Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (13): 2594-2597, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.2594.2597

CGSA Controller Design for Time Delay Processes

W. Guan, G.Q. Zhang, J.H. Cao and Y.H. Li
College of Navigation, Dalian Maritime University, Linghai Road No.1, 116026,
Dalian City, Liaoning Province, China

Abstract: In this study, a robust control scheme has been proposed based on the closed loop gain shaping algorithm, which offers a simplifying controller for processes with time delay. The purpose of this study is to give a comprehensive analysis of controller design procedure. The constraints imposed by the internal stability and robustness properties of the closed loop system are also investigated. Finally a typical design example is provided to illustrate the proposed method.

Key words: CGSA, concise robust control, time delay system

INTRODUCTION

Time delays are common phenomena in many industrial processes and they cause considerable difficulties in effective control of such processes (Zhang and Xu, 2002). Conventional controller design method such as Ziegler-Nichols PID (proportional integral derivative) (Ziegler and Nichols, 1993) controller is often ineffective for some processes with large time delay. The Smith predictor (Warwick and Rees, 1988), which acts as PID compensator for SISO (single input/single output) systems with time delays, provides the potential improvements over the PID controllers (Astrom *et al.*, 1994; Min 2012; Padhan and Majhi 2012). Although, those new controller based on the Smith predictor shown that their new scheme offered improved control performance for the processes with time delay, the Smith predictor based controllers have little robustness and the resulting controllers are too complex to deliver. Hence, a control scheme with simplifying form and strong robustness is required for time delay processes. Therefore, a straightforward robust control strategy named CGSA (close-loop gain shaping algorithm) (Guan *et al.*, 2013) is utilized to solve this control problem on account of its ability to deliver the controller which can guarantee levels of robust stability and control performance.

In this study, we wish to:

- Develop an analytical design procedure based on CGSA methodology and derive the final CGSA controller for time delay processes
- Investigate the conditions that guarantee the internal stability and robustness of the CGSA controller

CGSA CONTROLLER DESIGN PROCEDURE

For CGSA controller design, the unity closed-loop feedback control system is illustrated in Fig. 1. Referring to the control system shown in Fig. 1, C(s) represents the controller; d(s) is the environmental disturbance; r (s) is the reference signal; e(s) is the error signal; u(s) is the control action and z(s) is the output signal. The uncertainty of system can be represented by multiplicative uncertainty as the plant input, where G(s) denotes the plant and $G_0(s)$ is usually described as the nominal plant transfer function.

Hence, the norm multiplicative uncertainty can be expressed as:

$$\left\|\Delta(s)\right\|_\infty = \left\|\frac{G(s)-G_0(s)}{G_0(s)}\right\|_\infty = \left\|\Delta(j\omega)\right\|_\infty \le \left\|\Delta(\omega)\right\|_\infty \quad (1)$$

For further discussion, the transfer function $\Delta(s)$ is assumed to be stable and bounded by the H_∞ norm condition given in Eq. 2 (Doyle *et al.*, 1989):

$$\|\Delta\|_\infty = \lambda \quad (2)$$

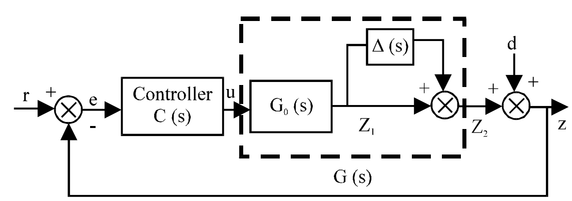

Fig. 1: Unity feedback control system with uncertainty

Corresponding Author: W. Guan, College of Navigation, Dalian Maritime University, Linghai Road No.1, 116026, Dalian City, Liaoning Province, China

where, λ is a scalar of the robustness and it will be discussed in the next section.

To proceed with the controller synthesis, the unity feedback control system depicted in Fig. 1 is represented in the equivalent H_∞ control configuration as shown in Fig. 2.

The equivalent H_∞ design problem is formulated as follow and given a state space realization of an augmented plant P(s):

$$\begin{bmatrix} y_\Delta \\ z \\ y \end{bmatrix} = P(s)\begin{bmatrix} u_\Delta \\ r \\ d \\ u \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & G_0 \\ 1 & 0 & 1 & G_0 \\ -1 & 1 & -1 & -G_0 \end{bmatrix}\begin{bmatrix} u_\Delta \\ r \\ d \\ u \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}\begin{bmatrix} u_\Delta \\ r \\ d \\ u \end{bmatrix} \quad (3)$$

Taken the augmented plant P(s) and controller C(s) as one augmented plant, along with the lower linear fractional transform, the all controllers that stabilize the closed-loop between u_Δ and y_Δ are:

$$N_\Delta = P_{11} + P_{12}(I - CP_{22})^{-1} CP_{21} = \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} \quad (4)$$

As shown in Fig. 3, the perturbation transfer function between u_Δ and y_Δ is N_{11} and its presentation is:

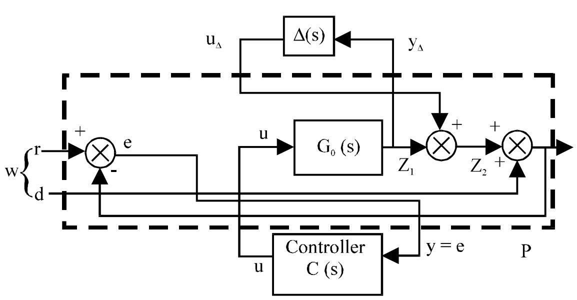

Fig. 2: Equivalent H_∞ design augmented systems

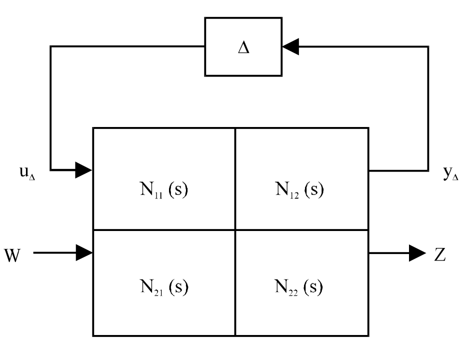

Fig. 3: Standard H_∞ design robust stabilization synthesis system

$$N_{11}(s) = \frac{u_\Delta(s)}{y_\Delta(s)} = \frac{-G_0(s)C(s)}{1+G_0(s)C(s)} \quad (5)$$

Thus it is possible to define the robust control problem as design an H_∞ robust controller C(s) that will stabilize the close-loop system for all plant uncertainties represented by $\Delta(s)$. Therefore, according to the small gain theory, the robust stability is met if and only if:

$$\|N_{11}(s)\cdot\Delta(s)\|_\infty \le \|N_{11}(s)\|_\infty \cdot \|\Delta(s)\|_\infty \le 1 \quad (6)$$

As we known, the complementary sensitivity function $T(s) = G_0(s)\ C(s)/(1+G_0(s)\ C(s))$, hence the Eq. 6 can be represented as:

$$\|T(s)\cdot\Delta(s)\|_\infty < 1 \quad (7)$$

Then the Eq. 8 can be arranged to show the infinity bounds of the plant uncertainties $\Delta(s)$:

$$\|\Delta(s)\|_\infty \le \|T(s)\|^{-1}_\infty = \|1 + 1/G_0(s)K(s)\|_\infty \quad (8)$$

Therefore the H_∞ norm of multiplicative uncertainty function Δ should be:

$$\|\Delta(\omega)\|_\infty = \lambda \ (0 < \lambda \le 1) \quad (9)$$

For time delay processes, the nominal plant of the system is usually described by the following model:

$$G_0(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \quad (10)$$

where, K is the gain, τ is the time constant, and θ is the time delay. We define the transfer function:

$$Q(s) = \frac{C(s)}{1+G_0(s)C(s)} \quad (11)$$

hence, the sensitive function of the closed loop system can be written as:

$$S(s) = 1 - G_0(s)Q(s) \quad (12)$$

and the complementary sensitive function is:

$$T(s) = G_0(s)Q(s) \quad (13)$$

also T(s) is the transfer function of the closed loop system.

With Padé approximation, the plant Eq. 10 becomes:

$$G_0(s) = K\frac{1-\theta s/2}{(\tau s+1)(\theta s/2+1)} \quad (14)$$

It will be regarded as the nominal plant to derive the CGSA robust controller.

As we known, the objective of H_∞ robust control is to obtain min$||\Delta(s)S(s)||_\infty$. Here, $\Delta(s)$ can be selected as 1 sec^{-1}, which implies that the system input is a unit step signal.

According to the maximum modulus theorem, a bounded function cannot attain its maximum value at the interior point. On the other hand, the G(s) has a zero at s = 2/θ in the open right half plane. Thus we get:

$$\left\|\Delta(s)S(s)\right\|_\infty = \left\|\Delta(s)\left[1-G_0(s)Q(s)\right]\right\|_\infty \geq \Delta(2/\theta) \quad (15)$$

Consequently we have:

$$\min\left\|\Delta(s)S(s)\right\|_\infty = \min\left\|\Delta(s)\left(1-G_0(s)Q(s)\right)\right\|_\infty = \theta/2 \quad (16)$$

In practical control process, the unique optimal control performance such as Eq. 16 may not be required. A suboptimal control performance is usually adopted, such as the performance of $||\Delta(s)S(s)||_\infty$ could be defined as:

$$||\Delta(s)S(s)||_\infty = \alpha\theta \quad (17)$$

where, $\alpha > 0.5$.

Then the control performance and robustness of the system can be met simultaneously if and only if:

$$\left\|\left|\Delta(\omega)T(j\omega)\right| + \left|\Delta(\omega)S(j\omega)/\alpha\theta\right|\right\|_\infty < 1 \quad (18)$$

Consequently we can get:

$$\left\|T(j\omega) + S(j\omega)/\alpha\theta\right\|_\infty < |1/\lambda| \quad (19)$$

The essence of the robust control is how to construct T(s) to satisfy the Eq. 19 and the controller C(s) can be deduced out directly. In this study, T(s) is constructed using the following low-pass filter Eq. 20 to roll T(s) off at high frequency:

$$J(s) = \frac{1}{(\tau_1 s+1)^m} \quad (20)$$

Here, m is the relative degree of $G_0(s)$. τ_1 is a positive real constant relating to the time constant of the closed loop control system, it can adjust the performance and robustness of the closed loop control system directly, when τ_1 approaches to zero, the nominal performance tends to be optimal, but the robustness would be decreased simultaneously. Also a J(s) with higher order than m can be chosen, however the complexity of the derived controller would also increase with little improvement of control performance.

For the plant 14, we can get:

$$G_0(s)Q(s) = \frac{1}{\tau_1 s+1} \quad (21)$$

The corresponding controller of the unity feedback loop is:

$$C(s) = \frac{1}{K\tau_1}\frac{(\tau s+1)(\theta s+2)}{(2-\theta s)s} \quad (22)$$

Here, there exists one right half pole which characterizes the controller 22 instability. Here, mirror-injection method (Zhang, 2008) is used for this unstable control loop, therefore the controller of the system becomes:

$$C(s) = \frac{1}{K\tau_1}\frac{(\tau s+1)(\theta s+2)}{(2+\theta s)s} = \frac{(\tau s+1)}{K\tau_1 s} \quad (23)$$

Note that there is only one adjustable parameter τ_1 in the controller 23. It has been shown that τ_1 relates to the system control performance and robust properties simultaneously.

Assuming the error introduced by the approximation as uncertainty, the actual time delay plant is in the form of Eq. 10, then we can get:

$$S(s) = \frac{\tau_1 s}{e^{-\theta s} + \tau_1 s} \quad (24)$$

$$T(s) = \frac{e^{-\theta s}}{e^{-\theta s} + \tau_1 s} \quad (25)$$

It can be seen that T(s) and S(s) do not depend on K and τ. This implies that the response of the control system relates only to tuning parameter τ_1 and the time delay θ. Also according to the Eq. 19, it can be known that the performance and robustness of the system can be adjusted by tuning parameter τ_1 monotonously. Assuming $\lambda = 1$, the control performance and robustness can be met if and only if:

$$\tau_1 > \theta - \frac{1}{\alpha}\ln\theta \quad (26)$$

SIMULATIONS AND ANALYSIS

In order to illustrate the effectiveness of the CGSA controller proposed in this study, the following plant 27 is considered:

$$G_0(s) = \frac{e^{-5s}}{s+1} \quad (27)$$

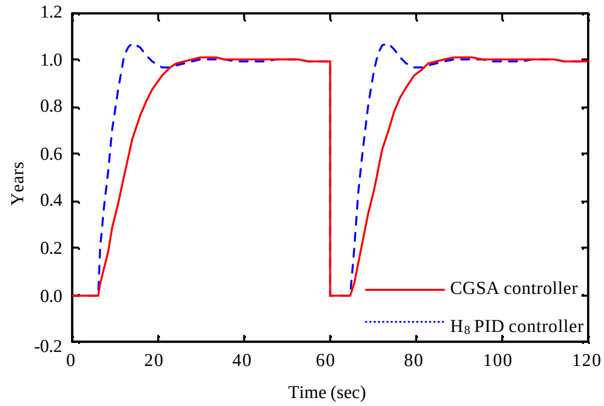

Fig. 4: Response of the system

A unit step signal is added at t = 0 s and a unit step load disturbance at t = 60 sec. Define the control performance as $\|\Delta(s)S(s)\|_\infty<5\theta$, then the tuning parameter τ_1 should be more than 4.6781. Also we can increase the value of τ_1 until the required closed loop response is obtained. In this example, the tuning parameter $\tau_1 = 11$. For the purpose of comparison, a H_8 PID controller from the reference (Zhang *et al*., 2003) is used. The closed-loop responses are shown in Fig. 4. It is found that the CGSA controller and the H_8 PID controller have the same settling time, but the CGSA controller provides a non-overshoot response and better disturbance rejection properties.

CONCLUSION

In this study, an efficient CGSA controller for time delay process is designed. The work is of significance in that the controller can be designed and tuned by explicit formulas in accordance with the design requirements, and provides insight into control system design procedures. This implies that the controller can be designed more directly and effectively. The robust stability and control performance are also discussed and sufficient and necessary conditions are given, which show that the tuning parameters of the CGSA controller have a monotonous relationship to the system robustness and control performance indices.

ACKNOWLEDGMENTS

This study is financially supported by the National Natural Science Foundation of China under Grant No. 51309043, Fundamental Research Funds for the Central University under Grant No. 313201337-1-7 and Natural Science Foundation of Liaoning Province of China under Grant No. 2013020003.

REFERENCES

Astrom, K.J., C.C. Hang and B.C. Lim, 1994. A new Smith predictor for controlling a process with an integrator and long dead-time. IEEE Trans. Autom. Control, 39: 343-345.

Doyle, J.C., K. Glover, P.P. Khargonekar and B.A. Francis, 1989. State-Space solution to standard H_2 and H_8 control problems. IEEE Trans. Autom. Control, 34: 831-847.

Guan, W., Z.J. Su and G.Q. Zhang, 2013. Integrated rudder/fin concise control based on frequency domain analysis. TELKOMNIKA Indonesian J. Electr. Eng., 11: 3841-3854.

Min, Z.Z., 2012. Research of smith predictor algorithm used in large time delay system. Int. J. Adv. Comput. Technol., 4: 209-218.

Padhan, D.G. and S. Majhi, 2012. Modified Smith predictor based cascade control of unstable time delay processes. ISA Trans., 51: 95-104.

Warwick, K. and D. Rees, 1988. Industrial Digital Control System. 2nd Edn., IET, USA., ISBN: 9780863411373, Pages: 523.

Zhang, W.D. and X.M. Xu, 2002. Optimal solution, quantitative performance estimation and robust tuning of the simplifying controller. ISA Trans., 41: 31-36.

Zhang, W.D., Y.G. Xi, G.K. Yang and X.M. Xu, 2003. Design PID controllers for desired time-domain or frequency-domain response. ISA Trans., 41: 511-520.

Zhang, X.K., 2008. Robust control of unstable process with dual pole. Syst. Eng. Electron., 30: 888-900.

Ziegler, J.G. and N.B. Nichols, 1993. Optimum settings for automatic controllers. J. Dyn. Syst. Meas. Control, 115: 220-222.