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Non-fragile Passive Filtering for a Class of Sampled-data System with Long Time-Delay

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Abstract: In this study, the problem of non-fragile passive filtering for a class of sampleded-data system with long time delay is addressed. The uncertain parameters are supposed to belong to norm-bounded uncertainties. A direct distribution processing methodology is developed to design a stable linear filter that assures asymptotic stability and a prescribed passive performance for the filtering error, in spite of the uncertainty and the long time-delay. The proposed algorithm is given in term of linear matrix inequality, whose feasibility and effectiveness has been shown by a numberical example.

Keywords: Long time-delay system, LMI, non-fragile passive filtering, sampled-data system

INTRODUCTION

Sampled-data system extensively exists in lots of industrial processes, such as welding industry, aeronautics and astronautics, chemical industry, etc., Chen and Francis (1995), which is characterized by a continuous control plant and discrete controller. Due to uncertainties and time-delay frequently appearing in sampled-data system, which makes the system instable and its performance deteriorated. Therefore, robust control and robust filtering have gradually become hot topics of control field and signal processing (Wu *et al.*, 2001; Wu *et al*., 2002; Theodor *et al*., 1994; Xie *et al.*, 1991; Xie *et al*., 1996; Li and Fu, 1997). However, above-mentioned results are based on the accurate feedback controllers. In fact, because of the existence of the accuracy problem parameter drift and other factors, it is shown that relatively small perturbation of the controller parameters might destabilize the closed-loop system, even lead to the performance degradation. Thus, it is necessary to design a controller which can tolerate some level of controller parameter variables. This is known as the non-fragile control problem. To data, this problem of non-fragile control and fitering has been widely investigated by many researchers, (Wang, 2011; Wang and Wu, 2011; Mahmoud, 2004; Yang and Che, 2008; Che and Yang, 2008).

On the other hand, passive theory has been important effect on stability analysis, which makes the product of the input and output as the supply of energy rate, in order to reflect energy decay characteristics in bounded input limit. In recent years, researches has made lots of works in passive theory, such as Mahmoud, (1988) and Zhang *et al*., (2006).

This study deals with non-fragile passive filtering problem for sampled- data systems whose delay is longer than a sampling period. The uncertain parameters are assumed to belong to a given norm-bounded type. A methodology for the design of a full- order stable linear filter that assures asymptotic stability and a prescribed passive performance for the filtering error system, irrespective of the uncertainty and long time delay, is developed by solving a set of LMIs.

PROBLEM FORMULATION

Consider sampled-data system:

$$\begin{cases} x(t) = A_0 x(t)(t-\tau)B_0\omega(t) \\ y(t) = C_0 x(t) + D\omega_0(t) \\ z(t) = L_0 x(t) \\ x(t) = x_0,\ t\in[-\tau,\ 0] \end{cases} \tag{1}$$

where, $x(t) \in R^n$ is the state vector and $y(t) \in R^r$ is the measured output, $z(t) \in R^l$ is the signal to be estimated, $\omega(t) \in R^p$ is the external disturbance input that belongs to $L_2[0,\infty]$, A_0, A_1, B_0, C_0, D_0 and L_0 are the constant matrices of approcaite dimensions. X_0 is the initial state vector. τ is time delay, which is uncertain and assumed to be evaluted between two agjacent sampling periods, namely, $(m-1)h \le \tau \le mh$, where $m \ge 1$ is a known constant.

Discretizing system (1) in one period, we can obtain the discrete state equation of the sampled-data system:

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$$\begin{cases} x(k+1) = G_0 x(k) + G_1 x(k-m+1) + \\ \qquad G_2 x(k-m) + H_0 \omega(k) \\ y(k) = C_0 x(k) + D_0 \omega(k) \\ z(k) = L_0 x(k) \\ x(k) = x_0,\ k \le 0 \end{cases} \tag{2}$$

where,

$$G_0 = e^{A_0 h}, G_1 = \int_0^{mh-r} e^{A_0 h}\, dt A_1$$
$$G_2 = \int_{mh-\tau}^{h} e^{A_0 h} dt A_1, H_0 = \int_0^{h} e^{A_0 h}\, dt B_0$$

Since time-delay τ is uncertain, G_1 and G_2 are uncertain matrices. Let

$$A_0 = L \text{ diag } \{\lambda_1, \ldots, \lambda_n\}\ L^{-1}$$

where, L is a n×n nonsingular matrix, $\lambda_1, \ldots, \lambda_n$ are the eigenvalues of matrix A_0, here, assuming that $\lambda_1, \ldots, \lambda_n$ are unequal to 0, then:

$$\begin{aligned} G_1(\tau) &= \overline{G_1} + DF(\tau)E \\ G_2(\tau) &= \overline{G_2} + DF(\tau)E \end{aligned} \tag{3}$$

where,

$$\overline{G_1} = -L\, diag\{1/\lambda_1, \ldots, 1/\lambda_n\} E$$
$$\overline{G_2} = L\, diag\{e^{\lambda_1 h}/\lambda_1, \ldots, e^{\lambda_n h}/\lambda_n\} E$$
$$D = L\, diag\{e^{\lambda_1 \beta_1}/\lambda_1, \ldots, e^{\lambda_n \beta_n}/\lambda_n\} E = L^{-1} A_1$$
$$F(\tau) = diag\{e^{\lambda_1 (mh-\tau-\beta_1)}, \ldots, e^{\lambda_n (mh-\tau-\beta_n)}\}$$

Selection of β_i make $e^{\lambda i(mh-\tau-\beta i)} \le I$. Thus it is clear that:

$$F^T(\tau)F(\tau) \le I \tag{4}$$

Remark 1 If A_0 can't be transformed into a diagonal matrix or it has $j(0 \le j \le n)$ eigenvalues equal to 0, a similar result can be obtained, but $\overline{G_1}, \overline{G_2}$, D, $F(\tau)$, E, should be changed correspondingly.

The aim of this section is to design a full-order, linear, time-invariant asymp- totically stable filter for system (2), The state-space realization of the filter has the form:

$$\begin{cases} \hat{x}(k+1) = A_f \hat{x}(k) + B_f y(k) \\ \hat{z}(k) = C_f \hat{x}(k) \end{cases} \tag{5}$$

where, $A_f \in R^{n\times n}$, $B_f \in R^{n\times r}$, $C_f \in R^{l\times n}$ are filter parameters to be determined.

$$\begin{aligned} A_f &= A_{f1}(I + \Delta_1) \\ B_f &= B_{f1}(I + \Delta_1) \\ C_f &= C_{f1}(I + \Delta_1) \end{aligned} \tag{6}$$

In order to be convenient to solve the following linear matrix inequality,
Letting $\tilde{x} = M\hat{x}(k)$
and then $\hat{x}(k) = M^{-1}\tilde{x}(k)$
filter transformed:

$$\begin{cases} \tilde{x}(k+1) = MA_f M^{-1}\tilde{x}(k) + MB_f y(k) \\ \tilde{Z}(k) = C_f M^{-1}\tilde{x}(k) \end{cases} \tag{7}$$

Denote:

$$\xi(k)\begin{bmatrix} x(k) \\ \tilde{x}(k) \end{bmatrix}, e(k) = z(k) - \tilde{z}(k)$$

Then, fitering error system:

$$\begin{cases} \xi(k+1) = \tilde{G}_0 \xi(k) + \tilde{G}_{m-1}\xi(k-m+1) + \\ \qquad \tilde{G}_m \xi(k-m) + \tilde{H}_0 \omega(k) \\ e(k) = z(k) - \tilde{z}(k) = \tilde{L}_0 \xi(k) \end{cases} \tag{8}$$

where,

$$\tilde{G}_0 = \begin{bmatrix} G_0 & 0 \\ MB_f C_0 & MA_f M^{-1} \end{bmatrix}, \tilde{G}_{m-1} = \begin{bmatrix} G_{m-1} & 0 \\ 0 & 0 \end{bmatrix}$$
$$\tilde{G}_{m-1} = \begin{bmatrix} G_{m-1} & 0 \\ 0 & 0 \end{bmatrix}, \tilde{H}_0 = \begin{bmatrix} H_0 \\ MB_f D_0 \end{bmatrix}$$
$$L_0 = \begin{bmatrix} L_0 - C_f M^{-1} \end{bmatrix}$$

The non-fragile passive filtering problem address in this section is stated as follows:
Given scalars $\eta > 0$, find a full-order, linear, time-invariant, asymptotically stable filter with a state-space realization of the form (7) for system (2), such that:

- Filtering-error system (8) with $\omega(k) = 0$ is asymptotically stable
- The passive performance

$$2\sum_{K=0}^{\infty} eT(k)\omega(k) \ge 0 \tag{9}$$

is guranateed under zero-initial conditions for all nonzero $\omega(k) \in l_2[0, \infty]$.

Lemma 1: For given matrices $Q = Q^T$, H and E, with appprociate dimension:

$Q+HF(k)E+E^TF^T(k)\,H^T<0$

holds for all F(k) satisfying $F^T(k)F(k)\leq I$ if and only if there exists ϵ >0, such that:

$Q+\epsilon HH^T+\epsilon^{-1}E^TE<0$

RESULTS AND DISCUSSION

Theorem 1: Consider the filtering error system (7), the system is asymptotically table and (9) is satisfied under zero- initial conditions for all nonzero ω(k)ϵ $l_2[0,\infty]$., if there exist matrices such that the following matrix inequalities hold:

$$\Omega=\begin{bmatrix}\Omega_{11} & \Omega_{21}^T\\ \Omega_{21} & \Omega_{22}\end{bmatrix}<0 \tag{10}$$

where,

$$\Omega_{11}=\begin{bmatrix}\Theta_1 & * & * & * & * & * & *\\ \Theta_1 & \Theta_2 & * & * & * & * & *\\ 0 & 0 & -R_1 & * & * & * & *\\ 0 & 0 & 0 & -R_2 & * & * & *\\ L_0-\hat{C}_f & L_0 & 0 & 0 & 0 & * & *\\ SG_0 & SG_0 & SG_{m-1} & SG_m & SH_0 & -S & *\\ \Theta_3 & \Theta_4 & \Theta_5 & \Theta_6 & \Theta_7 & -I & -R_0\end{bmatrix}$$

$$\Omega_{21}=\begin{bmatrix}0 & 0 & 0 & 0 & \Theta_8 & 0 & 0\\ E_3 & 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \Theta_9\\ E_2C_0 & E_2C_0 & 0 & 0 & E_2D_0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0 & \Theta_{10}\\ E_1 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}$$

$$\Omega_{22}=diag\left\{\varepsilon_0 I,-\varepsilon_0 I-\varepsilon_1 I,-\varepsilon_1 I,-\varepsilon_2 I,-\varepsilon_2 I\right\}$$

$$\Theta_1=-S+R_1+R_2$$

$$\Theta_2=-R_0+R_1+R_2$$

$$\Theta_3=R_0G_0+\hat{B}_fC_0+\hat{A}_f$$

$$\Theta_4=R_0G_0+\hat{B}_fC_0$$

$$\Theta_5=R_0G_{m-1}$$

$$\Theta_6=RG_m$$

$$\Theta_7=R_0H_0+\hat{B}_fD_0$$

$$\Theta_8=-\varepsilon_0H_3^T\hat{C}_f^T$$

$$\Theta_9=-\varepsilon_1H_2^T\hat{B}_f^T$$

$$\Theta_{10}=\varepsilon_2H_1^T\hat{A}_f^T$$

Proof. Select the Lyapunov function candidate:

$$V(\xi(k))=\xi^T(k)P\xi(k)+\sum_{j=k-m+1}^{k-1}\xi^T(k)Q_1\xi(k)+\sum_{j=k-m+1}^{k-1}\xi^T(k)Q_1\xi(k)$$

Denote:

$$\xi=\begin{bmatrix}\xi(k)\\ \xi(k-m+1)\\ \xi(k-m)\end{bmatrix}$$

$$\Delta V=\xi^T(k)\begin{bmatrix}-P_1+Q_1+Q_2 & * & *\\ 0 & -Q_1 & *\\ 0 & 0 & -Q_2\end{bmatrix}\xi(k)+\xi^T(k)\begin{bmatrix}\tilde{G}_0^T\\ \tilde{G}_{m-1}^T\\ \tilde{G}_m^T\end{bmatrix}P_1\begin{bmatrix}\tilde{G}_0 & \tilde{G}_{m-1} & \tilde{G}_m\end{bmatrix}\xi(k) \tag{11}$$

Firstly, we consider the fitering error system (8) is asymotically stable with ω (k) = 0 and then according to LMI (10) , the following matrix inequality is true:

$$\begin{bmatrix}-P_1+Q_1+Q_2 & * & * & *\\ 0 & -Q_1 & * & *\\ 0 & 0 & -Q_2 & *\\ \tilde{G}_0 & \tilde{G}_{m-1} & \tilde{G}_m & -P_1^{-1}\end{bmatrix}<0 \tag{12}$$

By Schur complement, (12) is equivalent to:

$$\begin{bmatrix}-P_1+Q_1+Q_2 & * & *\\ 0 & -Q_1 & *\\ 0 & 0 & -Q_2\end{bmatrix}+\begin{bmatrix}\tilde{G}_0^T\\ \tilde{G}_{m-1}^T\\ \tilde{G}_m^T\end{bmatrix}P_1\begin{bmatrix}\tilde{G}_0 & \tilde{G}_{m-1} & \tilde{G}_m\end{bmatrix}<0 \tag{13}$$

According to Lyapunov function, we are known that the filtering error system is inner-stable.

Secondly, passive performance index is considered to (8). Letting:

$$\Delta V-2e^T(k)\omega(k)=\begin{bmatrix}-P_1+Q_1+Q_2 & * & * & *\\ 0 & -Q_1 & * & *\\ 0 & 0 & -Q_2 & *\\ \tilde{L}_0 & 0 & 0 & 0\end{bmatrix}+\begin{bmatrix}\tilde{G}_0^T\\ \tilde{G}_{Ym-1}\\ \tilde{G}_m^T\\ \tilde{H}_m^T\end{bmatrix}P_1\begin{bmatrix}\tilde{G}_0 & \tilde{G}_{m-1} & \tilde{G}_m & \tilde{H}_0\end{bmatrix} \tag{15}$$

Applying Schur Complement:

$$\begin{bmatrix} -P_1+Q_1+Q_2 & * & * & * & * \\ 0 & -Q_1 & * & * & * \\ 0 & 0 & -Q_2 & * & * \\ \tilde{L}_0 & 0 & 0 & 0 & * \\ P_1\tilde{G}_0 & P_1\tilde{G}_{m-1} & P_1\tilde{G}_m & \tilde{H}_0 & -P_1 \end{bmatrix} \quad (16)$$

Setting

$$P_1\begin{bmatrix} R_0 & X_{12} \\ X_{12}^T & X_{22} \end{bmatrix}, P_1^{-1}\begin{bmatrix} S^{-1} & Y_{12} \\ Y_{12}^T & Y_{22} \end{bmatrix}$$

$$T_1=\begin{bmatrix} S^{-1} & I \\ Y_{12}^T & 0 \end{bmatrix}, Q_1=\begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix}, Q_2=\begin{bmatrix} R_2 & 0 \\ 0 & 0 \end{bmatrix}$$

Choose congruent transformation diag {I, I, I, T_1}, Pre- and Post-multiplying both sides of ineuqalities (16), one obtains the following inequality:

$$\begin{bmatrix} \theta_1 & * & * & * & * & * & * \\ \theta_2 & \theta_3 & * & * & * & * & * \\ 0 & 0 & -R_1 & * & * & * & * \\ 0 & 0 & 0 & -R_1 & * & * & * \\ \theta_4 & L_0 & 0 & 0 & 0 & * & * \\ G_0S^{-1} & G_0 & G_{m-1} & G_m & H_0 & -S^{-1} & * \\ \theta_5 & \theta_6 & \theta_7 & \theta_8 & \theta_9 & -I & -R_0 \end{bmatrix} \quad (17)$$

where,

$$\theta_1=-S+S^{-1}R_1S^{-1}+S^{-1}R_2S^{-1}$$
$$\theta_2=-I+R_1S^{-1}+R_2S^{-1}$$
$$\theta_3=-R_0+R_1+R_2$$
$$\theta_4=-L_0S^{-1}-C_f\,M^{-1}Y_{12}^T$$
$$\theta_5=R_0G_0S^{-1}+X_{12}MB_fC_0S^{-1}+X_{12}MA_f\,M^{-1}Y_{12}^T$$
$$\theta_6=R_0G_0+X_{12}MB_fC_0$$
$$\theta_7=R_0G_{m-1}$$
$$\theta_8=R_0G_m$$
$$\theta_9=R_0H_0+X_{12}MB_fD_0$$

Choose congruent transformation diga{S ,I, I, I, I, S, I,}, pre- and Post- multiplying both sides of ineuqalities (17), one obtains the following inequality:

$$\hat{\theta}_1=-S+R_1+R_2\begin{bmatrix} \hat{\theta}_1 & * & * & * & * & * & * \\ \hat{\theta}_1 & \hat{\theta}_2 & * & * & * & * & * \\ 0 & 0 & -R_1 & * & * & * & * \\ 0 & 0 & 0 & -R_2 & * & * & * \\ \hat{\theta}_3 & L_0 & 0 & 0 & 0 & * & * \\ SG_0 & SG_0 & SG_{m-1} & SG_m & SH_0 & -S & * \\ \hat{\theta}_4 & \hat{\theta}_5 & R_0G_{m-1} & R_0G_m & \hat{\theta}_6 & -I & -R_0 \end{bmatrix} \quad (18)$$

where,

$$\hat{\theta}_1=-S+R_1+R_2$$
$$\hat{\theta}_2=-R_0+R_1+R_2$$
$$\hat{\theta}_3=L_0-C_f$$
$$\hat{\theta}_4=R_0G_0+(S-R_0)B_fC_0+(S-R_0)A_f$$
$$\hat{\theta}_5=R_0G_0+(S-R_0)B_fC_0$$
$$\hat{\theta}_6=R_0H_0+(S-R_0)B_fD_0$$
$$M=Y_{12}^TS$$
$$X_{12}M=S-R_0$$
$$A_f=A_{f1}(I+\Delta_1)$$
$$B_f=B_{f1}(I+\Delta_2)$$
$$C_f=C_{f1}(I+\Delta_3)$$

(18) is separated from definite part to uncertain part:

$$\begin{bmatrix} \hat{\theta}_1 & * & * & * & * & * & * \\ \hat{\theta}_1 & \hat{\theta}_2 & * & * & * & * & * \\ 0 & 0 & -R_1 & * & * & * & * \\ 0 & 0 & 0 & -R_2 & * & * & * \\ \Pi_1 & L_0 & 0 & 0 & 0 & * & * \\ SG_0 & SG_0 & SG_{m-1} & SG_m & SH_0 & -S & * \\ \Pi_2 & \Pi_3 & R_0G_{m-1} & R_0G_m & \Pi_4 & -I & -R_0 \end{bmatrix} \quad (19)$$
$$+\Theta_1F(\tau)\Theta_2+\Theta_2^TF^T(\tau)\Theta_2^T+\Theta_3F(\tau)\Theta_4+$$

by Lemma 2:

$$\begin{bmatrix} \hat{\theta}_1 & * & * & * & * & * & * \\ \hat{\theta}_1 & \hat{\theta}_2 & * & * & * & * & * \\ 0 & 0 & -R_1 & * & * & * & * \\ 0 & 0 & 0 & -R_2 & * & * & * \\ \Pi_1 & L_0 & 0 & 0 & 0 & * & * \\ SG_0 & SG_0 & SG_{m-1} & SG_m & SH_0 & -S & * \\ \Pi_2 & \Pi_3 & R_0G_{m-1} & R_0G_m & \Pi_4 & -I & -R_0 \end{bmatrix}+$$
$$\varepsilon_0\Theta_1\Theta_1^T+\varepsilon_0^{-1}\Theta_2^T\Theta_2+\varepsilon_1\Theta_3\Theta_3^T+\varepsilon_1^{-1}\Theta_4\Theta_4^T+$$
$$\varepsilon_2\Theta_5\Theta_5^T+\varepsilon_2^{-1}\Theta_6\Theta_6^T$$

where,

$$\Theta_1=\left[0\;0\;0\;0-\left(\hat{C}H_3\right)T\;0\;0\right]$$
$$\Theta_2=\left[E_3\;0\;0\;0\;0\;0\;0\right]$$
$$\Theta_3=\left[0\;0\;0\;0\;0\;0\left(\hat{B}_fH_2\right)^T\right]$$
$$\Theta_4=\left[E_2C_0\;\;E_2C_0\;\;0\;0\;E_2D_0\;\;0\;\;0\right]$$
$$\Theta_5=\left[0\;0\;0\;0\;0\;0\;\;\hat{A}_fH_1\right]$$
$$\Theta_6=\left[E_1\;0\;0\;0\;0\;0\;0\right]$$

by Lemma1, we can attain Themema1.

Simulation results: We consider the system (1) with:

$$A_0 = \begin{bmatrix} 0.5 & -3.5 \\ -1.2 & 0.6 \end{bmatrix}, A_1 = \begin{bmatrix} -1 & 0.5 \\ 0 & 0.1 \end{bmatrix},$$
$$B_0 = \begin{bmatrix} -5.5 \\ 1 \end{bmatrix} C_0 = \begin{bmatrix} -3 & 0.2 \end{bmatrix}, D_0 = 0.5, L_0 = \begin{bmatrix} -2 & 1 \end{bmatrix}$$

Letting $h = 0.1$, $m = 2$ and discretizing system (1), a new state equation is attained with corresponding parameter:

$$G_0 = \begin{bmatrix} 1.0735 & -0.3724 \\ -0.1277 & 1.0841 \end{bmatrix}, H_0 = \begin{bmatrix} -0.5862 \\ 0.1381 \end{bmatrix}$$

$$G_1 = \begin{bmatrix} -0.1033 & 0.0498 \\ 0.0062 & 0.0073 \end{bmatrix}, G_2 = \begin{bmatrix} 0.1011 & -0.2337 \\ 0.6279 & -0.3188 \end{bmatrix}$$
$$D = \begin{bmatrix} 0.4982 & 0.4277 \\ 0.2847 & -0.2566 \end{bmatrix}, E = \begin{bmatrix} 0.5899 & -0.3933 \\ -0.5689 & 0.1849 \end{bmatrix}$$

Apply MATLAB LMI Toolbox to solve and then, filter parameter is given, as follows:

$$A_f = \begin{bmatrix} 3.0894 & -1.8758 \\ -1.5262 & -0.0562 \end{bmatrix}$$
$$B_f = \begin{bmatrix} 2.9608 & -1.2716 \end{bmatrix}^T$$
$$C_f = \begin{bmatrix} -1.9827 & 0.9591 \end{bmatrix}$$

By numerical experiment, fitering effect of non-fragile passive filter is better than regular filter obviously.

CONCLUSION

The problem of the non-fragile passive filtering for a class of sampled-data system with long time-delay has been investigated. Using direct solvable approach, dimension of state variable is deceased, a novel filter is established and sufficient condition for the passivity of the combined system is derived via linear matrix inequality (LMI). Finally, a simulation example is presented to show the validity and advantages of the proposed method.

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