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A new Smith Predictor for controlling a process with an integrator and long dead-time

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ABSTRACT

A new Smith predictor for control of a process with an integrator and long dead-time is proposed in this note. The controller decouples the setpoint response from the load response. This simplifies both design and tuning. Simulation results obtained by controlling a typical process show that the new controller has superior performance compared to previous algorithms.

1. Introduction

The smith predictor is well known as an effective dead time compensator for a stable process with large dead time [1], [2]. However it has been shown earlier [3], [4] that it cannot be used for processes having an integral mode since a constant load disturbance will result in a steady-state error. To overcome this problem, Watanabe, etc. [4] has proposed a modification where the main controller is either a PI or a PID controller. Simulation studies have shown that with a PI controller, the setpoint and load disturbance responses are either very oscillatory or highly damped when the process has a large dead time. The response of the system also tends to be slow. Much better performance is obtained when the main controller is of the PID type.

The controller structure proposed in this note will allow more freedom in choosing controller parameters. This results in much improved performance, both in the setpoint response and in the load rejection.

2. Watanabe's Smith predictor

A block diagram of Watanabe's Smith predictor is shown in Fig.1. The main controller G(s) is either a PI or a PID controller. The plant transfer function is

$$\frac{Y(s)}{U(s)} = G(s)e^{-sL} \tag{1}$$

where we also assume that

$$G(s) = \frac{1}{s} \tag{2}$$

In the conventional Smith predictor we have $G_1(s) = G(s)$. Watanabe's modification is to choose

$$G_1(s) = \frac{G(s)}{(1+sL)} \tag{3}$$

where L is the dead-time of the process.

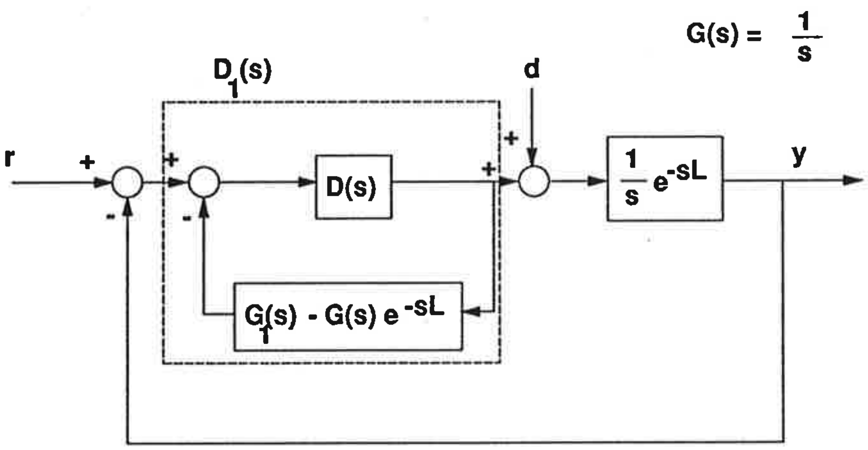

Figure 1. The Smith predictor proposed by Watanabe

The system can reject a load disturbance provided that the parameter L in the expression for $G_1(s)$ is exactly equal to the dead-time L of the process. If this is not the case there will be a small steady state error.

PI control

If a PI controller is used as the main controller, the setpoint response is given by the transfer function

$$H(s) = \frac{Y(s)}{R(s)} = \frac{k_p\left(s+\frac{1}{T_i}\right)\left(s+\frac{1}{L}\right)e^{-sL}}{s^3+\frac{1}{L}s^2+\frac{k_p}{L}s+\frac{k_p}{LT_i}} \tag{4}$$

The load response is given by

$$H_D(s) = \frac{Y(s)}{D_0(s)} = \frac{e^{-sL}\left(s^2(1+sL)+k_p\left(s+\frac{1}{T_i}\right)(1-(1+sL)e^{-sL})\right)}{s\left(s^3L+s^2+k_ps+\frac{k_p}{T_i}\right)} \tag{5}$$

where $D_0(s)$ is the Laplace transform of the load disturbance.

PID control

If the main controller is a PID controller, the setpoint response is given by the transfer function

$$H_D = \frac{Y(s)}{R(s)} = \frac{k_ps\left(s+\frac{1}{L}\right)\left(s^2T_d+s+\frac{1}{T_i}\right)e^{-sL}}{s^3+\frac{1+k_pT_d}{L}s^2+\frac{k_p}{L}s+\frac{k_p}{LT_i}} \tag{6}$$

and the load response is given by

$$H_D(s) = \frac{Y(s)}{D_0(s)} = \frac{e^{-sL}\left(s^2(1+sL)+k_p\left(s^2T_d+s+\frac{1}{T_i}\right)(1-(1+sL)e^{-sL}) \right)}{s\left(s^3L+(1+k_pT_d)s^2+k_ps+\frac{k_p}{T_i}\right)} \tag{7}$$

3. New Smith predictor

The structure of the new smith predictor is shown in Fig. 2.

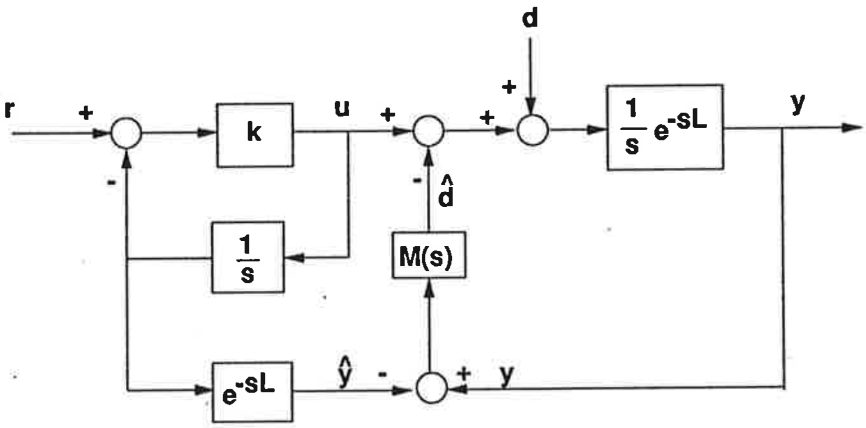

Figure 2. New smith predictor structure

The properties of the transfer function $M(s)$ will be discussed later. The setpoint response is given by

$$H(s) = \frac{Y(s)}{R(s)} = \frac{ke^{-sL}\left(1+M(s)\frac{1}{s}e^{-sL}\right)}{s+k\left(1+M(s)\frac{1}{s}e^{-sL}\right)} = \frac{k}{s+k}e^{-sL} \tag{8}$$

Notice that the factor $1+M(s)\frac{1}{s}e^{-sL}$ is cancelled. The load response is given by

$$H_D(s) = \frac{Y(s)}{D_0(s)} = \frac{\frac{1}{s}e^{-sL}}{1+M(s)\frac{1}{s}e^{-sL}} \tag{9}$$

Equation (9) shows that the following choice:

$$M(s) = \frac{D(s)}{1 + \frac{D(s)}{s(1+sL)} + \frac{D(s)}{s}e^{-sL}} \tag{10}$$

gives the same load disturbance response as Watanabe's controller. Compare with (5), the difference is that our new smith predictor has decoupled the load response from the setpoint response. It follows from equation (8) that the setpoint response is simply that of a first order system with delay. The setpoint response of the system can thus be improved compared to Watanabe's controller by choosing an appropriate value of the controller gain k.

However, it is possible to improve the load response also by choosing a different transfer function M(s). The controller M(s) which we propose has three adjustable parameters.

The following transfer function is proposed:

$$M(s) \;=\; \frac{k_4 + \frac{k_3}{s}}{1 + k_1 + \frac{k_2}{s} + \frac{k_3}{s^2} - \left(\frac{k_4}{s} + \frac{k_3}{s^2}\right)e^{-sL}} \tag{11}$$

where $k_4 \;=\; k_2 \,+\, k_3 L$

With this choice, the load response is given by

$$H_D(s) \;=\; \frac{e^{-sL}(s^2(1+k_1)+k_2 s+k_3-(k_4 s+k_3)e^{-sL})}{s(s^2(1+k_1)+sk_2+k_3)} \tag{12}$$

Note that the denominator is a third order polynomial. Watanabe's Smith predictor (equation 5) gives a fourth order denominator polynomial. Notice also that the transfer function (12) can be given arbitrary poles which is not the case for Watanabe's system (5). Intuitively, we can expect a better load response from the new Smith predictor.

It can be shown easily that $\lim\limits_{s \to 0} H_D(s) \;=\; 0$ which proves that there will be no steady state error with a constant step disturbance.

Comparing $M(s)$ with Watanabe's smith predictor in terms of the block diagram (see figure 1), we have maintained a PI controller for D(s), i.e.

$$D(s) = k_4 + \frac{k_3}{s} \tag{13}$$

but the transfer function $G_1(s)$ has been changed to

$$G_1(s) = G(s)\frac{s^2 k_1 + s k_2 + k_3}{s k_4 + k_3} \tag{14}$$

4. Simulation results

In the simulations below, we consider a process with the transfer function $G(s) = \frac{1}{s} e^{-5s}$. A unit step setpoint is introduced at time $t=0$. At time $t=70$, a load disturbance $d_0 = -0.1$ is introduced.

4.1 Performance comparison

Fig. 3 shows the response of the system using Watanabe's smith predictor using a PI controller. From our simulations, we found that the response is faster with a larger value of k_p but that this makes the system more oscillatory. Similarly, decreasing T_i also makes the system more oscillatory.

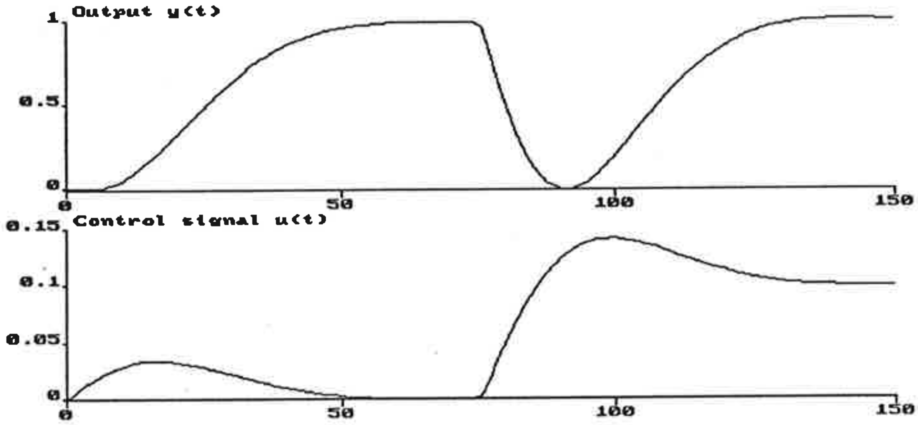

Figure 3. Response of the system using Watanabe's smith predictor

with PI controller ($K_p = 0.1, \quad T_i = 27.0$)

Fig. 4 shows the same system controller by Watanabe's smith predictor with a PID controller. Notice that there is a significant advantage to use a PID controller.

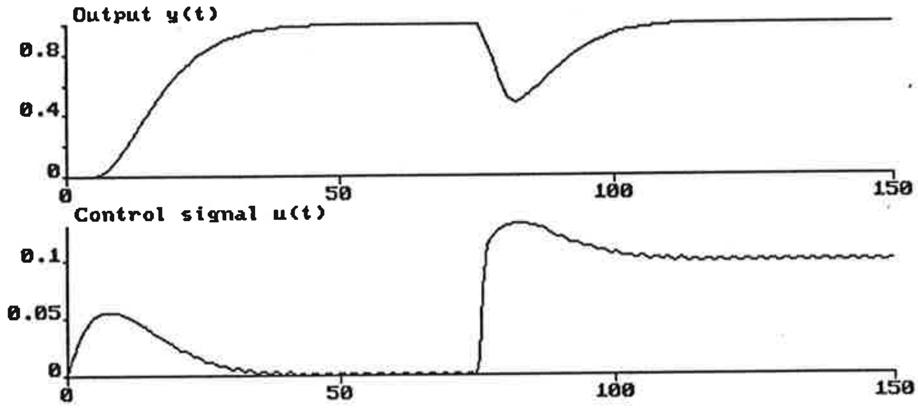

Figure 4. Response of the system using Watanabe's smith predictor

with PID controller ($K_p = 1.5$, $T_i = 10.0$, $T_d = 2.0$)

Fig. 5 shows the response of the same process when using the new Smith predictor.

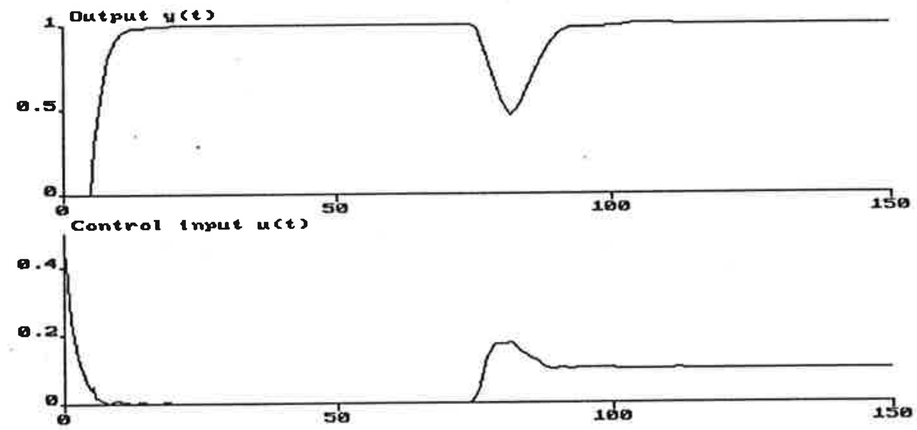

Figure 5. Response of the system using our Smith predictor

($k = 0.5$, $k_1 = 4$, $k_2 = 3$, $k_3 = 0.6$)

It is seen that the load response with the smith predictor is slightly better than Watanabe's system with a PID controller. The setpoint response, however, is much better.

The advantage of the new design is that the setpoint response is decoupled from the load response and hence can be independently optimised. When we compare the transfer functions of the closed loop systems described in earlier sections, it is easy to see that the new Smith predictor structure gives the designer more freedom to choose the closed loop poles. Hence it is not surprising to see a significant improvement in performance.

4.2 Uncertainty in dead-time

An analysis of the load response $H_D(s)$ reveals that both smith predictor structures rely on the fact that the dead time of the system is modelled accurately in order to reject a d.c. load disturbance.

We shall now compare the performance of the three controller structures when there is a 10% error in estimating the dead-time L. The process dead-time is 5. The estimated dead-time is 5.5.

Figures 6, 7 and 8 show the effect of a 10% error in estimating the dead time on the system response. The system employs Watanabe's smith predictor with a PI, PID controller and the new smith predictor respectively. All the controllers are found to be rather robust against this degree of mismodelling.

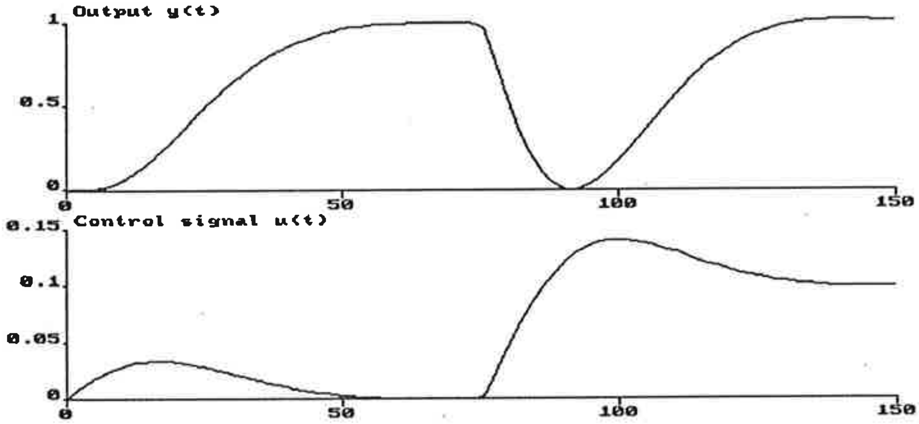

Figure 6. Response of system using Watanabe's smith predictor

with PI Controller. ($K_p = 0.1, \quad T_i = 27.0$)

There is a 10% error in estimating dead-time.

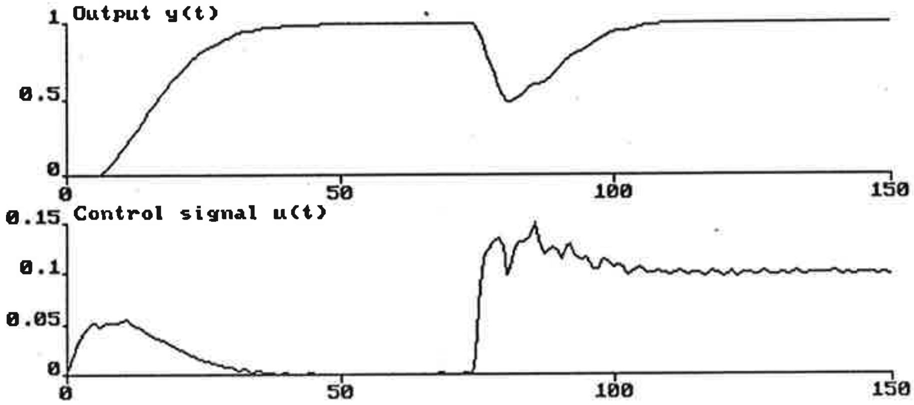

Figure 7. Response of system using Watanabe's smith predictor

with PID controller. ($k_p = 0.3, \quad T_i = 18.0, \quad T_d = 3.0$)

There is a 10% error in estimating dead-time.

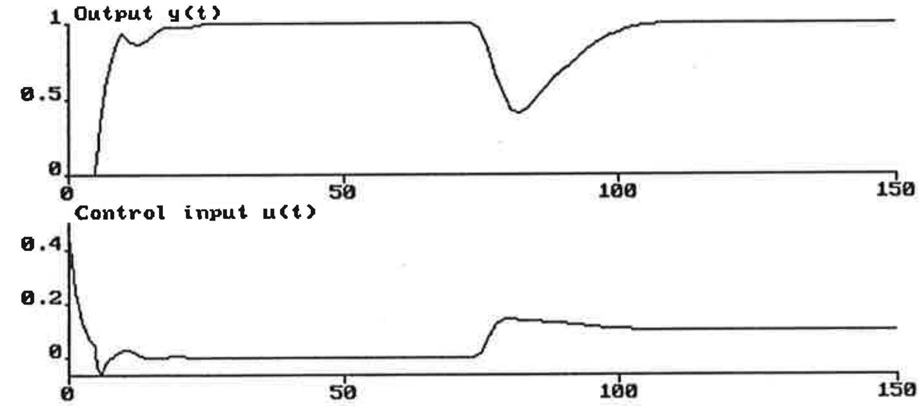

Figure 8. Response of system using our new smith predictor

($k = 0.6, \quad k_1 = 10.0, \quad k_2 = 4.0, \quad k_3 = 0.5$)

There is a 10% error in estimating dead-time.

5. Conclusion

An alternative Smith predictor for systems with an integral mode is proposed. The controller decouples setpoint response from load response. It is demonstrated that the controller gives better performance than the controller proposed by Watanabe et. al.

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