards for PID configurations, the widely used PID controller has the following form in continuous time.

$$u(s) = K\left\{ r(s) - y(s) - T_D s y(s) + \frac{r(s) - y(s)}{T_I s} \right\} \tag{3}$$

where $u(s), y(s)$, and $r(s)$ denote the Laplace transforms of the input, the output, and the reference commands, respectively. Here K, T_D, and T_I are the parameters of feedback loop gain, derivative time, and integral time, respectively.

When one implements the continuous PID controller in the domain of discrete time, there exist various forms of the digital controller with respect to discretization methods.[2,4] If we use simple Euler approximation method, the PID controller is represented as the following equation in discrete time.

$$\begin{aligned} u(k) = u(k-1) + K\Big\{ &\big(r(k) - r(k-1)\big) - \big(y(k) - y(k-1)\big) + \frac{T_s}{T_I} e(k) \\ &+ \frac{T_D}{T_s}\big(y(k) - 2y(k-1) + y(k-2)\big) \Big\} \end{aligned} \tag{4}$$

where $e(k) = r(k) - y(k)$, and T_s stands for the discrete sampling time.

2.2 Discrete TDC controller

The first step in the TDC design is to select a reference model such that the plant, (1), exhibits desirable linear behavior. In the context of model reference control, let the desired performances be specified by means of a stable linear invariant reference model as

$$\begin{aligned} \dot{\mathbf{x}}_m &= \begin{bmatrix} 0 & 1 \\ -K_P & -K_V \end{bmatrix} \mathbf{x}_m + \begin{bmatrix} 0 \\ K_P \end{bmatrix} r \\ y_m &= \begin{bmatrix} 1 & 0 \end{bmatrix} \mathbf{x}_m \end{aligned} \tag{5}$$

where $\mathbf{x}_m \in \Re^2$ denotes the state vector of the reference model, $r \in \Re^1$ the command vector, and K_P, and K_V the parameters of reference dynamics. For the nonlinear plant (1) to follow the linear stable dynamics (5), TDC uses an efficient estimation method called time delay estimation, which estimates both unknown plant dynamics and plant uncertainties.[8,9] Through this efficient estimation, the resulting TDC can be represented as

$$u(t) = u(t-L) + \frac{1}{\hat{b}}\left[-\dot{x}_2(t-L) - K_P x_1 - K_V x_2 + K_P r \right] \tag{6}$$

where L stands for the sufficiently small time delay, and $\hat{b}$ denotes the constant value that is determined in the range of $\mathbf{B}(\mathbf{x})$; the criterion of determining $\hat{b}$ and L is described in Hsia and Gao (1990)[8] and Youcef-Toumi and Ito (1990).[9]

When implementing the TDC of (6) in discrete time domain, there exist various forms of controllers with respect to the methods of discretizing $\dot{x}_2(t-L)$. If we use the Euler approximation with setting the time delay L to be the sampling time of digital implementation, T_s, then the resulting discrete TDC can be derived as the following form:

$$\begin{aligned} u(k) = u(k-1) + \frac{1}{\hat{b}}\Bigg\{ &K_P e(k) - K_V \frac{\big(y(k) - y(k-1)\big)}{T_s} \\ &- \frac{\big(y(k) - 2y(k-1) + y(k-2)\big)}{T_s^2} \Bigg\} \end{aligned} \tag{7}$$

2.3 Comparison of Two Controllers

As shown in (4) and (7), discrete TDC and PID controller have the same structure in regulation problem ($r(k) = r(k-1)$). There are differences in the physical meaning and selection methods of the two controller parameters. If one compare (4) and (7), term by term, one can easily find the relation between the parameters in two controllers. The relation of parameters between the PID and TDC controllers is listed in Table 1. This relation can give an insight to each controller designers. In other words, the designers for TDC can visualize and analyze TDC algorithm in terms of PID, and the designers for PID controller vise versa.

In the case of TDC, the parameters to be determined are $K_P, K_V, \hat{b}$, and L . Among these parameters, the values of K_P and K_V are usually pre-determined by the desired output dynamics; they are determined by such conditions as rise time, overshoot, damping, natural frequency, and so on. Accordingly, the remaining parameters to be selected are $\hat{b}$, and L . Following the guideline of parameters selection of TDC in Hsia and Gao (1990)[8] and Youcef-Toumi and Ito (1990),[9] $\hat{b}$ can be chosen in the range of $\mathbf{B}(\mathbf{x})$ with the condition of a closed loop stability and the time delay L by a sufficiently small value and considering the desired closed loop bandwidth. Since an excessive small L makes worse the performance of sensitivity to measurement noise, one must select proper L to compromise the robustness against plant uncertainty and the sensitivity to measurement noise.

Table 1 The relation between PID and TDC parameters

PID parameters	TDC parameters
K	$\frac{K_V}{\hat{b}L}$
T_D	$\frac{1}{K_V}$
T_I	$\frac{K_V}{K_P}$

3. Design of PID controllers Using the Concept of TDC

Based on the results of the previous section, this section presents a new selection method of PID parameters using the concept of TDC. After briefly reviewing of known design methods of PID controllers, we will present the proposed method.

3.1 Known Design Methods of PID Controllers

The design methods of PID controllers differ by the required information of the plant model. These methods can be divided mainly into two categories; the first includes the methods using the frequency response or step response of the plant, the second includes those using first or second order approximated plant model. The former methods include widely used Ziegler-Nichols(1990)[3] methods, and the latter includes dominant pole design method, pole placement method, and direct pole placement with cancellation methods.

In the position or velocity control of servo systems, the gains of the PID controller have to be tuned so that the response satisfies some pre-assigned constraints on rise time, damping, overshoot, and natural frequency. In addition, sensitivity to external disturbance has to be minimized without violating these requirements. However, in real application, the designed PID controllers do not always give the satisfied control performance. One of the difficulties is the unpredictable influence of unmodeled plant behavior, such as saturation, Coulomb friction, and higher order dynamics. Furthermore, several gain tuning procedures are required for optimal behavior. Often, these procedures appear to involve significant time and excessive cost. Especially, in MIMO systems, the difficulties may be larger.

3.2 Design of PID controllers Using the Concept of TDC

By comparing the parameters listed in Table 1, the parameters of PID controller can be selected by the following procedure using the concept of TDC.

1. Choose the desired dynamics of closed loop system; for example, let the desired natural frequency be ω_n and the desired damping ratio ζ ($K_P = \omega_n^2, K_V = 2\zeta\omega_n$).
2. Using the parameters' relation between PID controller and TDC controller, select T_I and T_D as

$$T_D = \frac{1}{2\zeta\omega_n}, T_I = \frac{2\zeta}{\omega_n} \tag{8}$$

3. Select the sampling time of the controller by a rule of thumb as

$$T_s = \frac{1}{\omega_n}(1/5 \sim 1/100) \tag{9}$$

4. From the results of Hsia and Gao,[8] and Youicef-Toumi and Ito,[9] select the value of $\hat{b}$ from this relation.[1)]

$$\hat{b} > 1/2b \tag{10}$$

5. Using the parameters' relation between PID controller and TDC controller, select K as

$$K = \frac{2\zeta\omega_n}{\hat{b}T_s} \tag{11}$$

6. Finally, if needed, tune the value of $\hat{b}$ more finely.

3.3 Characteristics of Proposed PID Structure

In order to investigate the characteristics of the proposed parameter selection method, consider a n-th order linear plant of the following form.

$$G(s) := \frac{y(s)}{u(s)} = \frac{K_M}{(1+s\tau_1)\cdots(1+s\tau_n)} = \frac{K_M}{C(s)} \tag{12}$$

Applying the proposed PID controller into (12), the closed loop input output transfer function can be represented as follows (Fig. 1).

$$F_1(s) := \frac{y(s)}{r(s)} = \frac{1}{\frac{\hat{b}L}{K_M}C(s) + (s^2 + K_V s + K_P)} \tag{13}$$

In addition, the output transfer function with respect to the disturbance $d(s)$ can be represented as

$$F_2(s) := \frac{y(s)}{d(s)} = \frac{\hat{b}Ls}{\frac{\hat{b}L}{K_M}C(s) + (s^2 + K_V s + K_P)} \tag{14}$$

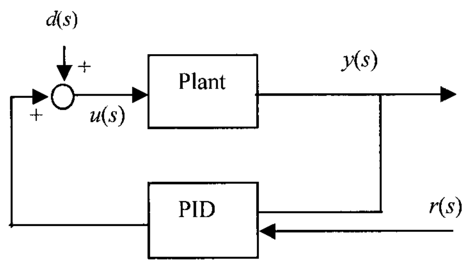

Fig. 1 Feedback System

If the desired closed loop dynamics is the critical damped system with the natural frequency of ω_n and with setting $\hat{b} = K_M$, then the values of K_V and K_P are $K_V = 2\omega_n$ and $K_P = \omega_n^2$. From these, (13) and (14) become to $F_1(s) = \frac{1}{(s+\omega_n)^2 + \Delta_1(s)}$ and $F_2(s) = \frac{\Delta_2(s)}{(s+\omega_n)^2 + \Delta_1(s)}$, respectively. Furthermore, $\Delta_1(s)$ and $\Delta_2(s)$ have a value close to zero as the time delay L becomes sufficiently small, thereby $F_1(s)$ and $F_2(s)$ are approximated by

$$F_1(s) \approx \frac{1}{(s+\omega_n)^2} \tag{15}$$

$$F_2(s) \approx \frac{0}{(s+\omega_n)^2} \tag{16}$$

In other words, by selecting the time delay L to be sufficiently small, one can obtain a response that the output follows the desired response well and does not affected by the external disturbance. However, excessively small value of L can make the performance of sensitivity to measurement noise worse. Therefore a careful tuning of L is required for a good compromise between robustness and sensitivity.

From now, we will investigate the feature of closed loop pole due to the variations of $\hat{b}$. Firstly, for a simple second order plant, $1/s^2$, we select gains, ζ, ω_n, and L by using the procedure of Section 3.2. With the fixed ζ, ω_n, and L, we make variations on $\hat{b}$. This is the same case with that K is varied with the fixed T_I, T_D, and T_S in the PID controller. The root locus in this case is plotted in Fig. 2 where the points by ∘ represent the desired closed loop poles. Shown in the Figure, as $\hat{b}$ gets smaller, the closed loop

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[1)] This result comes from the stability analysis of TDC. The larger values of $\hat{b}$ increases the stability margin, but decreases control performance.

poles go to desired poles. Therefore sufficiently small $\hat{b}$ can makes the closed loop dynamics to desired one. In contrast, as $\hat{b}$ gets larger, the damping of the complex poles in the closed loop system becomes smaller, thereby a little oscillation or overshoot may appear in the response.

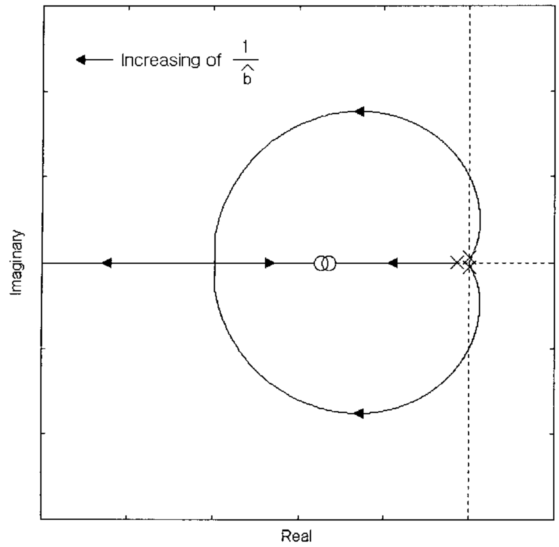


Fig. 2 Root locus of PID closed loop system

4. MIMO Design

This section extends the proposed gain selection method of Section 3 to MIMO plant having n inputs and n outputs. In general, since there exist inter-connections between each loop, the gain tuning problem is more complex and time-consuming than the SISO cases. For this plant, the number of parameters to be determined is $3n^2$ for full matrix PID controller, and $3n$ for decentralized PID controller.

For the analysis, considered MIMO plant can be approximated to the following $2n$-th order linear system.

$$\dot{\mathbf{x}} = \begin{bmatrix} \mathbf{0}_n & \mathbf{I}_n \\ & \mathbf{P} \end{bmatrix}\mathbf{x} + \begin{bmatrix} \mathbf{0} \\ \mathbf{B} \end{bmatrix}\mathbf{u} \qquad (17)$$
$$\mathbf{y} = \mathbf{C}\mathbf{x}$$

where $\mathbf{0}_n$ denotes n dimensional zero matrix, $\mathbf{I}_n$ n dimensional identity matrix, and

$$\mathbf{P} = \begin{bmatrix} p_{(1,1)} & \cdots & p_{(2n,1)} \\ \vdots & \ddots & \vdots \\ p_{(1,n)} & \cdots & p_{(2n,n)} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} b_{(1,1)} & \cdots & b_{(n,1)} \\ \vdots & \ddots & \vdots \\ b_{(1,n)} & \cdots & b_{(n,n)} \end{bmatrix}, \mathbf{C} = [\mathbf{I}_n \quad \mathbf{0}_n]$$

For the plant (17), let the desired performances be specified with the response of a stable linear time invariant model as

$$\dot{\mathbf{x}}_m = \begin{bmatrix} \mathbf{0}_n & \mathbf{I}_n \\ & \mathbf{A}_{mr} \end{bmatrix}\mathbf{x}_m + \begin{bmatrix} \mathbf{0}_n \\ \mathbf{B}_{mr} \end{bmatrix}\mathbf{r} \qquad (18)$$

where $\mathbf{x}_m \in \Re^{2n}$ denotes the state vector of the reference model, $\mathbf{r} \in \Re^n$ the command vector, $\mathbf{A}_{mr}$ the system matrix, and $\mathbf{B}_{mr}$ the command distribution vector. Here, $\mathbf{A}_{mr}$ and $\mathbf{B}_{mr}$ have the following elements from the desired dynamics.

$$\mathbf{A}_{mr} = [-\mathbf{K}_P \quad -\mathbf{K}_V], \mathbf{B}_{mr} = \mathbf{K}_P$$

with $\mathbf{K}_P = diag[K_{P1}, \cdots, K_{Pn}], \mathbf{K}_V = diag[K_{V1}, \cdots, K_{Vn}]$

Following the results in [5, 6], then the following control input

$$\mathbf{u} = \begin{bmatrix} u_1(t-L) \\ \vdots \\ u_n(t-L) \end{bmatrix} + \hat{\mathbf{B}}^{-1} \begin{bmatrix} \dot{x}_{n+1}(t-L) - K_{P1}x_1 - K_{V1}x_{n+1} + K_{P1}r_1 \\ \vdots \\ \dot{x}_{2n}(t-L) - K_{Pn}x_n - K_{Vn}x_{2n} + K_{Pn}r_n \end{bmatrix} \qquad (19)$$

makes the plant dynamics, (17) follows the reference model, (18), where $\hat{\mathbf{B}} = diag(\hat{b}_1, \cdots, \hat{b}_n)$ is $n \times n$ dimensional diagonal matrix. $\mathbf{B(x)}$ must be selected by the following condition.[6,7]

$$\left\| \mathbf{I} - \mathbf{B(x)}\hat{\mathbf{B}}^{-1} \right\| < 1 \qquad (20)$$

If the controller in (19) is discretized by Euler approximation, the resulting controller is the same structure with the following n-th order decentralized PID controller.

$$\mathbf{u}(s) = \begin{bmatrix} K_1 \left[r_1(s) - y_1(s) - T_{D1}sy_1(s) + \dfrac{r_1(s) - y_1(s)}{T_{I1}s} \right] \\ \vdots \\ K_n \left[r_n(s) - y_n(s) - T_{Dn}sy_n(s) + \dfrac{r_n(s) - y_n(s)}{T_{In}s} \right] \end{bmatrix} \qquad (21)$$

By using the previous results of PID controller gain tuning to (19) and (21), the gain selection methods for MIMO PID controller can be summarized as follows: 1) From the desired response of the i-th output, select the parameters, T_{Ii} and T_{Di}; 2) Based on the stable range of $\hat{\mathbf{B}}$, select K_i. Although the plant is MIMO, the resulting procedure is very simple and systematic.

5. Simulation

In order to demonstrate the effectiveness of the proposed gain selection method of PID controller, a fourth order linear system is simulated. The system is written below,

$$G(s) = \frac{1}{(1+s)(1+0.2s)(1+0.05s)(1+0.01s)} \qquad (22)$$

As mentioned earlier, Ziegler-Nichols method uses one-quarter decay ratio as the performance criterion for designing PID controllers and therefore it is not fair to compare the TDC controller which is based on a reference model for the desired response. It is noted that a critically damped response is chosen here as the desired response. Instead, it is suggested to use direct synthesis controllers designed for the same desired response.

The designed parameters by well known methods are listed in Table 2, and the procedures are discussed in depth in Ziegler and Nichols.[3] Then, the control performances when the unit step input is applied are tested.

Table 2 Selected PID parameters

Method	K	T_I	T_D
Ziegler-Nichols Step	10.9	0.32	0.08
Ziegler-Nichols Freq	15.0	0.31	0.08
Dominant pole design	11.9	0.45	0.12
Pole Placement	12.0	0.37	0.11

Fig. 3 shows the simulation results when the parameters in Table 2 are used. As shown in Fig. 3, the responses of Ziegler-Nichols methods have a relatively larger overshoot and smaller damping. These unsatisfactory responses can be analyzed by visualizing the PID gains in terms of TDC gains. If we change the selected gain by Ziegler-Nichols method into matched TDC gains using the relation in

Table 1, the matched TDC gain, K_P, K_V, and $\hat{b}$ can be the values of the following; $K_P = 36.1$, $K_V = 12.2$, and $\hat{b} = 600$ with $L = 0.002$ (critical damping system with a natural frequency of 6.1). However, since the matched $\hat{b} = 600$ is too large, the responses are largely deviated from the desired responses. In the pole placement method and dominant pole design method, even though the responses of the two methods have a smaller overshoot than Ziegler-Nichols method, the performances do not follow the desired one which does not have an overshoot.

In order to test the performance of proposed design method, the simulation was performed by setting $L = 0.002$, $\omega_n = 5.0$, and $\zeta = 1.0$ according to the variation of $\hat{b}$. It is seen that $\hat{b}$<30, the response is becoming unstable whereas when $\hat{b}$>600, there is an overshoot. If $\hat{b}$ is adequately selected ($40 < \hat{b} < 300$), the responses follows desired one pretty well without overshoot.

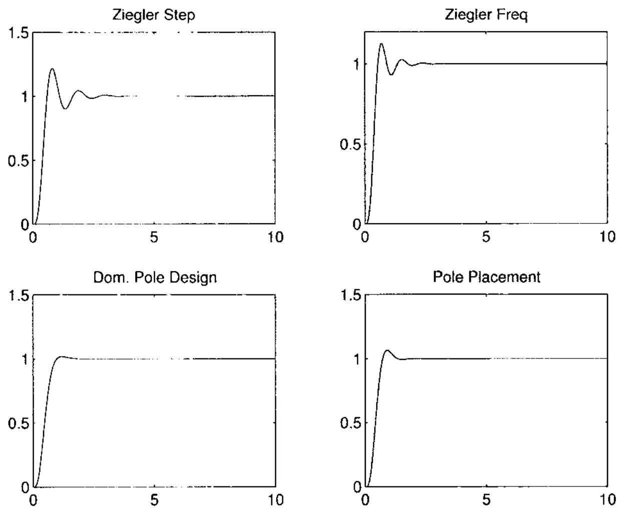


Fig. 3 Responses of well known PID gain selection methods

6. Experiments

In order to test performances of the proposed method to a real system, the proposed method is applied to the position control of two degree of freedoms SCARA robot. This system is categorized into a MIMO plant having two inputs and two outputs. Thus, MIMO design method is required for the controller design. In this experiment, MIMO PID controller is designed based on the concept of MIMO TDC.

The experimental system consists of the following components: Each joint of the joint, driven by through harmonic drives with reduction ratio of 100:1 for joint 1 and 80:1 for joint 2, has a resolver with a resolution of 4096 pulses/rev for position measurement. For link 1 and 2, the lengths are $l_1 = 35cm$ and $l_2 = 20cm$, the masses are $m_1 = 11.17kg$ and $m_2 = 6.82kg$, the moments of inertia are $I_1 = 1.03kgm^2$ and $I_2 = 0.224kgm^2$, and the distances from joints to the center of mass are $L_1 = 30cm$ and $L_1 = 28cm$, respectively. For this robot, an accurate dynamic model is available.[14] The digital implementation of the controller was made with the sampling frequency 200Hz in a multiprocessor based system called CONDOR.[15]

For link 1 and 2, the natural frequencies and damping ratios of desired response are set to be $\omega_{n1} = \omega_{n2} = 10.0$ and $\zeta_1 = \zeta_2 = 1.0$. Then, we make experiments varying the value of $\hat{\mathbf{B}}$. In addition, in order to check the robustness of the proposed method, the experiments are performed when the payload is increased to 10 *kg* payload.

Fig. 5 and Fig. 6 show the responses of proposed methods. As shown the figures, when the values of $\hat{\mathbf{B}}$ is larger than $\hat{b} = diag(1.7\times10^3, 3.3\times10^3)$, the control performances with the proposed method reveals more overshoot and oscillatory responses than the pre-determined desired response. In addition, as the payload is increased to 10*kg*, the deviations of responses are large. In contrast, as for well tuned $\hat{\mathbf{B}} = diag(1.7\times10^3, 3.3\times10^3)$, the control performances of the proposed method follow the desired responses well in both case without payload and with 10 *kg* payload, thereby demonstrating the robustness of the proposed methods to the payload variation.

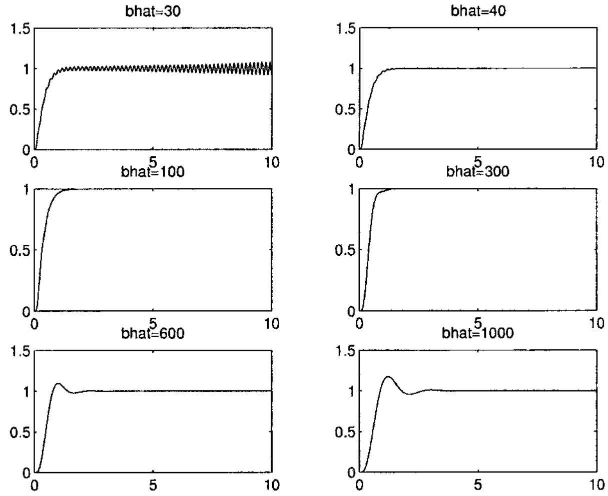
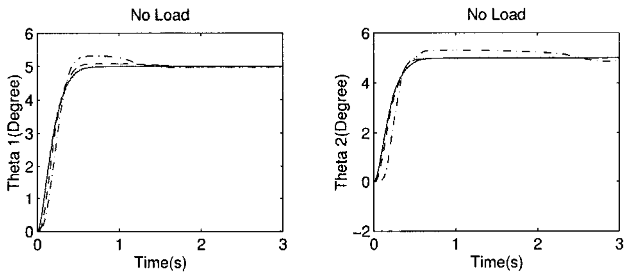
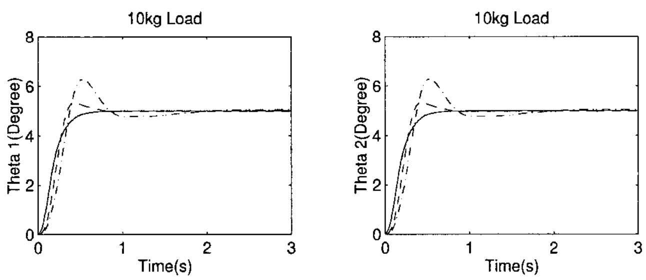


Fig. 4 Responses of proposed gain selection method



-.-.-: $\hat{\mathbf{B}} = diag(10\times10^3, 20\times10^3)$
-----: $\hat{\mathbf{B}} = diag(5\times10^3, 6.6\times10^3)$
_____: $\hat{\mathbf{B}} = diag(1.7\times10^3, 3.3\times10^3)$

Fig. 5 Experimental results of robot manipulator without payload



-.-.-: $\hat{\mathbf{B}} = diag(10\times10^3, 20\times10^3)$
-----: $\hat{\mathbf{B}} = diag(5\times10^3, 6.6\times10^3)$
_____: $\hat{\mathbf{B}} = diag(1.7\times10^3, 3.3\times10^3)$

Fig. 6 Experimental results of robot manipulator with 10 *kg* payload

7. Conclusion

Based on the study of discrete PID controller and discrete TDC, this paper proposed a new design method for PID controller using the concept of TDC. The proposed method makes it possible to understand the conventional PID controller newly with the concept of TDC. By the proposed method, one can design the PID controller which makes the plant follow the pre-designed desired response well in the face of modeling error and uncertainty in plant dynamics. Furthermore, the proposed method is so simple and systematic that it can solve some difficulties in the gain tuning of conventional PID controller.

Simulation results on fourth order linear SISO system verify that the proposed method is an effective and simple way to select the gains. From the experiment on a robot position control, we have shown that the proposed method may be effectively used in a real control system.

REFERENCES

1. Astrom, K. J. and Hagglund, T., "Automatic tuning of PID controllers," Instrument Society of America, 1988.
2. Franklin, G. F., Powell, J. D. and Naeini, A. E., "Feedback control of dynamic systems," MA: Addison-Wesley, 1986.
3. Ziegler, J. G. and Nichols, N. B., "Optimum setting for automatic controllers," Transactions of ASME, Vol. 64, pp. 759-768, 1942.
4. De Santis, R. M., "A novel PID configuration for speed and position control," ASME J. Dynamic Systems Measurement and Control, Vol. 116, No. 3, pp. 542-549, 1994.
5. Madhuranthakam, C. R., Elkamel, A. and Budman, H. "Optimal tuning of PID controllers for FOPTD, SOPTD and SOPTD with lead processes," Chemical Engineering and Processing: Process Intensification, Vol. 47, No. 2, pp. 251-264, 2008.
6. Kim, Y. S., Kim, G. M., Roh, C. H. and Fuller, C. R., "A Hybrid Control Development to Suppress the Noise in the Rectangular Enclosure using an Active/Passive Smart Foam Actuator," International Journal of Precision Engineering and Manufacturing, Vol. 6, No. 4, pp. 37-43, 2005.
7. Liu, H., Lee, J. C. and Li, B. R., "High Precision Pressure Control of a Pneumatic Chamber using a Hybrid Fuzzy PID Controller," International Journal of Precision Engineering and Manufacturing, Vol. 8, No. 3, pp. 8-13, 2007.
8. Hsia, T. C. and Gao, L. S., "Robot manipulator control using decentralized time-invariant time-delayed controller," In Proc. of IEEE Int. Conf. Robotics and Automation, pp. 2070-2075, 1990.
9. Youcef-Toumi, K. and Ito, O., "A time delay controller design for systems with unknown dynamics," ASME J. Dynamic Systems Measurement and Control, Vol. 112, No. 1, pp. 133-142, 1990.
10. Park, J. Y. and Chang, P. H., "Enhanced time delay control and its applications to force control of robot manipulator," International Journal of Human-friendly Welfare Robotic Systems, Vol. 4, No. 2, pp. 44-50, 2003.
11. Chang, P. H. and Park, S. H., "On improving time-delay control under certain hard nonlinearities," Mechatronics, Vol. 13, No. 1, pp. 393-412, 2003.
12. Chang, P. H., Lee, J. W. and Park, S. H., "Time delay observer: a robust observer for nonlinear plants," ASME J. Dynamic Systems Measurement and Control, Vol. 119, No. 3, pp. 521-527, 1997.
13. Komada, S., Ishida, M., Ohnishi, K. and Hori, T., "Disturbance observer-based motion control of direct drive motors," IEEE Trans. Energy Conservation, Vol. 6, No. 8, pp. 553-559, 1991.
14. Chang, P. H. and Lee, J. W., "A model reference observer for time-delay control and its application to robot trajectory control," IEEE Trans. Control System Technology, Vol. 4, No. 1, pp. 2-10, 1996.
15. Narasimhan, S., Siegel, D. M. and Hollerbach, J. M., "Condor: An architecture for controlling the Utah-MIT dexterous hand," IEEE Trans. Robotics and Automation, Vol. 5, No. 5, pp. 616-627, 1989.