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Robust PID controller design for two-way remote performance system in the presence of mass uncertainty and Smith predictor

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Abstract: Time delay is considered as the main problem in remote performance system design. In this study, the robustness of closed-loop system and adaptability with two separate local controller for the commander system and obedient system in the presence of uncertain delay time in communication channel and operation environment is can be obtained, such that the local controller of obedient is responsible to track obedient system location through commander system, and the second local controller complements the matching property intelligently in addition to ensure the stability of the closed-loop system. In this article, a graphical method has been proposed to obtain the entire ranges of PID controller application, leading to the robustness of a system with time delay; we also introduce mass uncertainty. This method depends on system frequency response by nature, decreasing the complexities to model the system. In fact, time delays and parametric uncertainties are often formed in time processes and cause controller design to be essential for system. Appropriate performance results and robustness will represent the stability of the system against time delay uncertainty.

Key words: PID controller design; Performance system; Mass uncertainty

1. Introduction

In most physical systems there is a time delay that complicates the analysis and design of control systems. Smith Predictor allows the designer to design a controller for a system with no delay. Adding Smith Predictor to the time delay system improves the performance of the system. Smith Predictor includes a model of the processes with time delay in the inner loop, which can easily be implemented. In this article, first the control structure used for remote performance system is explained. Next, Smith Predictor method and its disadvantages are introduced, and then robust PID controller design method for the systems with multiplicative uncertainty is described. For example, the application of this method to design a commander controller for a simple single-input/output system is offered. Finally, the results of designing controllers for remote performance systems with multiplicative uncertainties are presented.

Control engineering is faced with the recognition of operation system consisting of desired output with system limitations. In order to use proportional derivative integral controllers of PID in industrial processes, many efforts have been undertaken to achieve effective methods and optimizing controller coefficients, critical conditions of design and robustness are considered. With the combination of classical control basic concepts and robust control flexibility, we can design a good stable and reliable controller for systems. Robust Control is desired for control systems that the system model has uncertainties. Recent work has been conducted to find PID controller that makes the system stable. Researchers have used mathematical definitions of Hermit-Biller theory for all PID controllers, making the time-delay systems stable.

In (Abd-El-Fatah and El–Sayed Elewa, 1994) and (Mostafa et al., 1999), controller design method is presented that doesn't need to derivative mathematical equations. Authors of references (Abd-El-Fatah and El–Sayed Elewa, 1994) and ((Mostafa et al., 1999) have extended their research to find all PID controller, making the time-delay systems stable.

Here, controller design is described by mass uncertainty. In this article, first the control structure used for remote performance system is explained. Then, PID controller design method for mass uncertainty system is addressed. For example, the application of this method to design a commander controller for a simple single-input/output system is offered. Finally, the results of designing controllers for remote performance systems with multiplicative uncertainties are presented.

2. The control system

In (Tang and Xu, 1995; Kato et al., 2001) Alafi and Faroukhi proposed a new structure for two-way remote performance systems in the presence of uncertainty. In these references a simple control method is presented fortwo-way remote

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performance robotic systems with uncertainty in the time delay. For complete accuracy and consistency, the force is measured at the remote site and direct measure of the recurrent force in local site. At the core of this control structure, the known algorithm is extended, that isolates closed-loop system in addition to update time delay in stable systems. In direct measurement of force, recurrent force control and position / velocity signal are sent from commander to the obedient; and then force recurred from operational environment is sent to the commander using a force sensor in order to create feedback signal so that the operator will be informed about the operations in remote site. The control structure has advantage for the local controllers. A controller is for tracking orders and another for better tracking of the force so that the stability of the closed-loop system in the presence of uncertainty in time delay is guaranteed. The control structure used is schematically shown in Fig. 1.

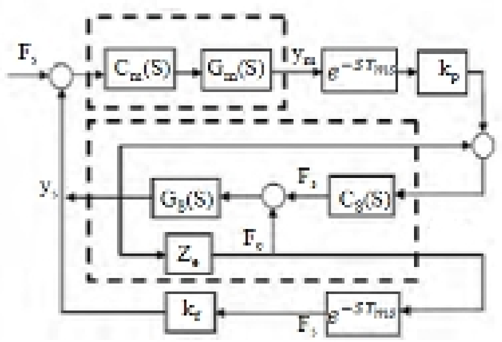

Fig. 1: the control structure

In the proposed method, for the accuracy of position/velocity given by the Commander, the contact forces in the obedient robot are used. In addition, direct measurement of force, recurrent force control occurs in the operating environment. Direct measurement of force, recurrent force control is a simple example of recurrent force schematic using a force sensor to return contact force to the operator. The main objective of the proposed control schematics is achieving precision and stability. In this method, the following conditions must be observed:

1. The overall closed-loop system with easy access conditions is stable.
2. Tracking position / velocity is guaranteed. Tracking position / velocity means that the obedient output y_s tracks commander output y_m with acceptable accuracy. Note that the output of commander and obedient is considered as position or speed.
3. Tracking force is guaranteed. This means that the recurrent force F_s tracks the operator applied force.

Conditions above are observed by designing two local controllers, one controller at the remote site Cs, and the other controller in the local site C_m. Remote site controller is responsible for tracking position / velocity and local site controller for tracking the force so that the stability of the overall system is maintained. Here we assume, position and force scaling factors are equal to one and F_e can be measured.

Obedient controller is designed based on the rules of control. For this purpose, measurements of the forces are performed at the local site. If the output of the commander and obedient robots is position as shown in Fig. 1, then the transfer function of commander position is writable as follows:

(1) $$\frac{Y_S(s)}{Y_m(s)} = \frac{C_S(s)G_S(s)}{1+Z_e G_S(s)+C_S(s)G_S(s)} e^{-sT_{ms}}$$

Since the time delay in trip does not appear in the above equation, transfer function in equation (Simoes et al., 1997) has limited dimensions. So info delay is used for the remote site obedient controller, then PD has no effect on stability. In addition, you can use a classic controller so that system will be stable in equation (Simoes et al., 1997). The position / velocity of commander robot converge with tracking error for the position.

3. PID controller design method for systems with uncertainty

Commander Controller is designed for direct measurement of force, recurrent force control. The controller should ensure tracking force and closed-loop system stability. Tracking force means that recurrent force $F_s(t)$ tracks the operator force $F_h(t)$. Variables are defined as follows:

(2) $$\widehat{G_s}(s) = \frac{Z_e C_S(s) G_S(s)}{1+Z_e G_S(s)+C_S(s)G_S(s)}$$

(3) $$G(s) = \widehat{G_s}(s) G_m(s)$$

$$F_r(s) = F_e(s)e^{-sT_{sm}}$$ and $$T = T_{ms} + T_{sm}$$

Considering force tracking, the contact force follows the operator force. Since tracking the force is done by sending force through returning way of the communication channel, we have:

$$M(s) = \frac{F_r(s)}{F_h(s)} = \frac{C_m(s)G(s)e^{-sT}}{1+C_m(s)G(s)e^{-sT}}$$

According to what was said, to simulate a PID controller we have:

Consider the controller system shown in Fig. 2. This Fig. shows that the control system is together with mass uncertainty. So what the Fig. shows is PID controller based on the following relations:

$$C_m(s) = K_{p+} \frac{K_i}{s} + K_d s$$

$$G(j\omega) = Re(\omega) + jIm(\omega)$$

$$C_m(j\omega) = K_p + \frac{K_i}{j\omega} + K_d(j\omega)$$

$$W_T(j\omega) = A_A(\omega) + jB_A(\omega)$$

To find robust for a random system, all PID controllers should be found to close stable-loop system.

$$\|W_T(j\omega)C_m(j\omega)S(j\omega)\|_\infty \le \gamma$$

S (jw) is the sensitivity function.

$$S(j\omega) = \frac{1}{1 + G(j\omega)C_m(j\omega)}$$

Weighting conditions of sensitivity for a single-input/output system is displayed by phase domain:

$$W_T(j\omega)C_m(j\omega)S(j\omega) = |W_T(j\omega)C_m(j\omega)S(j\omega)|e^{j\angle W_T(j\omega)}$$

Robust stability condition can be written as:

$$W_T(j\omega)C_m(j\omega)S(j\omega)e^{j\theta_A} \le \gamma \qquad \forall\omega$$

$$\frac{W_T(j\omega)C_m(j\omega)}{1 + G(j\omega)C_m(j\omega)} e^{j\theta_A} \le \gamma \ \forall\omega$$

$$\theta_A = -\angle W_T(j\omega)C_m(j\omega)S(j\omega)$$

It can be shown that all PID controller, which is in the certain range, are zero:

$$P(\omega, \theta_A, \gamma) = 1 + G(j\omega)C_m(j\omega) - \frac{1}{\gamma}\{W_T(j\omega)C_m(j\omega)e^{j\theta_A}\}$$

$$e^{j\theta_A} = \cos\theta_A + j\sin\theta_A$$

By replacing the relations we have:

$$P(\omega, \theta_A, \gamma) = 1 + \left((Re\,\omega + jIm(\omega))(K_p + \frac{K_i}{j\omega} + K_d(j\omega))\right) - \left(\frac{1}{\gamma}(A_A(\omega) + jB_A(\omega))(K_p + \frac{K_i}{j\omega} + K_d(j\omega))(\cos\theta_A + j\sin\theta_A\right)$$

By analyzing real and imaginary of relations we have:

$$X_{R_p}K_p + X_{R_i}K_i + X_{R_d}K_d = 0$$

$$X_{I_p}K_p + X_{I_i}K_i + X_{I_d}K_d = -\omega$$

$$X_{R_p} = -\omega(Im(\omega) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))$$

$$X_{R_i} = (Re(\omega) + \frac{1}{\gamma}(A_A\cos\theta_A - B_A\sin\theta_A))$$

$$X_{R_d} = -\omega^2(Re(\omega) + \frac{1}{\gamma}(A_A\cos\theta_A - B_A\sin\theta_A))$$

$$X_{I_p} = \omega(Re(\omega) + \frac{1}{\gamma}(A_A\cos\theta_A - B_A\sin\theta_A))$$

$$X_{I_i} = (Im(\omega) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))$$

$$X_{I_d} = -\omega^2(Im(\omega) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))$$

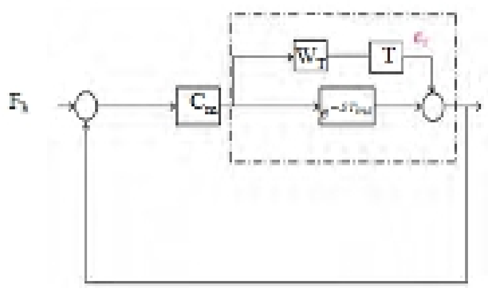

Fig. 2: Schematic view of PID controller

5. Design of PID controller with constant Kd

Considering constant K_d, we have:

$$\begin{bmatrix} X_{R_p} & X_{R_i} \\ X_{I_p} & X_{I_i} \end{bmatrix}\begin{bmatrix} K_p \\ K_i \end{bmatrix} = \begin{bmatrix} 0 - X_{R_d}\overline{K_d} \\ -\omega - X_{I_d}\overline{K_d} \end{bmatrix}$$

$$\theta_A \in [0, 2\pi],\ \omega \ne 0$$

$$K_p(\omega, \theta_A, \gamma) = \frac{-Re(\omega) - \frac{1}{\gamma}(A_A\cos\theta_A - B_A\sin\theta_A))}{X(\omega)}$$

$$K_i(\omega, \theta_A, \gamma) = \omega^2\overline{K_d} + \frac{-\omega(Im(\omega) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))}{X(\omega)}$$

$$X(\omega) = |G(j\omega)|^2 - \frac{1}{\gamma^2} + |W_T(j\omega)|^2 + \frac{2}{\gamma}(Re(\omega)(A_A\cos\theta_A - B_A\sin\theta_A) + Im(\omega)A_A\sin\theta_A + B_A\cos\theta_A)$$

$$|G(j\omega)|^2 = Re^2(\omega) + Im^2(\omega)$$

$$|W_T(j\omega)|^2 = A_A{}^2(\omega) + B_A{}^2(\omega)$$

6. Design of PID controller with constant Ki

Considering constant K_i, we have:

$$\begin{bmatrix} X_{R_p} & X_{R_d} \\ X_{I_p} & X_{I_d} \end{bmatrix}\begin{bmatrix} K_p \\ K_d \end{bmatrix} = \begin{bmatrix} 0 - X_{R_i}\overline{K_i} \\ -\omega - X_{I_i}\overline{K_i} \end{bmatrix}$$

$$\theta_A \in [0, 2\pi],\ \omega \ne 0$$

$$K_p(\omega, \theta_A, \gamma) = \frac{-Re(\omega) - \frac{1}{\gamma}(A_A\cos\theta_A - B_A\sin\theta_A))}{X(\omega)}$$

$$K_d(\omega, \theta_A, \gamma) = \frac{\overline{K_i}}{\omega^2} + \frac{Im(\omega) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))}{\omega X(\omega)}$$

7. Design of PID controller with constant Kp

Considering constant K_p, we have:

$$\begin{bmatrix} X_{R_i} & X_{R_d} \\ X_{I_i} & X_{I_d} \end{bmatrix}\begin{bmatrix} K_i \\ K_d \end{bmatrix} = \begin{bmatrix} 0 - X_{R_p}\overline{K_p} \\ \omega \quad X_{I_p}\overline{K_p} \end{bmatrix}$$

$$K_i(\omega_1, \theta_A, \gamma),\ K_d(\omega_1, \theta_A, \gamma) \qquad K_p(\omega_1, \theta_A, \gamma) = \overline{K_p} \ \text{if}\ \omega = \omega_1$$

$$K_d(\omega_1, \theta_A, \gamma) = \frac{K_i(\omega_1, \theta_A, \gamma)}{\omega_1{}^2} + \frac{Im(\omega_1) + \frac{1}{\gamma}(A_A\sin\theta_A + B_A\cos\theta_A))}{\omega_1 X(\omega_1)}$$

Finally, by applying proposed control we have:

$$G_m = \frac{1}{s(0.4s+2)}$$

$$G_s = \frac{1}{s(s+0.2)}$$

$$C_s = 44.4s + 499$$

$$G(s) = \frac{4.44s^2 + 94.3s + 499}{0.4s^4 + 20.88s^3 + 334.1s^2 + 1500s}$$

8. The final simulation

In this method, we first plotted the uncertainty:

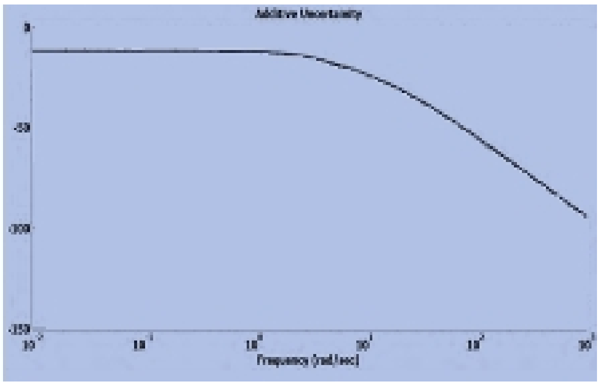

Fig. 3: Diagram of the uncertainty of outcome

Now, we obtain Wt with respect to the bands of uncertainty coefficient, as follows:

$$W_T = \frac{20}{s^2 + 28s + 75}$$

Then at each step, with constant coefficient of the PID controller and according to the resulting uncertainty coefficient, we draw the response band of two other factors:

A) Nominal stability band and robust stability in the plane (Kp, Ki), with constant coefficient $K_d = 0.4$ is plotted.

B) Nominal stability band and robust stability in the plane (Kd, Ki), with constant coefficient Kp = 0.004 is plotted.

C) To draw robust stability band and nominal stability band in the plane (Kp, Ki), answer for that is where Kp index is 2.

So we draw frequency range as described above.

D) Considering the robust stability and nominal stability bands in the plane (Kp, Ki), with constant Kp = 2, coefficient is plotted as follows:

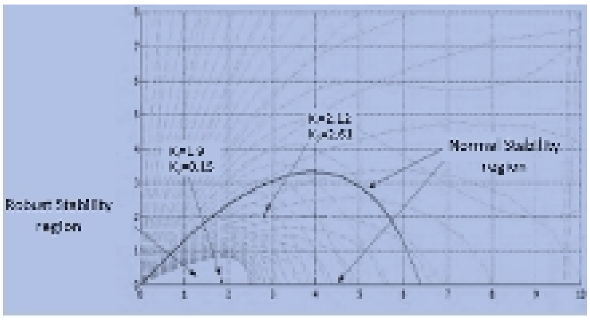

Fig. 4: Nominal stability band and robust stability in the plane (Kp, Ki), with constant coefficient $K_d = 0.4$ is plotted

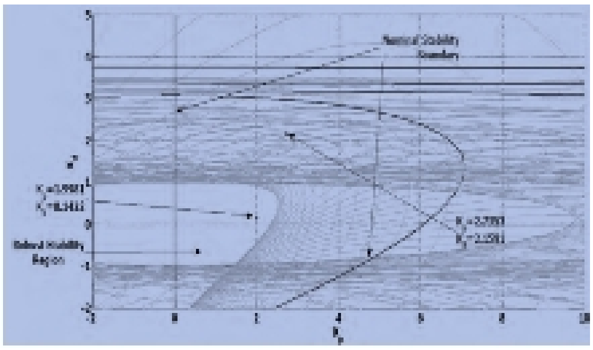

Fig. 5: Nominal stability band and robust stability in the plane (Kd, Ki), with constant coefficient Kp = 0.004 is plotted.

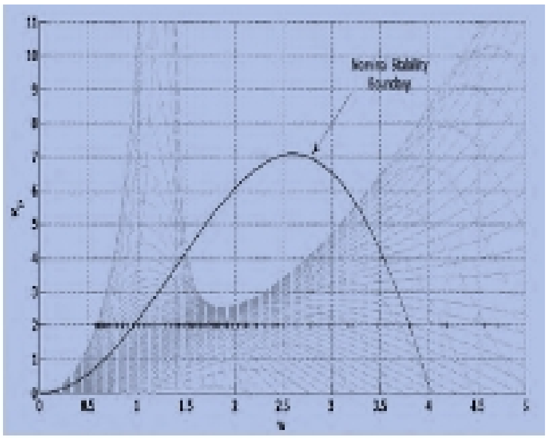

Fig. 6: To draw robust stability band and nominal stability band in the plane (Kp, Ki), answer for that is where Kp index is 2

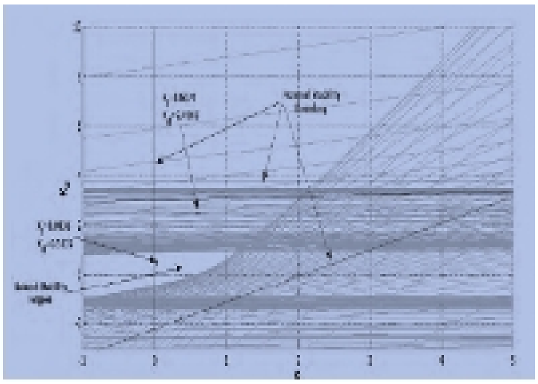

Fig. 7: the robust stability and nominal stability bands in the plane (Kp, Ki), with constant Kp = 2

9. The simulation results

1) The system with a time delay of 0.75 seconds in total round-trip path, robust PID based on mass uncertainty and unit step input

A) Considering constant Kd = 0.25, the chosen controller will beas follows:

$$C_m = 1.8478 + \frac{0.1130}{s} + 0.3s$$

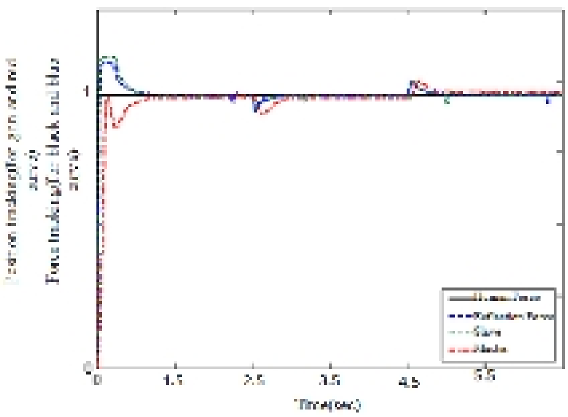

Fig. 7: tracking position and force with constant derived coefficients on the basis of mass uncertainty with time of 0.75s

By constant Ki = 0.01, controller is as follows:

$$C_m = 1.9981 + \frac{0.036}{s} + 0.1422s$$

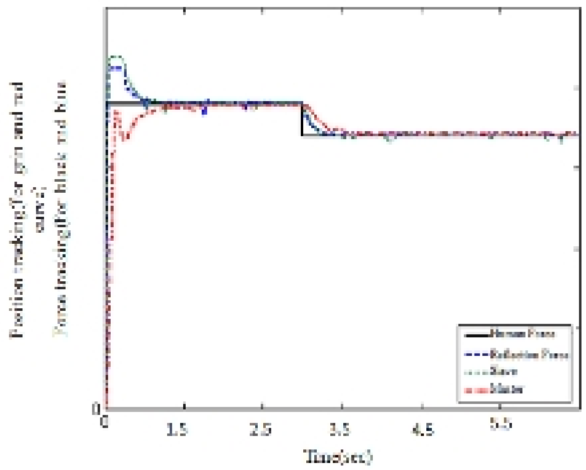

Fig. 8: V tracking position and force with constant integral coefficients on the basis of mass uncertainty with time of 0.75s

10. Conclusion

The major disadvantage of remote performance systems is uncertain time delay in communication channel and the operating environment. In practice, this delay can be arisen from different factors such as distance between commander and obedient system and the number of users. In this paper, a new controlling structure for two-way remote performance systems with uncertain time delay in communication channel and the operating environment is proposed by making use of two separate local controllers in order to achieve full compliance (position and force tracking together) and ensure the stability of the overall closed-loop system.

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