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Two Stage Control Method Using a Disturbance Observer and a Kalman Filter

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***Abstract*—**This paper describes the two stage control using a disturbance observer and a Kalman filter. The system feedback uses the estimated state when it controls the speed. After the change-over point, its feedback uses the controlled plant output when it controls the position. To change the system continually, a change-over point has to be determined pertinently, and the controlled plant input has to be adjusted by the addition of the appropriate value. The proposed method has noise-reduction effect. It changes the system continually, even if the controlled plant identification has the error. Although the conventional method needs a speed sensor, the proposed method does not need it. The proposed method has a superior robustness compared with the conventional two stage control.

***Keywords*—** Disturbance Observer, Kalman Filter, Optimal Control, Two Stage Control.

I. Introduction

A PID control system is one of the most widely used industrial applications [1]-[4], because of the effective method to control the plants with process noise. However PID gains have to be adjusted by the over-shoot, because it is changed by the set-point.

The two stage control based on an optimal control [5] is developed by K. Endo, et al. to control the over-shoot. It combines a speed control system and a position control system. It controls the speed before the change-over point, after the change-over point it controls the position, irrespective of the set-point. Although it is remained the steady-state error in the disturbance response, the two stage control with the feedback of the difference between the controlled plant output and the plant model output [6] does not have it.

In this paper, we propose a new system using a disturbance observer and a Kalman filter. It has the advantage for the dealing with a plant that we cannot model accurately using only a deterministic model, because of the presence of modeling uncertainties and measurement noise. From these advantages, it can be used wide variety of industrial applications, such as an actuator, a robot, a vehicle, a carrying device and so on.

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II. Optimal Control

The task of designing control systems that are optimal, in some sense, is one of the most important and complex problems facing control engineers today. Then, let us consider the following controllable and observable plant model of order n_p.

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u_P}(k), \tag{1}$$

$$\boldsymbol{y}(k) = \boldsymbol{C}\boldsymbol{x}(k). \tag{2}$$

Define $\boldsymbol{e}(k)$, $\Delta\boldsymbol{x}(k)$, $\Delta\boldsymbol{u_P}(k)$, $\Delta\boldsymbol{e}(k)$, as follows:

$$\boldsymbol{e}(k) = \boldsymbol{r}(k) - \boldsymbol{y}(k), \tag{3}$$

$$\Delta\boldsymbol{x}(k) = \boldsymbol{x}(k) - \boldsymbol{x}(k-1), \tag{4}$$

$$\Delta\boldsymbol{u_P}(k) = \boldsymbol{u_P}(k) - \boldsymbol{u_P}(k-1), \tag{5}$$

$$\Delta\boldsymbol{e}(k) = \boldsymbol{e}(k) - \boldsymbol{e}(k-1). \tag{6}$$

where $r(k)$ is the set-point, $y(k)$ is the controlled output. If the new state variable is defined as:

$$\boldsymbol{x_P}(k) = [\Delta\boldsymbol{x}(k) \quad \boldsymbol{e}(k-1)]^T. \tag{7}$$

Then the state equation and the output equation are obtained as follows:

$$\boldsymbol{x_P}(k+1) = \boldsymbol{A_P}\boldsymbol{x_P}(k) + \boldsymbol{B_P}\Delta\boldsymbol{u_P}(k), \tag{8}$$

$$\boldsymbol{e}(k-1) = \boldsymbol{C_P}\boldsymbol{x_P}(k), \tag{9}$$

where

$$\boldsymbol{A_P} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{0} \\ \boldsymbol{\text{-}C} & 1 \end{bmatrix}, \quad \boldsymbol{B_P} = \begin{bmatrix} \boldsymbol{B} \\ \boldsymbol{0} \end{bmatrix}, \quad \boldsymbol{C_P} = [\boldsymbol{0} \quad 1]. \tag{10}$$

The performance criterion is used in practice for quadratic optimal control formulation:

$$J = \sum_{k=0}^{\infty} \left\{ \Delta\boldsymbol{x_P}^T(k)\boldsymbol{Q}\Delta\boldsymbol{x_P}(k) + \boldsymbol{\Delta u_P}^T(k)R\boldsymbol{\Delta u_P}(k) \right\}, \tag{11}$$

where $\boldsymbol{Q}$ is a positive-semidefinite real symmetric matrix, R is a positive-definite real symmetric matrix, and $\Delta\boldsymbol{u_P}(k)$ represents the input as follows:

$$\Delta\boldsymbol{u_P}(k) = \begin{bmatrix} \boldsymbol{F_1} & \boldsymbol{F_2} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{x}(k) \\ \boldsymbol{e}(k-1) \end{bmatrix}, \tag{12}$$

where $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are the optimal feedback gains. In this paper, the controlled plant is a second-order system. F_1 and F_2 are defined as follows:

$$\boldsymbol{F}_1 = [f_{11} \quad f_{12}], \quad F_2 = f_{22}. \tag{13}$$

III. A Conventional Two Stage Control method

The two stage control method combines a speed control system and a position control system. It is designed for the 1 input 2 output system with position and velocity controlled variables. It has to use the plant model for the position control system, because the controlled plant input, $u_p(k)$, has to be equal to $u_p(k+1)$ at the change-over point.

The speed control system:

$$u_p(k) = f_{12}x_2(k) + f_{22}\sum_{i=0}^{k-1} e(i). \tag{14}$$

The position control system:

$$u_p(k+1) = f_{11}x_{m1}(k+1) + f_{12}x_{m2}(k+1) + f_{22}\sum_{i=0}^{k-1} e(i), \tag{15}$$

where $x_{m1}(k)$ is the plant model output, $x_{m2}(k)$ is its velocity. At the change-over-point, the plant model states are defined as follows:

$$\boldsymbol{x_m}(k+1) = [x_{m1}(k+1) \quad x_{m2}(k+1)]^T, \tag{16}$$

$$\approx [vT_s \quad v]^T, \tag{17}$$

where v is the velocity, T_s is the sampling time. The change-over point, p, is as follows:

$$p = r(k) - y(k), \tag{18}$$

$$= \frac{f_{11}vT_s}{f_{22}}. \tag{19}$$

IV. Proposed Method

If the conventional two stage control method has the process noise or the white noise, its output and velocity has the noise or are unstable, because the plant model parameters should be the same as the controlled plant parameters. To overcome this problem, we propose a new two stage control system with a disturbance observer and a Kalman filter. The proposed method uses the estimated state at speed control. Fig. 1 shows the proposed system. In Fig. 1, $v(k)$ is the velocity, $r(k)$ is a set-point, $u_p(k)$ is the controlled plant input, $d(k)$ is the white noise, $\boldsymbol{M}$ is the appropriate value, C_m' is [0 1 0]. When the system controls its speed, each switch is set to (i), $\boldsymbol{M}$ is $\mathbf{0}$, the feedback gain, $\boldsymbol{F_1}$, is [0 f_{12} 0]. Consider the second-order plant as follows:

$$\boldsymbol{x}(k+1) = \boldsymbol{Ax}(k) + \boldsymbol{Bu_P}(k) + \boldsymbol{G}w(k), \tag{20}$$

$$\boldsymbol{y}(k) = \boldsymbol{Cx}(k) + d(k), \tag{21}$$

Equations (20) and (21) represent a linear process with time-invariant parameters disturbed by noise inputs $\boldsymbol{w}(k)$ and $d(k)$ acting on the process input and output respectively. Then the system is expanded to the disturbance observer as follows:

$$\boldsymbol{x_o}(k+1) = \boldsymbol{A_o x_o}(k) + \boldsymbol{B_o u_P}(k) + \boldsymbol{G}w(k), \tag{22}$$

$$\boldsymbol{y_o}(k) = \boldsymbol{C_o x_o}(k), \tag{23}$$

where the state vector $\boldsymbol{x}_o(k)$ and the state Matrixes $\boldsymbol{A_o}$, $\boldsymbol{B_o}$, and $\boldsymbol{C_o}$ are as follows:

$$\boldsymbol{x_o}(k) = [x_{o1}(k) \quad x_{o2}(k) \quad w(k)]^T, \tag{24}$$

$$\boldsymbol{A_o} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{G_o} \\ \mathbf{0} & 0 \end{bmatrix}, \quad \boldsymbol{B_o} = \begin{bmatrix} \boldsymbol{B} \\ 0 \end{bmatrix}, \quad \boldsymbol{C_o} = [1 \quad \mathbf{0}], \tag{25}$$

where $\boldsymbol{G_o}$ is a vector of size (2×1) and represents the factor for the disturbance, $x_{o1}(k)$ is the estimated plant output, $x_{o2}(k)$ is the estimated plant velocity. Then the system is designed based on the Kalman filter theory as follows:

$$\boldsymbol{x_o}(k+1) = \boldsymbol{A_o x_o}(k) + \boldsymbol{B_o u_P}(k) + \boldsymbol{K}\left(y(k) - \boldsymbol{C_o x_o}(k)\right), \tag{26}$$

where $\boldsymbol{K}$ is a Kalman gain matrix as follows:

$$\boldsymbol{K} = \boldsymbol{XC_o}^T\left(\boldsymbol{C_o XC_o}^T + R_o\right)^{-1}, \tag{27}$$

where R_o is the power spectral density of $d(k)$, $\boldsymbol{X}$ is the symmetric positive definite solution of the discrete time Riccati equation as follows:

$$\begin{aligned} &-\boldsymbol{A_o XC_o}^T\left(\boldsymbol{C_o XC_o}^T + R_o\right)^{-1}\boldsymbol{C_o XA_o}^T \\ &\quad + \boldsymbol{A_o XA_o}^T + \boldsymbol{GWG}^T = 0. \end{aligned} \tag{28}$$

where $\boldsymbol{W}$ is the power spectral density of $w(k)$. When the system

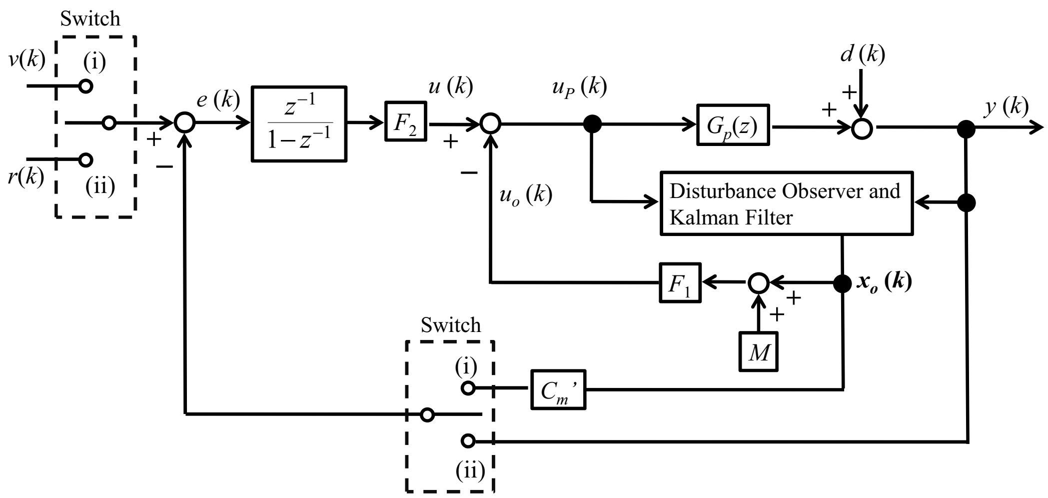


Fig. 1. The proposed method

controls the position, each switch changed (i) to (ii), the feedback gain, $\boldsymbol{F}_1$, is $[f_{11}\ \ f_{12}\ 0]$. For the peed control system and the position control system it uses the state feedback as follows:
For the speed control system:

$$u_o(k) = f_{12}x_{o2}(k), \tag{29}$$

For the position control system:

$$u_o(k) = f_{11}x_{o1}(k) + f_{12}x_{o2}(k). \tag{30}$$

At the change-over point these controlled variables have to be equal. Then at this time, the estimated state, $x_{o1}(k)$ is as follows:

$$x_{o1}(k) \approx r - p, \tag{31}$$

where the r is the sate-point. To change the system continuously the estimated state, $\boldsymbol{x_O}(k)$, is adjusted by the appropriate value $\boldsymbol{M}$ as follows:

$$\boldsymbol{M} = -\begin{bmatrix} r-p & \boldsymbol{0} \end{bmatrix}^T. \tag{32}$$

Then after the change-over point, the controlled plant is as follows:

$$u_p(k+1) = f_{11}x_{o1}(k+1) + f_{12}x_{o2}(k+1)$$

$$+f_{22}\sum_{i=0}^{k-1} e(i) + F_2M + f_{22}p, \tag{33}$$

$$= f_{11}vT_s + f_{12}x_{o2}(k+1) + f_{22}\sum_{i=0}^{k-1} e(i) + f_{22}p. \tag{34}$$

Then the controlled plant input has to be $u_p(k) \approx u_p(k+1)$.

Since the change-over point, p, is same as the conventional two stage control system.

V. Simulation Results

A. Example 1

This Example shows a case that the controlled plant output has the white noise. Consider the following second-order plant.

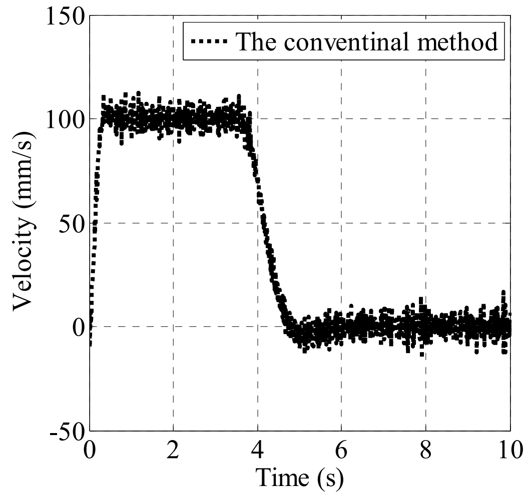
$$G(s) = \frac{180}{s(s+14)}. \tag{35}$$

The Controlled plant is the single-input single-output (SISO) system. The conventional method has to use the velocity, which is calculated by differential calculus. Then (35) is discretized by zero-order hold (T_s = 10 [ms]). The velocity is 100 [mm/s], a step set-point is 400 [mm], the disturbance $d(k)$ is the white noise whose power is $1.0\mathrm{e}^{-5}$. Then the feedback gains are determined by using the optimal control design method with the performance index ratio $Q / R = 5.0\ \mathrm{e}^{-5}$, $\boldsymbol{G_o}$, $\boldsymbol{GWG}^T$, and R_o are as follows:

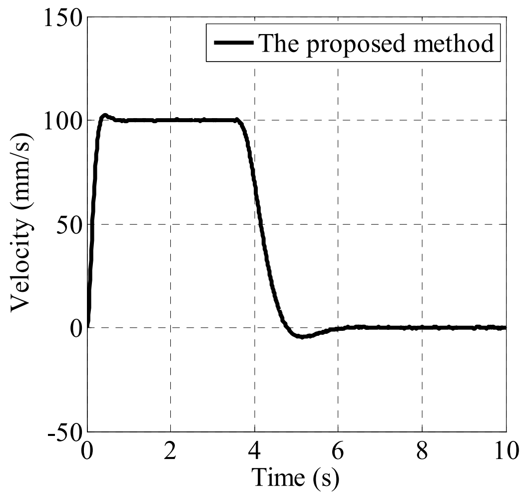
$$\boldsymbol{F_1} = [3.78e^{-1}\ \ 2.32e^{-2}],\ F_2 = 6.9e^{-3}, \tag{36}$$

$$\boldsymbol{G_o} = \boldsymbol{B_o},\ \boldsymbol{GWG}^T = 0.1,\ R_o = 0.01. \tag{37}$$

The simulation results are shown in Fig. 2 (a) and (b). From the results, although the conventional method has the white noise, the proposed method has noise-reduction effect.



(a). Simulation result of the conventional method velocity



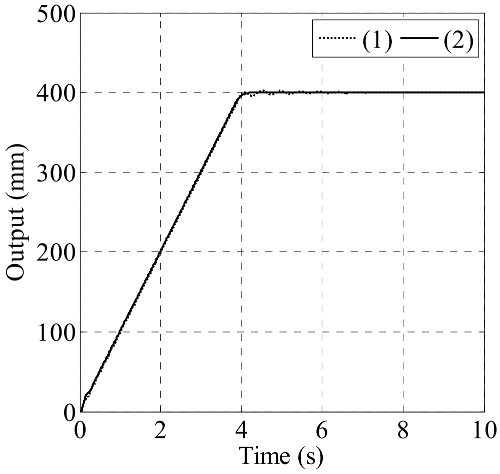
(b). Simulation result of the proposed method estimated velocity
Fig. 2. The controlled plant output has the white noise.

B. Example2

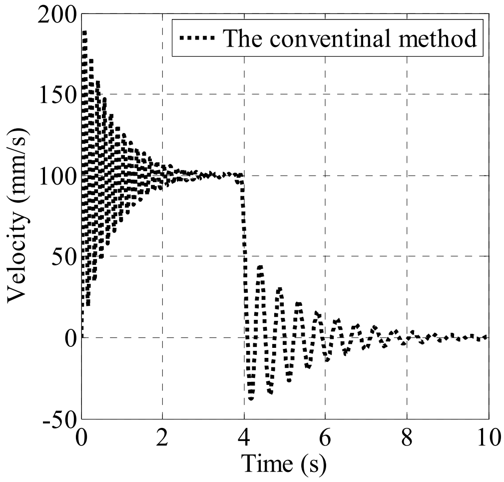
This Example shows a case that the system has the error of the plant parameters. In this case, they are the 30% errors as follows:

$$G(s) = \frac{180 \cdot 1.3}{s(s+14 \cdot 0.7)}. \tag{38}$$

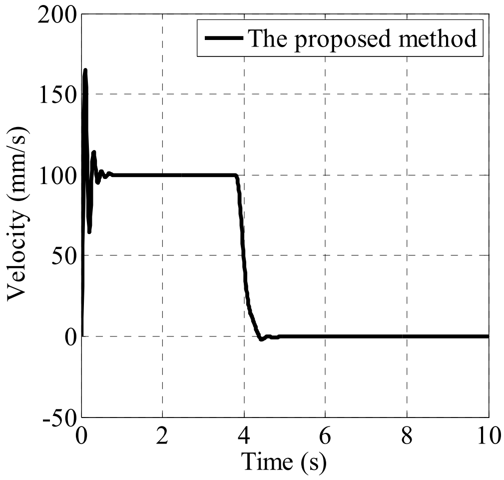
Then the feedback gains are determined by using the optimal control with the performance index ratio $Q / R = 5.0\ \mathrm{e}^{-3}$, $d(k)$ is equal to zero, and others are the same as *Examap1*. The simulation results are shown in Fig. 3(a), (b), and (c). From the results, the proposed method has a superior robustness compared with the conventional method.



(a). Simulation result of the controlled plant output
(1) is the conventional method, (2) is the proposed method.



(b). Simulation result of the conventional method



(c). Simulation result of the proposed method
Fig. 3. The system has the error of the plant parameters.

VI. Conclusion

In this paper, we have proposed a new two stage control method with a disturbance observer and a Kalman filter. The simulation results suggest that the proposed method is effective for the controlled plant with the process noise and the white noise. Moreover, it is not only used 2 output system, but also 1 output system.

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