Research Article

Robust and Nonfragile H_∞ Kalman-Type Filter Design for Parameter-Uncertain Time-Delay Systems: PLMI Approach

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This paper describes the synthesis of a robust and nonfragile H_∞ Kalman-type filter design for a class of time-delay systems with polytopic uncertainties, filter-gain variations, and disturbances. We present the sufficient condition for filter existence and the method for designing a robust nonfragile H_∞ filter by using LMIs (Linear Matrix Inequalities) technique. Because the obtained sufficient condition can be represented as PLMIs (Parameterized Linear Matrix Inequalities), which can generate infinite LMIs, we use a relaxation technique to find finite solutions for a robust nonfragile H_∞ filter. We show that the proposed filter can minimize estimation error in terms of parameter uncertainties, filter-fragility, and disturbances.

1. Introduction

The Kalman filtering approach is a popular state estimation method for a class of systems presented in linear models and thus has been widely applied in previous research on control engineering and target tracking, among others [1–3]. However, this approach does not provide reliable performance if there exist system uncertainties due to no full knowledge of the system model. So, the robust Kalman filtering for uncertain system has been studied on various issues [4–9]. Another serious issue in filter design is fragility. In practice, a filter designed by robust theory can be fragile because of the uncertainty associated with the implemented filter itself (e.g., limited word lengths and round-off error, etc.) [10]. To solve this problem in [11–13], nonfragile design methods have been investigated using LMIs and Riccati equation. Also, in practical applications, the noise effects must be considered to reduce estimation error and improve filter performance. To deal with this problem, H_∞ filtering approach was proposed [13–22].

The aforementioned research has motivated our research to construct the filter for practical application with better performance against uncertainties, various disturbances, and time-delay. This paper examines additional methods to design a robust and nonfragile Kalman-type filter for a class

of uncertain systems with disturbances and time-delay by taking the PLMIs (parameterized linear matrix inequalities) approach. Here, we represent the uncertain linear system by polytopic uncertainties, filter-gain variation, time-delay, and disturbances. Next, we rewrite the sufficient condition for filter existence as PLMIs and use a relaxation technique to find finite feasible solutions. Finally, a numerical example is provided to verify the performance of the proposed filter design method. The main contributions of this article are summarized as follows.

- (1) Since uncertainties in the system and filter are designed as structured uncertainties, it is possible to find filter-gain region which guarantees filter performance using PLMI and relaxation technique with less computational efforts.
- (2) The design method included all of factor increasing estimation error such as system uncertainties, filter-gain variations, disturbances, and time-delay. Therefore, it is more suitable for practical filter applications.

2. Problem Statement

Consider the following linear system with parameter uncertainties and time-varying delay:

$$\begin{aligned}\dot{x}(t) &= A(t, \alpha)x(t) + A_d(t, \alpha)x(t - \tau(t)) + B_w w(t), \\ y(t) &= C(t, \alpha)x(t),\end{aligned}\quad (1)$$

where $x(t) \in \mathfrak{R}^n$ is the state, $y(t) \in \mathfrak{R}^m$ is the measured output, $\tau(t) \in \mathfrak{R}$ is the time-varying delay, $w(t)$ is the disturbance, and B_w is constant matrix with appropriate dimension. Here, we define the parameter uncertainties as follows:

$$\begin{aligned}A(t, \alpha) &= A_0 + \sum_{i=1}^L \alpha_i(t) A_i, \\ A_d(t, \alpha) &= A_{d0} + \sum_{i=1}^L \alpha_i(t) A_{di}, \\ C(t, \alpha) &= C_0 + \sum_{i=1}^L \alpha_i(t) C_i, \\ \alpha(t) &\geq 0, \quad \sum_{i=1}^L \alpha_i(t) = 1, \quad i = 1, 2, \dots, L.\end{aligned}\quad (2)$$

Here, the value of L represents the number of parameter uncertainties for system matrices, and the time-varying delay satisfies

$$0 \leq \tau(t) \leq \infty, \quad \dot{\tau}(t) \leq d < 1. \quad (3)$$

We can express a full-order filter for system (1) as

$$\begin{aligned}\dot{x}_f(t) &= A_f x_f(t) + K(t, \beta) [y(t) - C_f x_f(t)], \\ y_f(t) &= C_f x_f(t),\end{aligned}\quad (4)$$

where $x_f(t)$ is the filter state, $y_f(t)$ is the estimated output, and A_f and C_f are filter matrices. In addition, we can define the estimation error of filter as

$$e(t) = x(t) - x_f(t) \quad (5)$$

and calculate next state of estimation error $\dot{e}(t)$ from (5) as

$$\begin{aligned}\dot{e}(t) &= \dot{x}(t) - \dot{x}_f(t) \\ &= A(t, \alpha)x(t) + A_d(t, \alpha)x(t - \tau(t)) + B_w w(t) \\ &\quad - \{A_f x_f(t) + K(t, \beta) [y(t) - C_f x_f(t)]\} \\ &= A_k(t, \alpha, \beta)x(t) + A_d(t, \alpha)x(t - \tau(t)) \\ &\quad - A_{kf}(t, \beta)x_f(t) + B_w w(t),\end{aligned}\quad (6)$$

where

$$\begin{aligned}A_k(t, \alpha, \beta) &= A(t, \alpha) - K(t, \beta)C(t, \alpha), \\ A_{kf}(t, \beta) &= A_f - K(t, \beta)C_f.\end{aligned}\quad (7)$$

Here, we consider a robust and nonfragile filter for the system (4) as

$$\begin{aligned}K(t, \beta) &= K_0 + \sum_{j=1}^L B_j(t) \tilde{K}_j, \quad \tilde{K}_j = K_j - K_0, \\ B_j(t) &\geq 0, \quad \sum_{j=1}^L B_j(t) = 1, \quad j = 1, 2, \dots, L,\end{aligned}\quad (8)$$

where $K(t, \beta)$ is the region of filter-gain variations, K_j is the vertex of the polytope, and $\tilde{K}_j$ is the measure of nonfragility against filter-gain variation.

3. Robust and Nonfragile H_∞ Filter Design

In this section, we consider system performance and obtain the filter-gain $K(t, \beta)$. We can solve the parameters by using PLMI method because the system (1) and the filter (4) are transformed into matrix inequalities through the Lyapunov method.

Theorem 1. *The estimation error (5) is asymptotically minimizable with H_∞ norm bound γ with the filter-gain (8) if there are positive definite matrices P and R such that*

$$\begin{bmatrix} A_k^T(t, \alpha, \beta)P + PA_k(t, \alpha, \beta) + R & PA_d(t, \alpha) & -PA_{kf}(t, \beta) - A_k^T(t, \alpha, \beta)P & PB_w & C_f^T \\ * & -(1-d)R & -A_d^T(t, \alpha)P & 0 & 0 \\ * & * & A_{kf}^T(t, \beta) + PA_{kf}(t, \beta) & -PB_w & 0 \\ * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & -I \end{bmatrix} < 0. \quad (9)$$

Proof. We define a Lyapunov candidate functional as

$$V(e, x, t) = e^T(t)Pe(t) + \int_{t-\tau(t)}^t x^T(s)Rx(s)ds. \quad (10)$$

When assuming the zero input, we have

$$\begin{aligned}\dot{V}(e, x, t) &:= \dot{e}^T(t)Pe(t) + e^T(t)P\dot{e}(t) \\ &\quad + [x^T(t)Rx(t) - (1-d) \\ &\quad \times x^T(t - \tau(t))Rx(t - \tau(t))].\end{aligned}\quad (11)$$

In the next place, assume the zero initial condition and introduce

$$J = \int_0^\infty [y^T(t) y(t) - \gamma^2 w^T(t) w(t)] dt. \quad (12)$$

Noting

$$J \leq \int_0^\infty [y^T(t) y(t) - \gamma^2 w^T(t) w(t) + \dot{V}(e, x, t)] dt \quad (13)$$

and further substituting (11) to (13).

Let $\xi(t) = [x^T(t) \ x^T(t - \tau(t)) \ x_f^T(t) \ w^T(t)]^T$, then

$$J \leq \int_0^\infty \xi^T(t) Z \xi(t), \quad (14)$$

where Z is defined as

$$\begin{bmatrix} A_k^T(t, \alpha, \beta) P + PA_k(t, \alpha, \beta) + R & PA_d(t, \alpha) & -PA_{kf}(t, \beta) - A_k^T(t, \alpha, \beta) P & -PB_w \\ * & -(1-d)R & -A_d^T(t, \alpha) P & 0 \\ * & * & A_{kf}^T(t, \beta) + PA_{kf}(t, \beta) + C_f^T C_f & PB_w \\ * & * & * & -\gamma^2 I \end{bmatrix}. \quad (15)$$

Therefore, when $Z < 0$, $t \geq 0$, the estimation error is minimized with H_∞ norm bound γ . The inequality (15) is transformed into (9) using Schur complements [23]. $\square$

We present the proposed condition for a robust and nonfragile filter by PLMIs, which involve an infinite number of LMIs, and thus transform PLMIs into a finite number of LMIs by using relaxation technique.

Theorem 2. *The estimation error from linear parameter uncertain system (1) and filter (4) with time-delay is asymptotically minimizable with disturbance attenuation γ and nonfragility whenever there exist matrices M_0 , M_j ($j = 1, 2, \dots, L$), positive definite matrices P , R , and positive constant ρ such that*

$$\begin{aligned} & x^T M_0(z) x + \sum_{i=1}^L \alpha_i x^T M_i(z) x + \sum_{j=1}^L \beta_j x^T N_j(z) x \\ & + \sum_{1 \leq i \leq j \leq L} \max \left\{ -x^T M_{ij}(z) x \right. \\ & \quad \times \left(\frac{\alpha_i^2 + \beta_j^2}{2} - \frac{\alpha_i + \beta_j}{2} + 0.125 \right), \\ & \quad \left. x^T M_{ij}(z) x \cdot \frac{\alpha_i^2 + \beta_j^2}{2} \right\} < 0, \\ & \forall \|x\| = 1, \quad (\alpha_i, \beta_j) \in \text{vert } \Gamma, \end{aligned} \quad (16)$$

where z is the decision variable, $M_i(z)$, $N_j(z)$, $M_{ij}(z)$, are affine symmetric matrix-valued functions of z . Here, (16) holds for z , $M_0(z)$, $M_i(z)$, $N_j(z)$, and $M_{ij}(z)$ defined below.

$$M_0(z) = \begin{bmatrix} \phi_1 & PA_{d0} & \phi_2 & PB_w & C_0^T \\ * & -(1-d)R & -A_{d0}^T P & 0 & 0 \\ * & * & \phi_3 & -PB_w & 0 \\ * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & -I \end{bmatrix},$$

$$M_i(z) = \begin{bmatrix} \phi_4 & PA_{di} & \phi_5 & 0 & C_i^T \\ * & 0 & -A_{di}^T P & 0 & 0 \\ * & * & 0 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix},$$

$$N_j(z) = \begin{bmatrix} \phi_6 & 0 & \phi_7 & 0 & 0 \\ * & 0 & 0 & 0 & 0 \\ * & * & \phi_8 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix},$$

$$M_{ij}(z) = \begin{bmatrix} \phi_9 & 0 & \phi_{10} & 0 & 0 \\ * & 0 & 0 & 0 & 0 \\ * & * & 0 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix},$$

(17)

where

$$M_0 = PK_0, \quad M_j = PK_j, \quad \rho = \gamma^2,$$

$$\phi_1 = A_0^T P + PA_0 - C_0^T M_0^T - M_0 C_0 + R,$$

$$\phi_2 = -A_0^T P - PA_f + C_0^T M_0^T + M_0 C_f,$$

$$\phi_3 = A_f^T P + PA_f - C_f^T M_0^T - M_0 C_f,$$

$$\phi_4 = A_i^T P + PA_i - C_i^T M_0^T - M_0 C_i,$$

$$\phi_5 = -A_i^T P + C_i^T M_0^T,$$

$$\phi_6 = -C_0^T M_j^T - M_j C_0,$$

$$\phi_7 = C_0^T M_j^T + M_j C_f,$$

$$\phi_8 = -C_f^T M_j^T - M_j C_f,$$

$$\phi_9 = -C_i^T M_j^T - M_j C_i,$$

$$\phi_{10} = C_i^T M_j^T.$$

(18)

Proof. The inequality (9) in Theorem 1 is same as follows:

$$\begin{bmatrix} A_k^T(t, \alpha, \beta)P + PA_k(t, \alpha, \beta) + R & PA_d(t, \alpha) & -PA_{kf}(t, \beta) - A_k^T(t, \alpha, \beta)P & PB_w & C^T \\ * & -(1-d)R & -A_d^T(t, \alpha)P & 0 & 0 \\ * & * & A_{kf}^T(t, \beta) + PA_{kf}(t, \beta) & -PB_w & 0 \\ * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & -I \end{bmatrix} < 0 \quad (19)$$

$$\begin{aligned} \Leftrightarrow & \begin{bmatrix} \phi_1 & PA_{d0} & \phi_2 & PB_w & C_0^T \\ * & -(1-d)R & -A_{d0}^T P & 0 & 0 \\ * & * & \phi_3 & -PB_w & 0 \\ * & * & * & -\gamma^2 I & 0 \\ * & * & * & * & -I \end{bmatrix} + \sum_{i=1}^L \alpha_i \begin{bmatrix} \phi_4 & PA_{di} & \phi_5 & 0 & C_i^T \\ * & 0 & -A_{di}^T P & 0 & 0 \\ * & * & 0 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix} \\ & + \sum_{j=1}^L \beta_j \begin{bmatrix} \phi_6 & 0 & \phi_7 & 0 & 0 \\ * & 0 & 0 & 0 & 0 \\ * & * & \phi_8 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix} + \sum_{i=1}^L \alpha_i \sum_{j=1}^L \beta_j \begin{bmatrix} \phi_9 & 0 & \phi_{10} & 0 & 0 \\ * & 0 & 0 & 0 & 0 \\ * & * & 0 & 0 & 0 \\ * & * & * & 0 & 0 \\ * & * & * & * & 0 \end{bmatrix} < 0. \end{aligned} \quad (20)$$

The inequality (20) is converted to the (16) using the relaxation technique [24], because the fourth term in (16) is a tight upper bound of the fourth term in (20). $\square$

Since the filter implementation accompanied by imprecision inherent in analog-digital and digital-analog conversion, finite word length, and finite resolution measuring instruments and round-off errors in numerical computation, we have to consider a design procedure which has sufficient space for coefficients readjustment. Inequality (16) provides a sufficient condition for the existence of the robust H_∞ filter under additive filter-gain perturbations.

4. Numerical Example

Consider nominal system matrices for parameter uncertain linear system with

$$A_0 = \begin{bmatrix} -10 & 1 \\ 3 & -4 \end{bmatrix}, \quad (21)$$

$$C_0 = [1 \ 1],$$

and assume a system uncertainty range as $\pm 10\%$. Then, we can obtain the parameter uncertain matrices A_i and C_i as

$$\begin{aligned} A_1 &= \begin{bmatrix} -11 & 1.1 \\ 3.3 & -4.4 \end{bmatrix}, \\ A_2 &= \begin{bmatrix} -9 & 0.9 \\ 2.7 & -3.6 \end{bmatrix}, \\ C_1 &= [1.1 \ 1.1], \\ C_2 &= [0.9 \ 0.9] \end{aligned} \quad (22)$$

and the filter system matrices are

$$A_f = A_0, \quad C_f = C_0. \quad (23)$$

To solve this problem, we use the LMI toolbox with a parameter relaxation technique and obtain all feasible solutions as follows:

$$\begin{aligned} \sigma &= 0.7368, \\ P &= \begin{bmatrix} 0.5471 & -0.5194 \\ -0.5194 & 0.5577 \end{bmatrix}, \\ R &= \begin{bmatrix} 21.6870 & 0.0030 \\ 0.0030 & 21.6278 \end{bmatrix}, \\ M_0 &= \begin{bmatrix} 3.5087 \\ 7.7695 \end{bmatrix}, \\ M_1 &= \begin{bmatrix} -7.8882 \\ -5.7857 \end{bmatrix}, \\ M_2 &= \begin{bmatrix} -0.9740 \\ -1.0059 \end{bmatrix}. \end{aligned} \quad (24)$$

In this way, we obtain robust and nonfragile filter-gain with time-delay and vertices of the perturbation satisfying the nonfragility condition as follows:

$$\begin{aligned} \gamma &= 0.8584, \\ K_0 &= \begin{bmatrix} 169.6605 \\ 171.9380 \end{bmatrix}, \\ \bar{K}_1 &= \begin{bmatrix} -209.6399 \\ -205.6144 \end{bmatrix}, \\ \bar{K}_2 &= \begin{bmatrix} -30.1728 \\ -29.9039 \end{bmatrix}. \end{aligned} \quad (25)$$

— $w_1(t)$ (a) Trajectories of the $w_1(t)$ — $w_2(t)$ (b) Trajectories of the $w_2(t)$ FIGURE 1: Simulation results of disturbances $w(t)$.

For the simulation, we define the time-varying parameter as follows:

$$\begin{aligned}
 A(t, \alpha) &= A_0 + \tilde{A}_1 \sin^2 at + \tilde{A}_2 \cos^2 at, \\
 A_d(t, \alpha) &= A_{d0} + \tilde{A}_{d1} \sin^2 bt + \tilde{A}_{d2} \cos^2 bt, \\
 C(t, \alpha) &= C_0 + \tilde{C}_1 \sin^2 ct + \tilde{C}_2 \cos^2 ct, \\
 K(t, \beta) &= K_0 + \tilde{K}_1 \sin^2 dt + \tilde{K}_2 \cos^2 dt, \\
 a &\in \Re, \quad b \in \Re, \quad c \in \Re, \quad d \in \Re, \quad a \neq b \neq c \neq d.
 \end{aligned} \tag{26}$$

— Nominal state $x_1(t)$
... Nominal filter $x_{f1}(t)$ (a) System state $x_1(t)$ and filter state $x_{f1}(t)$ — Nominal state $x_2(t)$
... Nominal filter $x_{f2}(t)$ (b) System state $x_2(t)$ and filter state $x_{f2}(t)$

FIGURE 2: Simulation results of states for the nominal system and filter.

If the initial values of all states are zero and the value of $w(t)$ is defined as

$$\begin{aligned}
 |w_1(t)| &\leq 1, \quad \text{if } 1 \leq t \leq 5, \\
 |w_2(t)| &\leq 1, \quad \text{if } 3 \leq t \leq 7, \\
 w(t) &= 0, \quad \text{otherwise.}
 \end{aligned} \tag{27}$$

We simulate that the proposed nominal filter-gain K_0 for the system (1) with uncertainties and disturbances in Figure 1~Figure 4. It is demonstrated that the proposed nominal filter-gain K_0 guarantees the asymptotic minimization and disturbance attenuation with $\gamma = 0.8584$ from the simulation results Figures 2 and 3 because the trajectories of filter

FIGURE 3: Simulation results of output for the nominal system and filter.

FIGURE 4: Simulation result of estimation error for the nominal system and filter.

(estimated) output $y_f(t)$ converged to system output $y(t)$ through computer simulation. Figure 4 shows the minimized estimation error between nominal system and filter.

Next, it is demonstrated that the practical filter $K_0 + \beta_1(t)\bar{K}_1 + \beta_2(t)\bar{K}_2$ with filter-gain perturbations has the nonfragility as well as the robustness in Figures 5, 6, and 7. Through the simulation results, the proposed robust and nonfragile H_∞ filter guarantees the asymptotic minimization of estimation error and disturbance attenuation with $\gamma = 0.8584$ from the results in Figures 5 and 7. Figure 8 demonstrates that the proposed filter shows good performance even though there exist uncertainties, disturbances, and time-delay in system.

(a) System state $x_1(t)$ and filter state $x_{f1}(t)$

(b) System state $x_2(t)$ and filter state $x_{f2}(t)$

FIGURE 5: Simulation results of states for the practical system and filter.

5. Conclusion

This paper proposes a method for designing a robust and nonfragile H_∞ Kalman-type filter for linear time-delay systems with parameter uncertainties. We obtain filter regions satisfying the nonfragility condition by taking the relaxation technique based on PLMI approach, and the proposed filter is robust against parameter uncertainties in the system. Finally, even though there exist filter-gain variations in the polytopic region and disturbances, the obtained Kalman-type filter ensures the satisfactory filter performance and disturbance attenuation for the system.

FIGURE 6: Simulation results of output for the practical system and filter.

FIGURE 8: Comparisons of estimation error between nominal filter and practical filter.

FIGURE 7: Simulation result of estimation error for the practical system and filter.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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