第 29 卷 第 6 期 自 动 化 学 报 Vol. 29, No. 6
2003 年 11 月 ACTA AUTOMATICA SINICA Nov., 2003

New Approach to Robust L_2-L_∞ Filter Design for Uncertain Continuous-Time Systems[1)]

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Abstract With the help of Projection Lemma, a new L_2-L_∞ performance criterion is derived, which exhibits a kind of decoupling between Lyapunov matrix and system matrices. This kind of decoupling is enabled by introduction of an additional slack variable and enables us to obtain a parameter-dependent Lyapunov function for polytopic uncertain systems. Upon the proposed performance condition and by means of linear matrix inequality technique, both full-order and reduced-order robust L_2-L_∞ filtering problems are solved in a unified framework. The proposed approach can be further extended to deal with filtering problems with pole constraint. Compared with earlier result in the quadratic framework, our approach turns out to be less conservative.

Key words Robust filtering, linear matrix inequality, L_2-L_∞ performance, reduced-order filter

1 Introduction

The filtering problem for uncertain systems has received much attention in recent years[1~3]. For systems with parametric uncertainties, the control and filtering problems are mainly solved in the quadratic framework, which entails a fixed Lyapunov function for all admissible uncertain parameters. The quadratic stability, however, has been generally regarded as conservative and many researchers are intrigued to develop multiple or parameter-dependent Lyapunov functions[4,5].

The main purpose of the present paper is to apply the idea of parameter-dependent Lyapunov stability[4] to the L_2-L_∞ filtering problem for continuous-time systems with polytopic uncertainties, which has been solved in [6] through quadratic stability approach. With the help of Projection Lemma, we first propose a new L_2-L_∞ performance condition. This new criterion exhibits a kind of decoupling between Lyapunov matrix and system matrices, which is enabled by introduction of an additional slack variable and enables us to obtain a parameter-dependent Lyapunov function for polytopic uncertain systems. Upon the proposed performance condition and by means of linear matrix inequality technique, both full-order and reduced-order robust L_2-L_∞ filtering problems are solved in a unified framework. The proposed approach can be further extended to deal with filtering problems with pole constraint. Compared with earlier results in the quadratic framework, our approach turns out to be less conservative.

2 Problem formulation

Consider the following uncertain continuous-time system:

$$\dot{x}(t) = Ax(t) + B\omega(t), \quad y(t) = Cx(t) + D\omega(t), \quad z(t) = Lx(t) \tag{1}$$

where $x(t) \in R^n$ is the state vector, $\omega(t) \in R^q$ is the disturbance input, $y(t) \in R^m$ is the measurement output, and $z(t) \in R^p$ is the signal to be estimated. Suppose the system matrices are uncertain but belong to a given polytope:

$$M \doteq (A, B, C, D, L) \in \Re \tag{2}$$

1) Supported by National Natural Science Foundation of P. R. China (69874008)
Received April 20, 2002; in revised form Jauuary 20, 2003
收稿日期 2002-04-20; 收修改稿日期 2003-01-20

$$\mathfrak{R} \doteq \left\{(A,B,C,D,L) \mid (A,B,C,D,L) = \sum_{i=1}^{k} \tau_i (A_i,B_i,C_i,D_i,L_i); \tau_i \geqslant 0; \sum_{i=1}^{k} \tau_i = 1\right\}$$

We are interested in designing filters of order k described by

$$\dot{\hat{x}}(t) = A_F \hat{x}(t) + B_F y(t), \quad \hat{z}(t) = C_F \hat{x}(t) \tag{3}$$

where $\hat{x}(t) \in R^k$ ($k=n$ for full-order filtering, and $1 \leqslant k < n$ for reduced-order filtering). Then the filtering error system can be described by

$$\dot{\xi}(t) = \bar{A}\xi(t) + \bar{B}\omega(t), \quad e(t) = \bar{C}\xi(t) \tag{4}$$

where $\xi(t) \doteq \{x(t)^T, \hat{x}(t)^T\}^T$, $e(t) \doteq z(t) - \hat{z}(t)$, $\bar{A} = \begin{bmatrix} A & 0 \\ B_F C & A_F \end{bmatrix}$, $\bar{B} = \begin{bmatrix} B \\ B_F D \end{bmatrix}$, $\bar{C} = [L \quad -C_F]$.

The transfer function from $\omega(t)$ to $e(t)$ can be given by

$$T(s) = \bar{C}(sI - \bar{A})^{-1}\bar{B} \tag{5}$$

Definition 1. The L_2-L_∞ norm of the transfer function $T(s)$ is defined as:

$$\|T(s)\|_{L_2\text{-}L_\infty} \doteq \sup_{0 \neq \omega \in L_2} \left(\sup_t \|e(t)\|_2 \Big/ \left(\int_0^\infty \|\omega(t)\|_2^2 \mathrm{d}t \right)^{1/2} \right)$$

Our purpose is to design filters of form (3) for system (1), which guarantee the filtering error system (4) to be asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma (\gamma > 0)$. Filters satisfying the above conditions are called L_2-L_∞ filters.

Remark 1. Reduced-order filters, i. e., filters of order lower than the order of the system to be estimated, are often desirable to reduce the complexity and computational burden of the real-time filtering process. Compared with the full-order case[3,6], the reduced-order filtering problem receives relatively less attention and still remains a challenge. In this paper, we propose a new approach to solving both full-order and reduced-order filtering problems in a unified framework.

Lemma 1 (Projection Lemma[5]). Given a symmetric matrix $\Psi \in R^{m \times m}$ and two matrices M and N of column dimension m, there exists an X such that the following LMI holds:

$$\Psi + M^T X^T N + N^T X M < 0 \tag{6}$$

if and only if the following projection inequalities with respect to X are satisfied

$$M_\perp^T \Psi M_\perp < 0, \quad N_\perp^T \Psi N_\perp < 0 \tag{7}$$

where $M_\perp$ and $N_\perp$ denote arbitrary bases of the nullspaces of M and N, respectively.

3 Main results

Lemma 2[6]. Consider system (1) with $M \in \mathfrak{R}$ fixed and let $\gamma > 0$ be a given constant. Then the filtering error system (4) is asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma$ if and only if there exists a positive definite matrix $P \in R^{(n+k)\times(n+k)}$ satisfying

$$\bar{C}P\bar{C}^T < \gamma^2 I, \quad \bar{A}P + P\bar{A}^T + \bar{B}\bar{B}^T < 0 \tag{8),(9}$$

Extending Lemma 2 to polytopic uncertain systems, we have

Corollary 1. Consider system (1) with $M \in \mathfrak{R}$ representing an uncertain system and let $\gamma > 0$ be a given constant. Then the filtering error system (4) is asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma$ if there exists a positive definite matrix $P \in R^{(n+k)\times(n+k)}$ satisfying

$$\begin{bmatrix} -\gamma^2 I & \bar{C}_i P \\ P\bar{C}_i^T & -P \end{bmatrix} < 0, \quad \begin{bmatrix} \bar{A}_i P + P\bar{A}_i^T & \bar{B}_i \\ \bar{B}_i^T & -I \end{bmatrix} < 0, \quad \forall i = 1,2,\cdots,k \tag{10}$$

where $(\bar{A}_i, \bar{B}_i, \bar{C}_i)$ denotes matrices $(A_i, B_i, C_i, D_i, L_i)$ evaluated at each vertex of the polytope.

Corollary 1 is the robust L_2-L_∞ performance condition based on the quadratic stability notion, which entails a fixed positive definite matrix P to satisfy all the uncertain parameters of the polytope. In the following, we will derive another performance criterion by means of Projection Lemma.

Theorem 1. Consider system (1) with $M \in \Re$ fixed and let $\gamma > 0$ be a given constant. Then the filtering error system (4) is asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma$ if and only if there exist positive definite matrix $Y \in R^{(n+k)\times(n+k)}$ and matrix $G \in R^{(n+k)\times(n+k)}$ satisfying

$$\begin{bmatrix} -\gamma^2 I & \bar{C} \\ \bar{C}^{\mathrm{T}} & -Y \end{bmatrix} < 0, \quad \begin{bmatrix} -G^{\mathrm{T}} - G & G^{\mathrm{T}}\bar{A} + Y & G^{\mathrm{T}} & G^{\mathrm{T}}\bar{B} \\ \bar{A}^{\mathrm{T}}G + Y & -Y & 0 & 0 \\ G & 0 & -Y & 0 \\ \bar{B}^{\mathrm{T}}G & 0 & 0 & -I \end{bmatrix} < 0 \qquad (11),(12)$$

Proof. Define $P \doteq Y^{-1}$; then the equivalence between (8) and (11) can be easily established by Schur complement. Rewrite (12) as

$$\begin{bmatrix} 0 & Y & 0 & 0 \\ Y & -Y & 0 & 0 \\ 0 & 0 & -Y & 0 \\ 0 & 0 & 0 & -I \end{bmatrix} + M^{\mathrm{T}}G^{\mathrm{T}}N + N^{\mathrm{T}}GM < 0 \qquad (13)$$

where $M = [I \quad 0 \quad 0 \quad 0]$, $N = [-I \quad \bar{A} \quad I \quad \bar{B}]$. Then $M_\perp^{\mathrm{T}} = \begin{bmatrix} 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{bmatrix}$, $N_\perp^{\mathrm{T}} = \begin{bmatrix} \bar{A}^{\mathrm{T}} & I & 0 & 0 \\ I & 0 & I & 0 \\ \bar{B}^{\mathrm{T}} & 0 & 0 & I \end{bmatrix}$.

By Lemma 1 (Projection Lemma), (13) is equivalent to

$$\begin{bmatrix} Y\bar{A} + \bar{A}^{\mathrm{T}}Y - Y & Y & Y\bar{B} \\ Y & -Y & 0 \\ \bar{B}^{\mathrm{T}}Y & 0 & -I \end{bmatrix} < 0 \qquad (14)$$

A congruence transformation to (14) by $\mathrm{diag}\{Y^{-1}, Y^{-1}, I\}$ together with a Schur complement operation yields the equivalence between (14) and (9).

Extending Theorem 1 to uncertain cases leads to the following corollary.

Corollary 2. Consider system (1) with $M \in \Re$ representing an uncertain system and let $\gamma > 0$ be a given constant. Then the filtering error system (4) is asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma$ if there exist positive definite matrices $Y_i \in R^{(n+k)\times(n+k)}$, $i = 1, 2, \cdots, k$, and matrix $G \in R^{(n+k)\times(n+k)}$ satisfying

$$\begin{bmatrix} -\gamma^2 I & \bar{C}_i \\ \bar{C}_i^{\mathrm{T}} & -Y_i \end{bmatrix} < 0, \quad \begin{bmatrix} -G^{\mathrm{T}} - G & G^{\mathrm{T}}\bar{A}_i + Y_i & G^{\mathrm{T}} & G^{\mathrm{T}}\bar{B}_i \\ \bar{A}_i^{\mathrm{T}}G + Y_i & -Y_i & 0 & 0 \\ G & 0 & -Y_i & 0 \\ \bar{B}_i^{\mathrm{T}}G & 0 & 0 & -I \end{bmatrix} < 0, \quad \forall i = 1, 2, \cdots, k \qquad (15)$$

Remark 2. It should be noted that Lemma 2 and Theorem 1 are equivalent for systems with exact data. The difference between them lies in the fact that Theorem 2 exhibits a kind of decoupling between Lyapunov matrix and system matrices (i. e. , there is no product between matrix Y and system matrices). This kind of decoupling is enabled by introduction of a slack variable G and enables us to obtain a parameter-dependent L_2-L_∞ performance condition for polytopic uncertain systems (see Corollary 2).

Then the following theorem solves both full-order and reduced-order filtering problems in a unified framework on the basis of Corollary 2.

Theorem 2. Consider system (1) with $M \in \Re$ representing an uncertain system. Then an admissible robust L_2-L_∞ filter (3) exists if there exist matrices $\bar{Y}_{1i} = \bar{Y}_{1i}^{\mathrm{T}} > 0$, $\bar{Y}_{1i} \in R^{n\times n}$, $\bar{Y}_{2i} \in R^{n\times k}$, $\bar{Y}_{3i} = \bar{Y}_{3i}^{\mathrm{T}} > 0$, $\bar{Y}_{3i} \in R^{k\times k}$, $i = 1, 2, \cdots, k$, $R \in R^{n\times n}$, $F \in R^{k\times k}$, $V \in R^{n\times k}$, $\bar{A}_F \in R^{k\times k}$, $\bar{B}_F \in R^{k\times m}$, $\bar{C}_F \in R^{p\times k}$ satisfying

$$\begin{bmatrix} -\gamma^2 I & L_i & -\bar{C}_F \\ * & -\bar{Y}_{1i} & -\bar{Y}_{2i} \\ * & * & -\bar{Y}_{3i} \end{bmatrix} < 0, \quad \forall i = 1,2,\cdots,k \tag{16}$$

$$\begin{bmatrix} -R^T - R & -EF - V & R^T A_i + E\bar{B}_F C_i + \bar{Y}_{1i} & E\bar{A}_F + \bar{Y}_{2i} & R^T & EF & R^T B_i + E\bar{B}_F D_i \\ * & -F - F^T & V^T A_i + \bar{B}_F C_i + \bar{Y}_{2i}^T & \bar{A}_F + \bar{Y}_{3i} & V^T & F & V^T B_i + \bar{B}_F D_i \\ * & * & -\bar{Y}_{1i} & -\bar{Y}_{2i} & 0 & 0 & 0 \\ * & * & * & -\bar{Y}_{3i} & 0 & 0 & 0 \\ * & * & * & * & -\bar{Y}_{1i} & -\bar{Y}_{2i} & 0 \\ * & * & * & * & * & -\bar{Y}_{3i} & 0 \\ * & * & * & * & * & * & -I \end{bmatrix} < 0,$$

$$\forall i = 1,2,\cdots,k \tag{17}$$

where $E \doteq [I_{k\times k} \quad 0_{k\times(n-k)}]^T$, and I denotes an identity matrix. Then an admissible filter can be given by

$$A_F = F^{-1}\bar{A}_F, \quad B_F = F^{-1}\bar{B}_F, \quad C_F = \bar{C}_F \tag{18}$$

Proof. Since (17) implies $F^T + F > 0$, F is nonsingular. Therefore, we can always find square and non-singular matrices G_{21} and G_{22} satisfying $F = G_{21}^T G_{22}^{-1} G_{21}$. Now introduce the following matrices

$$J \doteq \begin{bmatrix} I & 0 \\ 0 & G_{22}^{-1}G_{21} \end{bmatrix}, \quad G_{11} \doteq R, \quad G_{12} \doteq VG_{21}^{-1}G_{22}, \quad G \doteq \begin{bmatrix} G_{11} & G_{12} \\ G_{21}E^T & G_{22} \end{bmatrix},$$

$$Y_i \doteq \begin{bmatrix} Y_{1i} & Y_{2i} \\ * & Y_{3i} \end{bmatrix} = J^{-T}\begin{bmatrix} \bar{Y}_{1i} & \bar{Y}_{2i} \\ * & \bar{Y}_{3i} \end{bmatrix}J^{-1}, \quad \begin{bmatrix} A_F & B_F \\ C_F & 0 \end{bmatrix} \doteq \begin{bmatrix} G_{21}^{-T} & 0 \\ 0 & I \end{bmatrix}\begin{bmatrix} \bar{A}_F & \bar{B}_F \\ \bar{C}_F & 0 \end{bmatrix}\begin{bmatrix} G_{21}^{-1}G_{22} & 0 \\ 0 & I \end{bmatrix} \tag{19}$$

By some routine matrix manipulations, it can be readily established that (16) and (17) are equivalent to

$$\begin{bmatrix} -\gamma^2 I & \bar{C}_i J \\ * & -J^T Y_i J \end{bmatrix} < 0, \quad \forall i = 1,2,\cdots,k \tag{20}$$

$$\begin{bmatrix} -J^T(G^T + G)J & J^T(G^T\bar{A}_i + Y_i)J & J^T G^T J & J^T G^T \bar{B}_i \\ * & -J^T Y_i J & 0 & 0 \\ * & * & -J^T Y_i J & 0 \\ * & * & * & -I \end{bmatrix} < 0, \quad \forall i = 1,2,\cdots,k \tag{21}$$

Performing congruence transformations to (20) by diag$\{I, J^{-1}\}$ and to (21) by diag$\{J^{-1}, J^{-1}, J^{-1}, I\}$ yields (15). Therefore, from Corollary 2 we can conclude that the filter with a state-space realization (A_F, B_F, C_F) defined in (19) guarantees the filtering error system (4) is asymptotically stable and $\|T(s)\|_{L_2\text{-}L_\infty} < \gamma$.

In addition, from the above proof we know that an admissible filter can be constructed by (19). However, there seems to be no systematic way to determine matrices G_{21} and G_{22} needed for the filter matrices. To deal with such a problem, let us denote the filter transfer function from $y(t)$ to $\hat{z}(t)$ by $T_{\hat{z}y}(s) = C_F(sI - A_F)^{-1}B_F$. Substituting the filter matrices with (19) and considering the relationship $F = G_{21}^T G_{22}^{-1} G_{21}$, we have $T_{\hat{z}y}(s) = \bar{C}_F(sI - F^{-1}\bar{A}_F)^{-1}F^{-1}\bar{B}_F$. Therefore, an admissible filter can also be given by (18).

Remark 3. Note that (16) and (17) are LMIs which are not only over the matrix variables, but also over the scalar γ^2. This implies that the scalar γ^2 can be included as one of the optimization variables for LMIs (16) and (17) to obtain the minimum noise attenuation level.

Remark 4. It should be noted that the standard linearization procedures proposed in [3,6] assume the off-diagonal entry of certain matrix (the matrix to be partitioned) to be square and nonsingular, therefore they can not be used to deal with the reduced order filtering problem. To keep the reduced order filter design tractable, here we have found a different linearization procedure, which solves both the full-order and reduced-order filtering synthesis problems in a unified framework. For the full-order filtering, matrix E defined in Theorem 2 becomes an identity matrix of dimension n, and for the reduced-order case, we have imposed certain structural restriction on the (2,1) block entry of matrix G, which introduces some overdesign into the filter design.

Remark 5. It is conjectured that the approach proposed in this paper can be further extended to deal with robust filtering problems with pole constraint, which have been addressed in prior works[9,10] in the quadratic framework.

4 An illustrative example

Consider the following uncertain system borrowed from [7,8]:

$$\dot{x}(t) = \begin{bmatrix} 0 & -1+0.3\alpha \\ 1 & -0.5 \end{bmatrix} x(t) + \begin{bmatrix} -2 & 0 \\ 1 & 0 \end{bmatrix} \omega(t),$$

$$y(t) = [-100 \quad 100]x(t) + [0 \quad 1]\omega(t), \quad z(t) = [1 \quad 0]x(t)$$

where α represents an uncertain parameter satisfying $-1 \leqslant \alpha \leqslant 1$.

By Theorem 2, the minimum guaranteed L_2-L_∞ cost for the full-order filtering is given by $\gamma^* = 1.1250$, with the associate filter matrices

$$A_F = \begin{bmatrix} -104.9370 & 104.7751 \\ 88.0213 & -88.0878 \end{bmatrix}, \quad B_F = \begin{bmatrix} -1.5130 \\ 1.2408 \end{bmatrix}, \quad C_F = [-0.7973 \quad 0.1401]$$

By the method proposed in [6], we can obtain $\gamma^* = 1.5241$, showing less conservativeness of our approach.

When using our approach to design reduced-order filters, the minimum guaranteed L_2-L_∞ cost is found to be $\gamma^* = 1.9830$, with the associate filter matrices

$$A_F = -0.7673, \quad B_F = 0.0120, \quad C_F = -0.7980$$

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不确定连续系统的鲁棒 L_2-L_∞ 滤波新方法

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摘　要　借助投影定理提出了一个新的连续系统 L_2-L_∞ 性能准则. 与已有的判据相比，该准则呈现出 Lyapunov 矩阵与系统矩阵之间分离的特性，使得将其应用于不确定系统时能够得到参数依赖型 Lyapunov 函数. 利用该判据，采用线性矩阵不等式技术推导了多面体不确定系统的全阶和降阶鲁棒 L_2-L_∞ 状态估计新方法. 所提出的方法可被进一步用于研究具有极点约束的 L_2-L_∞ 滤波问题. 与已有的基于二次稳定的滤波方案相比，本文提出的方法具有较低的保守性.

关键词　鲁棒滤波，线性矩阵不等式，L_2-L_∞ 性能，降阶滤波

中图分类号　TP13

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