Smith predictor based fuzzy estimator for uncertain time-delayed systems

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In this paper, a novel robust control method is proposed for uncertain time-delayed systems. The objective is to guarantee system stability and robustness against modeling errors. A fuzzy estimator is developed to predict the uncertain plant time-delay. Smith predictor is exploited. An adaptive tuning law is developed to further improve the control system performance. The proposed robust control method is successfully applied to a heat exchanger control system. Simulation results show that the approach is indeed effective. System robustness as well as stability is achieved.

Keywords: Time-Delayed Systems, Predictive Control, Fuzzy Control, Robustness, Smith Predictor.

1. INTRODUCTION

Time-delays are frequently encountered in many real systems, such as information networks, chemical processes, hydraulic and rolling mill systems, electrical heating, and long transmission lines in pneumatic devices.[1-3] In general, time-delayed systems arise as a result of delay in transmission of information between different parts of the whole system. Because the existence of time-delay in a physical system often induces instability and poor performance, research on time-delay systems is a topic of great practical and theoretical importance.

Because time-delays place limits on the achievable bandwidth and allowed maximum gain, feedback control in the presence of time-delays leads to particular difficulties.[2-5]. Many conventional control techniques are not applicable to the systems with time-delays. For example, conventional PID controllers are not effective for time-delayed systems. Smith predictors have been proposed to be the supplementary technique for designing time-delayed control systems.[1,6,7] With the Smith predictor, a controller designed for a control system with no time-delay can be adopted if the plant model matches the real plant. However, unless the plant time-delay is exactly known, the control system would likely become unstable using the prevailing control methods involving the Smith predictors. Therefore, the determination of the system model, the model time-delay, and the corresponding parameters of the controller are very important.

Various approaches for time-delayed systems have been proposed. An artificial neural network was applied to on-line estimate the plant time-delay and to identify the frequency response of the control system at the same time.[8] Minimizing the output error, an adaptive I-PD controller was obtained for time-delayed systems. Further, a fuzzy logic with linear quadratic regulator (LQR) controller was addressed for networked control systems with time-variant delays.[4] The problem of H-infinity sliding mode control for uncertain time-delay systems subjected to input nonlinearity was investigated.[5] However, the above computation structures were complicated. No general solution was achieved. If the model time-delay in a Smith predictor is not exactly equal to the actual plant time-delay, the control system may become unstable when the estimation error increases.

In this paper, based on the concept of Smith predictor we propose a fuzzy logic controller (FLC) to predict the unknown plant time-delay and on-line tune the model time-delay accordingly. Further modification is developed to improve the transient system response. An example is carried out to

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demonstrate that the proposed fuzzy estimator with adaptive law and Smith predictor can effectively achieve system stability and robustness.

2. SMITH PREDICTOR

Consider the diagram of the Smith predictor as shown in Fig. 1, where $G_c(s)$ is the transfer function of the controller, $G(s)$ is the transfer function of the plant, and τ is the time-delay. In Fig. 1, the region within the dashed line is designed to cancel the time-delay characteristic of the original feedback signal. It is seen that if the control system has no Smith predictor, the closed-loop transfer function of the control system is

$$\frac{Y(S)}{R(S)} = \frac{G_c(s)\cdot G(s)\cdot e^{-\tau s}}{1+G_c(s)\cdot G(s)\cdot e^{-\tau s}}\,. \tag{1}$$

It is seen that a time-delay exists in the characteristic polynomial in (1). The control system may have a poor performance and instability. Referring to Fig. 1, if the output of the Smith predictor $Y'(s)$ satisfies

$$Y'(s) = G(s)\cdot(1-e^{-\tau s})\,, \tag{2}$$

the closed-loop transfer function of the time-delayed system becomes

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)\cdot G(s)\cdot e^{-\tau s}}{1+G_c(s)\cdot G(s)}\,. \tag{3}$$

Remarkably, the characteristic polynomial in (3) has no time-delay. Therefore, the control system performance and stability can be improved. Better time response can be achieved. The above effect relies on exact knowledge of the time-delay. Unfortunately, the time-delay is uncertain for most physical systems. In the following, an improved approach for the uncertain time-delayed systems is proposed.

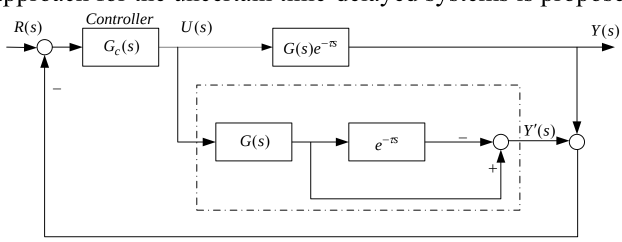

Fig. 1. Structure of Smith predictor control system.

3. CONTROL METHODOLOGY

The proposed control system structure is shown in Fig. 2, where $G_c(s)$ is the transfer function of the dominant controller, $G(s)$ is the transfer function of the plant, T_d is the plant time-delay, y is the system output, y_d is the desired output, $G_m(s)$ is the mathematical model of the plant $G(s)$, T is the model time-delay, ΔT is fuzzy output, y_m is the output of mathematical model, and y_s is the output of the Smith predictor. The goal is to estimate the value of T_d, and adjust T to achieve satisfactory response of the control system. In Fig. 2, the region within the dashed line is the modified Smith predictor. The time-delay T is estimated through the use of fuzzy logic controller (FLC).

The system output y and the output of mathematic model, y_m, can be described as

$$y = G(s)e^{-T_d s}\cdot u(s)\,, \tag{4}$$

$$y_m = G_m(s)e^{-Ts}\cdot u(s)\,. \tag{5}$$

Hopefully, by introducing the Smith predictor, the mathematical model $G_c(s)$ is equal to the plant $G(s)$, and $y = y_m$. When $T=0$ or $T_d \neq T$, the Smith predictor fails to compensate for the effect of time-delay. The output error would be large and may cause instability. Thus, the model time-delay must be adjusted such that y and y_m become equal.

$$y_{fb} = G(s)\cdot e^{-T_d s}u(s) - [G_m(s)\cdot e^{-Ts} - G_m(s)]\cdot u(s)$$

$$y_{fb} \cong G(s)\cdot u(s)\,. \tag{6}$$

From (6), when $T=T_d$, the control system performs like there is no time-delay. With Smith predictor applied to this system, the controller design can be simplified since the time-delay effect is eliminated. In the next section, we show how to on-line adjust the model time-delay T for uncertain time-delayed systems.

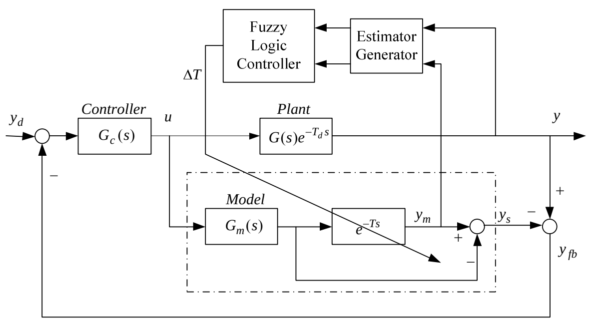

Fig. 2. Fuzzy estimator based Smith predictor time-delayed control system.

4. FUZZY ESTIMATOR DESIGN

4.1. Estimator generator

Consider the case of $T_d \neq T$. Referring to the estimator generator in Fig. 2, there are two main time responses: one is the plant output y and the other is the model output y_m. In fact, the response tendency of y and y_m should be similar. But they are asynchronous and even divergent for $T_d \neq T$. This implies that the Smith predictor does not work well.

Define the area $A(k)$ as

$$A(k) = \int_0^k \left|y(t) - y_m(t)\right| dt\,. \tag{7}$$

As shown in Fig. 3, it is obvious that the area $A(k)$ increases because the response curves of y and y_m do not overlap. For example, suppose $T_d = 1.5$ and let $T=0$. Since the proposed fuzzy estimator has not yet been adopted to tune the model time-delay, the Smith predictor cannot compensate for this system. The output y and y_m retain the 1.5 sec phase difference. Figure 3(b) shows the divergence of the area $A(k)$.

Now proceed to adjust T with the proposed FLC to compensate the output responses. Once $T \cong T_d$, $A(k)$ stops enlarging and stays bounded. At this point, it is reasonable to recognize that $A(k)$ increases more and more slowly as y_m approaches y.

4.2. Fuzzy logic control

According to the above investigation, the fuzzy logic control can be established as follows. There are four principal components of the FLC: fuzzifier, fuzzy rule base, inference engine, and defuzzifier.[9] The fuzzifier module performs the fuzzification so that the measurement values are converted into fuzzy number and degrees of membership function. Hence, it can be defined as a mapping from a crisp input space to fuzzy set labels. All the fuzzy set membership functions adopted here are triangular-shaped functions, as shown in Fig. 4. The fuzzy rule base is given several IF-THEN statements and displays a simple mapping relationship between the input and the output. The rule notation form is

$$\text{Rule } i: \ \text{IF } e \text{ is } M_j \text{ and } \Delta e \text{ is } N_k \text{ THEN } \Delta T \text{ is } O_l, \tag{8}$$

where the fuzzy inputs e and Δe stand for the error of area, and the variation of the error e at every sampling time, i.e.

$$e(k+t_s) = A(k+t_s) - A(k), \tag{9}$$

$$\Delta e(k+t_s) = e(k+t_s) - e(k). \tag{10}$$

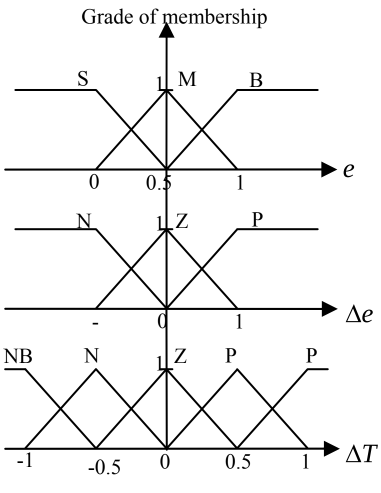

Fig. 4. Membership functions of fuzzy input and output.

The symbol t_s is the sampling time. The fuzzy output is the variation of the model time-delay, noted as ΔT. In (8), $M_j, j = 1,2,3$, $N_k, k = 1,2,3$, and $O_l, l = 1,2,3$ perform the fuzzy sets of e, Δe and ΔT, respectively. Those features described above are introduced to set up a series of fuzzy rules as shown in Table 1, where each fuzzy set label, NB, NM, N, Z, P, S, M, B, PM, and PB, denotes negative big, negative medium, negative, zero, positive, small, medium, big, positive medium, and positive big, respectively.

Table. 1. Fuzzy rule table.

Δe \ e	S	M	B
N	Z	PM	PB
Z	Z	Z	Z
P	Z	NM	NB

In this paper, the center of gravity method is used in the module of defuzzification, i.e.

$$\Delta T = \frac{\sum_{q=1}^{r} y_q \cdot \mu_q(y_q)}{\sum_{q=1}^{r} \mu_q(y_q)}, \tag{11}$$

where r is the quantitative number and $Y = \{y_1, y_2, \cdots, y_r\}$, where y_q denotes qth value, and $\mu_q(y_q)$ is the fired degree from y_q.

4.3. Numerical examples

A heat exchanger is shown in Fig. 5.[10] The temperature output is controlled by controlling the flow rate of steam in the exchanger jacket. The temperature sensor is several meters downstream from the steam control valve, which generates a transportation lag. A suitable transfer function can be given by

$$G(s) = \frac{e^{-5s}}{(10s+1)(60s+1)}. \tag{12}$$

Choose a controller as

$$G_c(s) = \frac{0.25s + 0.45}{s^2 + 0.28s + 0.0925}. \tag{13}$$

The controller (13) is designed for the transfer function without plant time-delay T_d =5; namely, (14) cannot be controlled well if only (13) is used. The different output responses are shown in Figs. 6(a) and 6(b). The response with 5 sec time-delay has serious oscillation which could be improved though it is still under control. To improve this, the proposed control method provides better compensation to overcome the oscillation, as shown in Fig. 6(c) and Fig. 7. The model time-delay T reaches the plant time-delay T_d as soon as the $A(k)$ stops increasing. Another simulation indicates that the Smith predictor with the ultimately estimated T compensates for the plant time-delay T_d. The delay phenomenon is eliminated entirely. Fig. 8 shows the comparison with different cases.

5. CONCLUSIONS

This paper proposes a novel robust control method for a class of unknown time-delayed systems. The developed fuzzy estimator and adaptive law are valuable support to the proposed Smith predictor structure. The advantage is the precise estimation of the unknown time-delay and the adjustment of the estimated time-delay of the mathematical model. Further, the proposed method can potentially stabilize a class of divergent or oscillating system. The proof of the effectiveness and correctness of the fuzzy estimator is given. Applying this approach, one can easily design a suitable controller for unknown time-delayed systems.

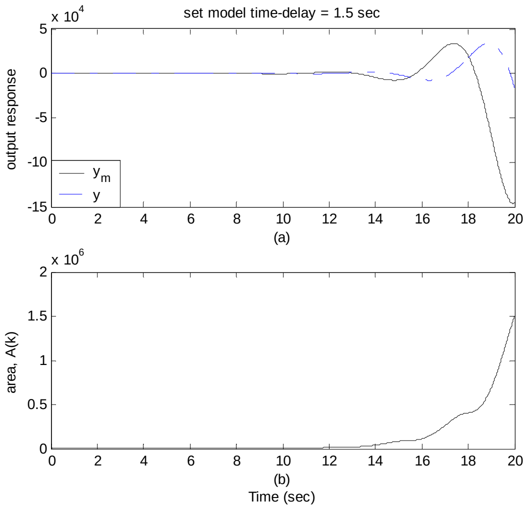

Fig. 3. Performance before tuning T (a) output response (b) area $A(k)$.

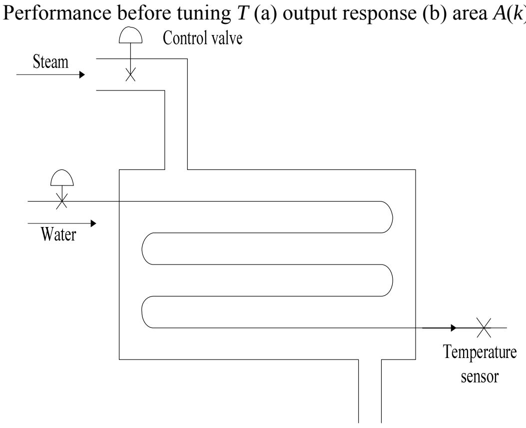

Fig. 5. Sketch of the heat exchanger.

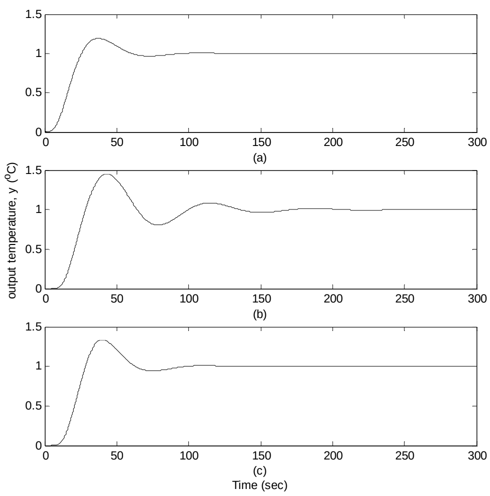

Fig. 6. Heat exchanger performance (a) without time-delay (b) with time-delay (c) with time-delay and fuzzy estimator.

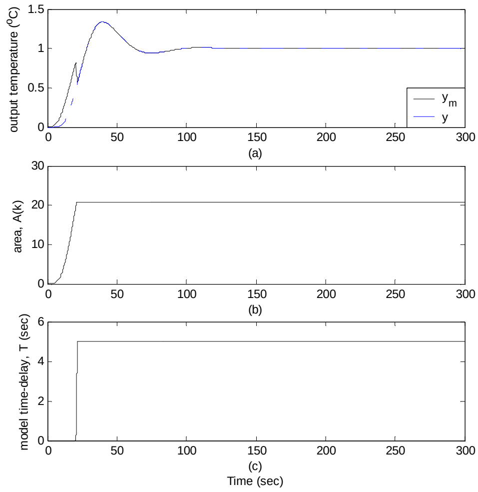

Fig. 7. Heat exchanger performance (a) output response (b) area $A(k)$ (c) estimation of the model time-delay.

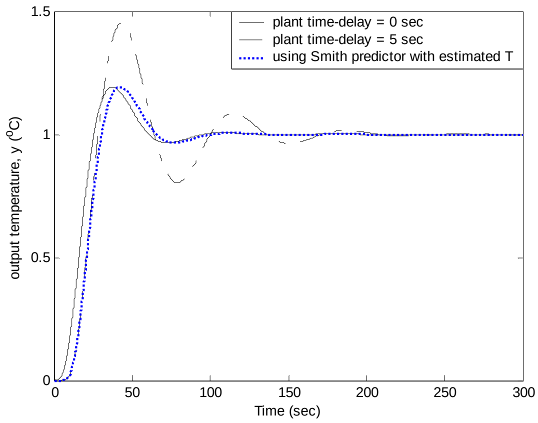

Fig. 8. Heat exchanger performance comparison.

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