Design of a Data-Driven Controller with Evaluating Controller Performance

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Abstract

Data-driven controller systems have been proposed to achieve the desired control performance without using any system identifications. The effectiveness of these control schemes has been shown through experimental results. For time-variant and nonlinear systems, it is important to evaluate the controller performance and redesign controller when the performance is poor. According to the proposed scheme, the controller performance calculator and controller design are integrated using only input and output data.

Keywords: PID controller, controller assessment, data-driven controller, least squares method.

1. Introduction

In most industries, it is very important to get desired control performance. Data-driven control schemes[1, 2, 3] have been proposed to achieve the aforementioned desired control performance without using any system identifications. For time-variant systems, performance-driven controller[4] has been proposed to improve the steady state control performance only when the performance is poor. However, performance-driven controller cannot evaluate the transient state.

In this paper, the scheme of evaluating controller performance without using any system identifications is proposed. According to the proposed scheme, the control performance is evaluated system output error including transient state. Furthermore, the controller performance calculator and controller design are integrated using only input and output data.

2. Schematic figure of the proposed scheme

The schematic figure of the proposed control system is shown in Fig. 1. $C(z^{-1})$, $G(z^{-1})$, $G_m(z^{-1})$, and $\hat{G}(z^{-1})$ are the controller, controlled system, reference model and estimated system model, respectively.

The purpose of the proposed control system is to achieve the desired control performance by minimizing the following criterion J_r:

$$J_r = \frac{1}{2}\phi_r(t)^2 \tag{1}$$

$$\phi_r(t) = y(t) - y_r(t), \tag{2}$$

where $y(t)$ and $y_r(t)$ are the control output and reference output, respectively.

Another purpose is to design the estimated system model $\hat{G}(z^{-1})$ by minimizing the following equation:

$$J_r = \frac{1}{2}\hat{\phi}(t)^2 \tag{3}$$

$$\hat{\phi}(t) = y(t) - \hat{y}(t), \tag{4}$$

where $\hat{y}(t)$ is the estimated output. In the proposed scheme, $\hat{G}(z^{-1})$ can be introduced by using the controller parameters and reference model parameters

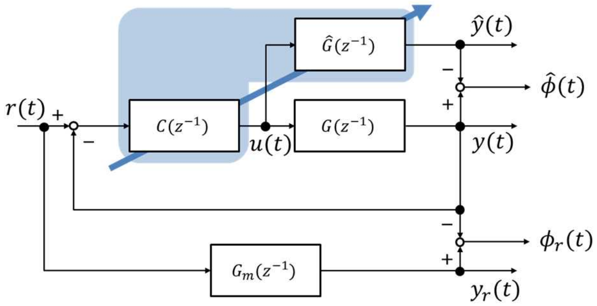

Fig. 1. Schematic figure of the proposed control system.

without any system identifications. Therefore, controller and estimated system model can be designed simultaneously.

In addition, user set a desired reference model expressed by following equation:

$$y_r(t) = G_m(z^{-1})r(t) \tag{5}$$

$$G_m(z^{-1}) := \frac{z^{-(1+d)}P(1)}{P(z^{-1})} \tag{6}$$

where $r(t)$ is the reference signal and $P(z^{-1})$ is user-specified polynomial. $P(z^{-1})$ is designed based on the reference design[5] as follows:

$$P(z^{-1}) := 1 + p_1 z^{-1} + p_2 z^{-1} \tag{7}$$

$$\begin{cases} p_1 = -2\exp\left(-\frac{\rho}{2\mu}\right)\cos\left(\frac{\sqrt{4\mu-1}}{2\mu}\rho\right) \\ p_2 = \exp\left(-\frac{\rho}{\mu}\right) \\ \rho := \frac{T_s}{\sigma} \\ \mu := 0.25(1-\delta) + 0.51\delta \end{cases}, \tag{8}$$

where σ is a parameter related to the rise-time and δ is a parameter related to the damping oscillation. User set them arbitrarily. σ denotes the time when output reaches about 60% of the step reference value. Moreover, δ is set between $0 \le \delta \le 2.0$ desirably. In particular, $\delta = 0$ indicates the response of Butterworth model and $\delta = 1.0$ indicates the response of Binominal model.

3. Relationship between controller and estimated system model

The following equation can be obtained by introducing the optimized controller $C^*(z^{-1})$ which achieves $\phi_r(t) = 0$:

$$\frac{G(z^{-1})C^*(z^{-1})}{1 + G(z^{-1})C^*(z^{-1})} = G_m(z^{-1}). \tag{9}$$

The controlled system $G(z^{-1})$ is expressed as follows by using the aforementioned equation:

$$G(z^{-1}) = \frac{G_m(z^{-1})}{C^*(z^{-1})\{1 - G_m(z^{-1})\}}. \tag{10}$$

Here, the following estimated system model $\hat{G}(z^{-1})$ is defined using a controller $C(z^{-1})$ instead of $C^*(z^{-1})$ because it is difficult to obtain the optimized controller $C^*(z^{-1})$:

$$\hat{G}(z^{-1}) = \frac{G_m(z^{-1})}{C(z^{-1})\{1 - G_m(z^{-1})\}}. \tag{11}$$

Note that the estimated controlled system $\hat{G}(z^{-1})$ is expressed by using a controller $C(z^{-1})$ and reference model $G_m(z^{-1})$ without any system identifications.

$\hat{G}(z^{-1})$ equals to $G(z^{-1})$ when the optimized controller $C^*(z^{-1})$ is obtained. It mentions that $\hat{\phi}(t) = 0$ because of $\hat{G}(z^{-1}) = G(z^{-1})$. Therefore, the optimized controller $C^*(z^{-1})$ achives $\phi_r(t) = 0$ and $\hat{\phi}(t) = 0$ simultaneously.

4. Evaluation of the controller performance

The optimized controller $C^*(z^{-1})$ makes $\hat{\phi}(t)$ equals to zero. In contrast, $\hat{\phi}(t)$ becomes large when the performance of the controller $C(z^{-1})$ is poor. Hence, this paper considers the performance of the controller $C(z^{-1})$ based on $\hat{\phi}(t)$.

5. Tuning scheme of the PID gains

In this paper, the controller is utilized as following I-PD controller:

$$\Delta u(t) = K_I e(t) - K_P \Delta y(t) - K_D \Delta^2 y(t) \tag{12}$$

$$e(t) := r(t) - y(t), \tag{13}$$

where K_P, K_I and K_D are the proportional gain, integral gain and derivative gain, respectively.

The estimated system model $\hat{G}(z^{-1})$ is expressed by using I-PD controller is as follows:

$$\hat{G}(z^{-1}) = \frac{G_m(z^{-1})}{\frac{K_I}{\Delta} - C(z^{-1})G_m(z^{-1})}, \tag{14}$$

where

$$C(z^{-1}) = \frac{K_P\Delta + K_I + K_D\Delta^2}{\Delta}. \tag{15}$$

The estimated output is calculated as follows:

$$\hat{y}(t) = \frac{G_m(z^{-1})}{\frac{K_I}{\Delta} - C(z^{-1})G_m(z^{-1})} u(t), \tag{16}$$

where $u(t)$ is control input. In order to apply the least squares method, $\hat{\phi}(t) = 0$ is considered and the following equation is derived by using Eq. (2) and (18):

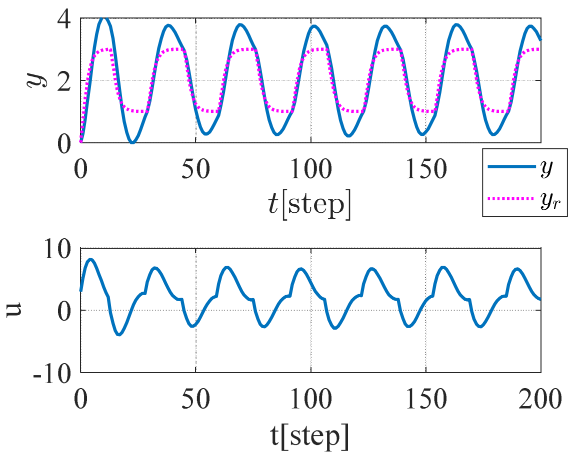

Fig. 2. Control result by using the initial PID gains.

$$G_m(z^{-1})u(t) = \left\{\frac{K_I}{\Delta} - \frac{K_P\Delta + K_I + K_D\Delta^2}{\Delta}G_m(z^{-1})\right\}y(t) \quad (17)$$

$$\Delta G_m(z^{-1})u(t) = K_I\{1 - G_m(z^{-1})\}y(t) - (K_P\Delta + K_D\Delta^2)G_m(z^{-1})y(t). \quad (18)$$

Therefore, the PID gains are calculated by using the following least squares method:

$$\boldsymbol{\theta} = (\boldsymbol{\Phi}^T\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^T\boldsymbol{\nu}, \quad (19)$$

$$\begin{cases} \psi(t) = \begin{bmatrix} -\Delta G_m(z^{-1})y(t) \\ \{1 - G_m(z^{-1})\}y(t) \\ -\Delta^2 G_m(z^{-1})y(t) \end{bmatrix}^{\mathrm{T}} \\ \boldsymbol{\Phi} = [\psi(1), \psi(2), \cdots, \psi(N)]^T \\ \boldsymbol{\nu} = [\Delta G_m(z^{-1})u(1), \cdots, \Delta G_m(z^{-1})u(N)]^T \\ \boldsymbol{\theta} = [K_P,\ K_I,\ K_D]^T \end{cases}. \quad (20)$$

6. Numerical example

The controlled system $G(s)$ is given as follows:

$$\begin{cases} G(s) = \dfrac{1}{1 + 10s} \ (t < 100) \\ G(s) = \dfrac{2}{1 + 20s} \ (t \geq 100) \end{cases}. \quad (21)$$

The parameters of the reference model $G_m(z^{-1})$ are set as follows:

$$\sigma = 3.0, \delta = 0. \quad (22)$$

Finally, the initial PID gains are set as follows:

$$K_P = 1.0, K_I = 1.0, K_D = 1.0. \quad (23)$$

In this section, the following three simulations are shown.

A) Fig. 2: Control result by using initial PID gains of Eq. (23).

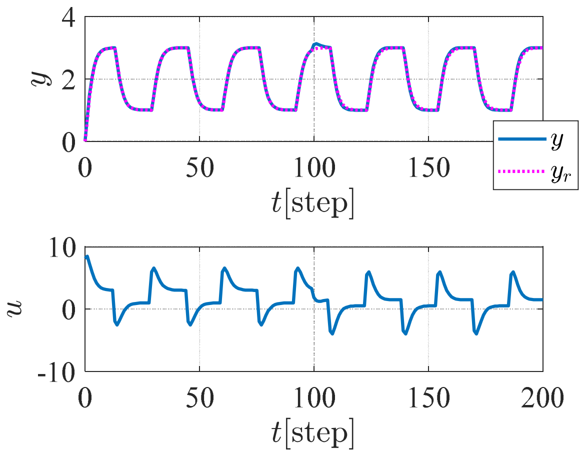

Fig. 3. Control result of the proposed scheme without controller retuning.

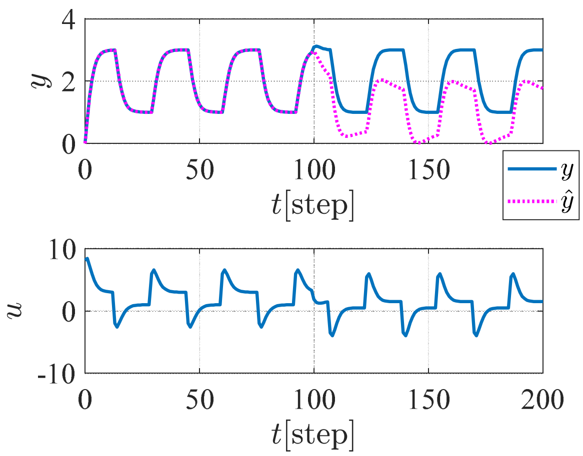

Fig. 4. Trajectory of the estimated output $\hat{y}(t)$ corresponding to Fig. 3.

B) Fig. 3: Control result of the proposed scheme without controller retuning.

C) Fig. 5: Control result of the proposed scheme with controller retuning.

Control results

Fig. 2 shows the control result by using initial PID gains of Eq. (23). The control performance is poor because control output $y(t)$ does not track to reference output $\hat{y}(t)$.

Fig. 3 shows the control result of the proposed scheme. The following PID gains were calculated applying Eq. (19) by using the data between t = 0 to 100 [step] in Fig. 2:

$$K_P = 6.74, K_I = 2.49, K_D = 0.0. \quad (24)$$

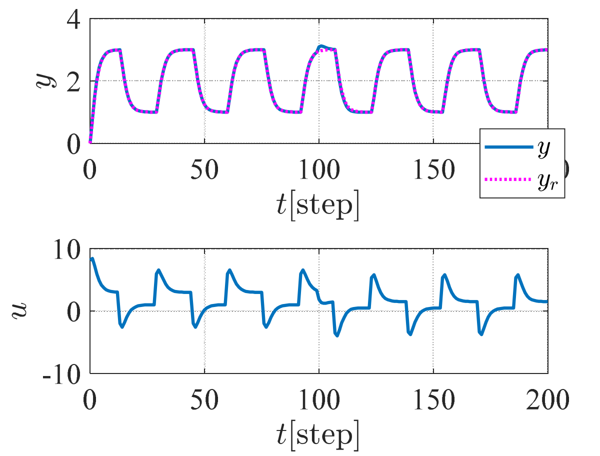

Fig. 5. Control result of the proposed scheme with controller retuning at 120 [step].

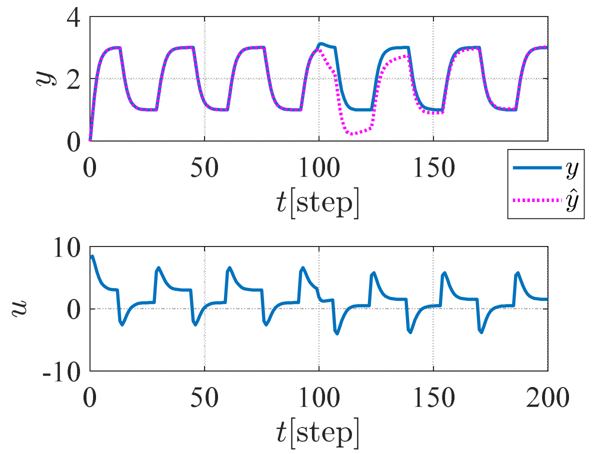

Fig. 6. Trajectory of the estimated output $\hat{y}(t)$ corresponding to Fig. 5.

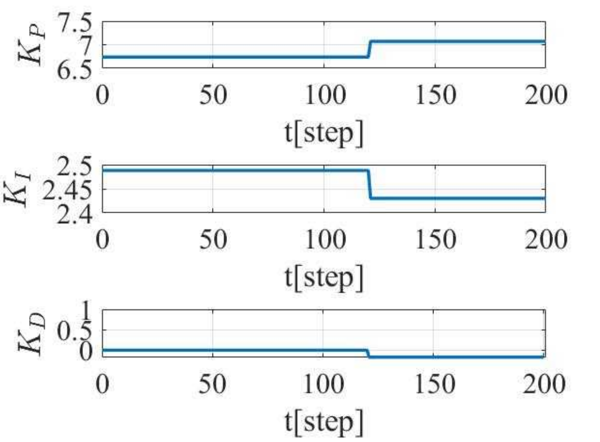

Fig. 7. Trajectories of the PID gains corresponding to Fig. 5.

In Fig. 3, the control performance is good even though the system $G(z^{-1})$ is changed at $t = 100$ [step]. It mentions that it is difficult to detect the system parameters are changed. On the other hand, Fig. 4 shows the trajectories of the estimated output $\hat{y}(t)$. It easier to detect the system parameters are changed than Fig. 3.

Finally, Fig. 5 shows the control result with controller retuning at 120 [step]. Fig. 6 shows the estimated output $\hat{y}(t)$, and Fig. 7 shows the trajectories of the PID gains corresponding to Fig. 5. In Fig. 7, each PID gains are slightly adjusted, however, the estimated output $\hat{y}(t)$ of Fig. 6 is significantly improved. Therefore, the proposed scheme can diagnose the system parameters are changed strictly.

7. Conclusions

This paper has proposed the design of data-driven control system with evaluating controller performance The features of the proposed scheme are as follows:

- Controller and estimated system model can be designed simultaneously.
- Satirical diagnosis of that system parameters are changed.

The proposed scheme has been verified by numerical examples.

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