L₁ filtering for networked control systems with stochastic communication delay

Yanhui Li¹, Wang Xu²

¹ College of Electrical and Information Engineering, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China
² College of Electrical and Information Engineering, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China

Corresponding author’s e-mail: 751054805@qq.com

Abstract. In view of the time-delay phenomena in the network, a new method for describing the input vectors of filters is proposed, considering the randomness of the observed outputs and using Bernoulli sequence to describe them. By constructing Lyapunov-Krasovskii function and analyzing it with infinitesimal operator, a criterion to ensure the mean square asymptotic stability of the filtering error system and satisfy the given L₁ performance is obtained. The validity of the designed filter is verified by numerical simulation.

1. Introduction

Networked control systems (NCSs) are used widely in such industries as industrial production and Unmanned Aerial Vehicle (UAV). The sensors, filters, actuators and other components of the system are connected with each other through the communication network. However, problems such as induced delay, measurement loss and sequential disorder often occur during signal transmission. Some literature takes into consideration the control input delay in NCSs, but fails to cover the measured output delay [1]. In addition, some literature fails to reflect the delay randomness in the sensor, or the measured output and network transmission [2]. With the rapid network development nowadays, wireless network transmission is drawing greater attention in the aspect of cost saving. For wireless network signal transmission, delay and packet loss have a greater impact compared to the wired transmission. Therefore, it is of great significance to conduct research on the filter technique of random network control systems with communication delay. Fuzzy theory is an effective means to solve nonlinear problems. The mathematical model based on T-S fuzzy has only a few fuzzy rules, and the T-S fuzzy with strong robustness is little affected by internal and external factors. Therefore, Since T-S fuzzy can be used to effectively solve nonlinear problems of NCSs, which is highly nonlinear.

Filtering is used to estimate the state of the system, which means to estimate the internal state by measuring the output data [3-4]. The limitation of traditional Kalman filtering and H∞ filtering lies in the energy-bounded external disturbances. For some systems, the amplitude of external interference signals is bounded, for example, the continuous interference of the friction between the air and the spacecraft, the water pressure on the submarine, and of the constant temperature changes underwater. L₁ filtering can be more effectively applied in those cases than Kalman filtering and H∞ filtering, thus L₁ filtering is studied widely around the world.

This paper describes the randomness of delay in continuous NCSs using the Bernoulli sequence and establishes the mathematical model with random delay based on the filter input represented by...
random variables. Then, this paper processes the selected Lyapunov-Krasovskii functional using the
infinitesimal operator, thus obtaining the conditions for $L_1$ filter design. Finally, this method is verified
based on numerical simulations.

2. Problem description

The control object in the system using the T-S fuzzy model is described as follows:

Rule $i$: If $\theta_i(t)$ is $F_{i1}, \theta_2(t)$ is $F_{i2}$ and...and $\theta_n(t)$ is $F_{in}$, then

$$
\begin{align*}
\dot{x}(t) &= A_i x(t) + B_i w(t) \\
y(t) &= C_i x(t) + D_i w(t) \\
z(t) &= L_i x(t),
\end{align*}
$$

(1)

$i = 1, 2, \ldots, r$ is the number of fuzzy rules; $\theta_i(t)$, $\theta_2(t)$, $\ldots$, $\theta_n(t)$ are the measurable predecessor
variables; $F_{ij}$ ($j = 1, 2, \ldots, n$) is a fuzzy set; $x(t) \in R^l$ is the system state vector while $y(t) \in R^m$ is the
system output vector; $w(t) \in R^q$ is the interference input, which belongs to $L_\infty[0, \infty)$; $A_i$, $B_i$, $C_i$, $D_i$
and $L_i$ are constant matrices with appropriate dimensions.

The output variable of the fuzzy system is the weighted average of the output of each subsystem:

$$
\begin{align*}
\dot{x}(t) &= A(t)x(t) + B(t)w(t) \\
y(t) &= C(t)x(t) + D(t)w(t) \\
z(t) &= L(t)x(t)
\end{align*}
$$

(2)

in which,

$$
\begin{align*}
v_i(\theta(t)) &= \prod_{j=1}^{n} F_{ij}(\theta_j(t)), & \mu_i(\theta(t)) &= \frac{v_i(\theta(t))}{\sum_{j=1}^{n} v_j(\theta(t))}, & A(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) A_i, & B(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) B_i, \\
C(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) C_i, & D(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) D_i, & L(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) L_i.
\end{align*}
$$

Moreover, $F_{ij}(\theta_j(t))$ is the membership function of $\theta_j(t)$ that belongs to the fuzzy set $F_{ij}$. For
any $t$,

$$
\mu_i(\theta(t)) \geq 0 (i = 1, 2, \ldots, n), \sum_{i=1}^{r} \mu_i(\theta(t)) = 1
$$

Based on the PDC principle, the following fuzzy filter is taken into consideration:

Rule $i$: If $\theta_i(t)$ is $F_{i1}, \theta_2(t)$ is $F_{i2}$ and...and $\theta_n(t)$ is $F_{in}$, then

$$
\begin{align*}
\dot{x}_f(t) &= A_f x_f(t) + B_f y(t) \\
z_f(t) &= C_f x_f(t)
\end{align*}
$$

(3)

The corresponding fuzzy filter is

$$
\begin{align*}
\dot{x}_f(t) &= A_{fi} x_f(t) + B_{fi} y(t) \\
z_f(t) &= C_{fi} x_f(t)
\end{align*}
$$

(4)

in which,

$$
\begin{align*}
A_f(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) A_i, & B_f(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) B_i, & C_f(t) &= \sum_{i=1}^{r} \mu_i(\theta(t)) C_i.
\end{align*}
$$

The influence of communication delay, or $\hat{y}(t) = y(t)$, is often ignored in traditional control
systems. However, when this effect on system stability is taken into consideration in the control
system in the network, and communication delay and packet loss are regarded as equivalent dead time,
then we have $\dot{y}(t) = y(t - h(t))$. Based on this, this paper continues to explore the random occurrence of equivalent dead time in the transmission process and assumes the measured output of the random communication delay to be

$$\dot{y}(t) = \delta(t)y(t) + (1 - \delta(t))y(t - h(t))$$  \hspace{1cm} (5)

$\delta(t)$ is the sequence that satisfies the Bernoulli distribution, and the equivalent delay is $0 < h(t) \leq h$. When there is a communication delay in the measured output, $\delta(t) = 0$; otherwise, $\delta(t) = 1$. Their probabilities are:

$$P[\delta(t) = 0] = \delta, \quad P[\delta(t) = 1] = 1 - \delta,$$

$$E[\delta(t) - \delta] = 0, \quad E[(\delta(t) - \delta)^2] = \delta(1 - \delta); \quad \delta \in [0, 1]$$ is a known constant.

Then, establish an augmented system model. Based on Equations (2), (4) and (5), we can obtain the T-S fuzzy filtering error system:

$$\begin{align*}
\dot{\xi}(t) &= A_F(t)\xi(t) + A_{Fd}(t)B_F(t)v(t) \\
e(t) &= C_F(t)\xi(t)
\end{align*}$$  \hspace{1cm} (6)

in which,

$$\xi(t) = [x^T(t) \quad x_f^T(t)]^T, \quad v(t) = [w^T(t) \quad w^T(t - h(t))]^T, \quad e(t) = z(t) - z_f(t),$$

$$A_F(t) = \sum_{i=1}^{r} \mu_i(\theta(t)) \sum_{j=1}^{r} \mu_j(\theta(t)) \begin{bmatrix} A_i & 0 \\
0 & \delta(t)B_{ij}C_i \end{bmatrix},$$

$$A_{Fd}(t) = \sum_{i=1}^{r} \mu_i(\theta(t)) \sum_{j=1}^{r} \mu_j(\theta(t)) \begin{bmatrix} 0 & 0 \\
(1 - \delta(t))B_{ij}C_i & (1 - \delta(t))B_{ij}C_i \end{bmatrix},$$

$$C_F(t) = \sum_{i=1}^{r} \mu_i(z(t)) \sum_{j=1}^{r} \mu_j(\theta(t))[L_i - C_{ij}] = [L(t) - C_f(t)], \quad G = [I \quad 0],$$

$$B_F(t) = \sum_{i=1}^{r} \mu_i(\theta(t)) \sum_{j=1}^{r} \mu_j(\theta(t)) \begin{bmatrix} B_i & 0 \\
0 & \delta(t)B_{ij}D_i \end{bmatrix}.$$  

Definition 1 [5]:

For the fuzzy filtering error system, under the zero initial condition, if the designed global fuzzy filter (4) makes the system (6) asymptotically stable, and if $\|P_{\alpha}(s)\|_{\alpha} < \gamma$ is true for any non-zero $v(t) \in L_{\infty}[0, \infty)$, then the filter can be called the robust $L_1$ filter. In the meantime, the maximum peak-to-peak gain of the system is less than $\gamma$.

3. $L_1$ Performance analysis of fuzzy filter error system

Theorem 1

Based on the fuzzy networked closed-loop system (6), ($\alpha \in R^+$), if there exist normal numbers $\bar{h}, \delta$, positive definite matrix $P$, and matrices of appropriate dimensions including $Q_i > 0$, $Q_{2i} > 0$, $R_i > 0$, $\tilde{Q}_i > 0$, $\tilde{Q}_{2i}$ and $\tilde{S}_i$ to make the following hold:

\begin{align*}
&\begin{align*}
\sum_{i=1}^{r} \mu_i(z(t)) \sum_{j=1}^{r} \mu_j(\theta(t)) \begin{bmatrix} B_i & 0 \\
0 & \delta(t)B_{ij}D_i \end{bmatrix} \in L_{\infty}[0, \infty) \\
&\text{and}\quad \|P_{\alpha}(s)\|_{\alpha} < \gamma
\end{align*}
\end{align*}
\[
\begin{bmatrix}
\Phi_{11} P\bar{A}_{Fij} & 0 & P\bar{B}_{Fi} & \bar{h}_F A_{Fij}^T G^T & \tilde{h}_G \delta A_{Fij}^T G^T \\
\ast & \Phi_{22} & 0 & 0 & \bar{h}_F A_{Fij}^T G^T & \tilde{h}_G \delta A_{Fij}^T G^T \\
\ast & \ast & 0 & 0 & 0 & 0 \\
\ast & \ast & \ast & -\alpha_2 & \bar{h}_F B_{Fij}^T G^T & \tilde{h}_G \delta B_{Fij}^T G^T \\
\ast & \ast & \ast & -S_i & 0 & 0 \\
\ast & \ast & \ast & \ast & -S_i & 0
\end{bmatrix} < 0
\] (7)

\[
\begin{bmatrix}
-\alpha P & 0 & C_{Fij}^T \\
\ast & -(\gamma - \alpha)I & 0 \\
\ast & \ast & -\gamma I
\end{bmatrix} < 0
\] (8)

\[G^T (a Q_{ij} - (1 - \alpha \delta) R_{ii}) G < 0\] (9)

\[G^T (a Q_{ij} - (1 - \tau - \alpha \delta) R_{ii}) G < 0\] (10)

Then, the fuzzy filter error system is asymptotically stable while satisfying \(\gamma\), the \(L_1\) noise suppression level.

In the formula,
\[
\Phi_{11} = P\bar{A}_{Fij} + \bar{A}_{Fij}^T P + G^T Q_{ii} + Q_{2i} + \tilde{h}_F R_{ii} + \bar{h}_G \delta R_{ii}) G + \alpha P, \quad \Phi_{22} = -(1 - \tau) \bar{Q}_{2i},
\]

\[I_2 = \text{diag}\{1, 1\}, \quad \delta = \sqrt{\delta(1 - \delta)} \]

Proof: Select the Lyapunov functional as follows:
\[
V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t) + V_5(t) + V_6(t)
\]

\[
V_1(t) = \xi^T(t) P \xi(t), \quad V_2(t) = \int_{t-h}^{t} \xi^T(s) G^T Q_{ii}(s) G \xi(s) ds
\]

\[
V_3(t) = \int_{t-h}^{t} \xi^T(s) G^T Q_{ij}(s) G \xi(s) ds, \quad V_4(t) = \int_{t-h}^{t} \int_{s}^{t} \xi^T(\beta) G^T R_{ij}(\beta) G \xi(\beta) d\beta ds
\]

\[
V_5(t) = \int_{t-h}^{t} \int_{s}^{t} \xi^T(\beta) G^T R_{ii}(\beta) G \xi(\beta) d\beta ds
\]

\[
V_6(t) = \tilde{h} \int_{t-h}^{t} \int_{s}^{t} E \{ \xi^T(\beta) G^T S(\beta) \tilde{G} \xi(\beta) \} d\beta ds
\]

In which,
\[
Q_{ii}(s) = \sum_{i=1}^{n} \mu_i(\theta(s)) Q_{ii}, \quad Q_{ij}(s) = \sum_{i=1}^{n} \mu_i(\theta(s)) Q_{ij}, \quad R_{ii}(\beta) = \sum_{i=1}^{n} \mu_i(\theta(\beta)) R_{ii},
\]

\[
R_{ij}(\beta) = \sum_{i=1}^{n} \mu_i(\theta(\beta)) R_{ij}, \quad S(\beta) = \sum_{i=1}^{n} \mu_i(\theta(\beta)) S_i, \quad Q_{ii} > 0, \quad Q_{ij} > 0, \quad R_{ii} > 0, \quad R_{ij} > 0, \quad S_i > 0
\]

\(\ell\), the infinitesimal operator [6] here is defined as:
\[
\ell V(\xi_i) = \lim_{\Delta \rightarrow 0} \frac{1}{\Delta} \{ E(V(\xi_{i+\Delta}) - V(\xi_i)) \}
\] (12)

Perform infinitesimal operations on the above \(V(t)\), and we can get:
\[ \ell V_1(t) = 2 \xi^T(t) P(E(\dot{\xi}(t))) \]
\[ \ell V_2(t) = \xi^T(t) G^T Q_s(t) G \xi(t) - \xi^T(t - \tilde{h}) G^T Q_s(t - \tilde{h}) G \xi(t - \tilde{h}) \]
\[ \ell V_3(t) \leq \xi^T(t) G^T Q_s(t) G \xi(t) - (1 - \tau) \xi^T(t - h(t)) G^T Q_s(t - h(t)) G \xi(t - h(t)) \]
\[ \ell V_4(t) = \tilde{h} \xi^T(t) G^T R_1(t) G \xi(t) - \int_{t - \tilde{h}}^{t} \xi^T(s) G^T R_1(s) G \xi(s) ds \]
\[ \ell V_5(t) \leq h(t) \xi^T(t) G^T R_2(t) G \xi(t) - (1 - \tau) \int_{t - h(t)}^{t} \xi^T(s) G^T R_2(s) G \xi(s) ds \]
\[ \ell V_6(t) = \tilde{h}^2 E\{\dot{\xi}^T(t) G^T S(t) G \dot{\xi}(t)\} - \tilde{h} \int_{t - \tilde{h}}^{t} E\{\dot{\xi}^T(s) G^T S(s) G \dot{\xi}(s)\} ds \]

From Equation 6, we can get:
\[
E\{A_f(t)\} = \begin{bmatrix} A(t) \\ \partial B_f(t) C(t) \end{bmatrix} E\{A_{fd}(t)\} = \begin{bmatrix} 0 \\ (1 - \delta) B_f(t) C(t) \end{bmatrix} = \bar{A}_f(t),
\]
\[
E\{B_f(t)\} = \begin{bmatrix} B(t) \\ \partial B_f(t) D(t) \end{bmatrix} (1 - \delta) B_f(t) D(t) = \bar{B}_f(t).
\]
So,
\[
E\{\dot{\xi}(t)\} = \bar{A}_f(t) \xi(t) + \bar{A}_{fd}(t) G \xi(t - h(t)) + \bar{B}_f(t) v(t).
\]

Transform the coefficient matrix of the filter error system into:
\[
A_f(t) = A_{f0}(t) + (\delta(t) - \delta(t)) A_{f1}(t), \quad A_{fd}(t) = A_{fd0}(t) - (\delta(t) - \delta(t)) A_{fd1}(t),
\]
\[
B_f(t) = B_{f0}(t) + (\delta(t) - \delta(t)) B_{f1}(t), \quad A_{f0}(t) = \begin{bmatrix} A(t) \\ \partial B_f(t) C(t) \end{bmatrix}, \quad A_{f1}(t) = \begin{bmatrix} 0 \\ B_f(t) C(t) \end{bmatrix},
\]
\[
A_{fd0}(t) = (1 - \delta(t)) B_f(t) C(t), \quad A_{fd1}(t) = \begin{bmatrix} 0 \\ B_f(t) C(t) \end{bmatrix}, \quad B_{f0}(t) = \begin{bmatrix} B(t) \\ \partial B_f(t) D(t) \end{bmatrix}, \quad B_{f1}(t) = \begin{bmatrix} 0 \\ B_f(t) D(t) \end{bmatrix}.
\]

We can have:
\[
\ell V(t) < \eta^T(t) \Omega \eta(t) - \alpha \xi^T(t) P \xi(t) + \alpha \xi^T(t) G \xi(t) - \alpha \int_{t - \tilde{h}}^{t} \xi^T(s) G^T Q_s(s) G \xi(s) ds
\]
\[-\alpha \int_{t - h(t)}^{t} \xi^T(s) G^T Q_s(s) G \xi(s) ds + \alpha \int_{t - \tilde{h}}^{t} \xi^T(s) G^T (\alpha Q_s(s) - R_s(s)) G \xi(s) ds + \tilde{h} \int_{t - \tilde{h}}^{t} E\{\dot{\xi}^T(s) G^T S(s) G \dot{\xi}(s)\} ds
\]

In which,
\[
\eta(t) = \begin{bmatrix} \xi(t) \\ \xi(t - h(t)) G^T \xi(t - \tilde{h}) G^T v(t) \end{bmatrix}
\]
\[
\Omega = \begin{bmatrix} \Omega_{11} & P \bar{A}_{fd}(t) & 0 & P \bar{B}_f(t) \\ \ast & \Omega_{22} & 0 & 0 \\ \ast & \ast & - Q_s(t - \tilde{h}) & 0 \\ \ast & \ast & \ast & - \alpha I \end{bmatrix} + \tilde{h}^2 \begin{bmatrix} A_{f0}^T(t) \\ A_{fd0}^T(t) \\ B_{f0}^T(t) \\ 0 \end{bmatrix} G^T S(t) G \begin{bmatrix} A_{f0}^T(t) \\ A_{fd0}^T(t) \\ B_{f0}^T(t) \\ 0 \end{bmatrix}^T
\]
Based on \( \Omega_{11} = P\bar{A}_r(t) + \bar{A}_r^T(t)P + G^T(Q_r(t) + Q_z(t) + \bar{h}R_1(t) + \bar{h}R_2(t))G + \alpha P \), \( \Omega_{22} = -(1 - r)Q_z(t - h(t)) \).

Based on Equations (9), (10), (15) and
\[
\int_{-h}^{t} \int_{s}^{t} \xi^T(\theta)(R(\theta) - \alpha Q(\theta))\xi(\theta)d\theta ds \leq \bar{h} \int_{-h}^{t} \xi^T(s)(R(s) - \alpha Q(s))\xi(s)ds
\]
we can get:
\[
\ell V(t) < \eta^T(t)\Omega \eta(t) - \alpha V(t) + \alpha \nu^T(t)v(t)
\]
where
\[
\text{Note: } \bar{S}(t) = S^{-1}(t), \quad \bar{Q}_{ik} = Q_z(t - h), \quad \bar{Q}_{z2} = Q_z(t - h(t)).
\]

According to the Schur complement lemma, it can be known from Equation (7) that \( \Omega < 0 \), then \( \ell V(t) < \alpha \nu^T(t)v(t) - \alpha V(t) \).

Therefore, for all \( \eta(t) \neq 0 \), \( v(t) = 0 \), we can get \( \ell V(t) < 0 \). So, \( \dot{V}(t) < 0 \), and the fuzzy filtering error system (6) is asymptotically stable.

Definition \( \Xi = \{ \xi_t: V(t) \leq 1 \} \). Based on \( \xi(t) \), the state of the fuzzy filter error system under zero initial conditions, and when \( \| v(t) \|_\infty \leq 1 \), it is easy to know that \( \Xi \) is an invariant set.

Performance indicators are defined as:
\[
f(t) = \frac{1}{\gamma} e^T(t)e(t) - \alpha \xi^T(t)P\xi(t) - (\gamma - \alpha)\nu^T(t)v(t)
\]

From Equation (8), we can get \( f(t) < 0 \). Since \( V(t) \leq 1 \), we can have \( \xi^T(t)P\xi(t) < 1 \). And for all \( \| v(t) \|_\infty \leq 1 \), \( \| e(t) \|_\infty < \gamma^2 \) holds. Therefore, Equations (7)–(10) can ensure that the fuzzy filtering error system is asymptotically stable and the peak-peak gain is less than \( \gamma \). In this way, Theorem 1 can be proved.

Note: Since the expectation in this paper is about \( \xi(t) \), the expectations of \( \gamma \) and \( \alpha \) in \( \ell f(t) \) are both constants, and \( \ell f(t) = f(t) \), it is feasible to directly obtain the performance index \( f(t) \).

4. Design of fuzzy filter
Theorem 2

When \( \alpha \in R^+ \), if there exist positive constants \( \bar{h} \), \( \delta \), and a matrices with the appropriate dimensions, including \( X > 0 \), \( W > 0 \), \( Q_{ih} > 0 \), \( Q_{iz} > 0 \), \( R_{ii} > 0 \), \( R_{iz} > 0 \), \( \bar{Q}_{ih} > 0 \), \( \bar{Q}_{iz} > 0 \), \( \bar{S}_i \), \( \bar{A}_d \), \( \bar{B}_d \), \( \bar{C}_d \) to make the following linear matrices hold:
The system matrix of the T-S fuzzy model (1) is as follows ($r=2$):

$A_i = \begin{bmatrix} -2.1 & 0.1 \\ 1 & -2 \end{bmatrix}$, $B_i = \begin{bmatrix} 0.4 \\ -0.2 \end{bmatrix}$, $C_i = [0.2 \ -0.4]$, $D_i = 0.4$, $L_i = [1 \ -0.5]$

$A_2 = \begin{bmatrix} -1.9 & 0 \\ -0.2 & -1.1 \end{bmatrix}$, $B_2 = \begin{bmatrix} 0.3 \\ 0.1 \end{bmatrix}$, $C_2 = [0.5 \ -0.6]$, $D_2 = 0.6$, $L_2 = [-0.2 \ 0.3]$

According to Theorem 2, when $\alpha = 0.2$, the optimal $L_1$ performance index is $\gamma^* = 0.1909$. At this time, the fuzzy filter parameters are:
Take the membership functions as: \( F_1(x(t)) = \exp(-0.5x(t)^2) \), \( F_2(x(t)) = 1 - F_1(x(t)) \).

The initial state is set as \( x(0) = [0 \ 0]^T \), \( x_f(0) = [0.1 \ 0.1]^T \), the peak of external disturbance is assumed to be bounded, and \( w(t) = 5 \cdot \sin(\pi t) \) is selected in this paper. Then, use the fuzzy filter parameters obtained for simulation, and we can get \( z(t) \), the filtered estimated signal and \( z_f(t) \), the estimated value, as well as the estimated error curve \( e(t) \), as shown in Figure 1. It can be seen that the designed fuzzy filter performs well in measuring the signal to be estimated, thus proving the effectiveness of the proposed design method.

![Figure 1 Filter estimation and filtering error](image-url)
6. Conclusion
This paper uses Bernoulli distribution to describe the random occurrence of communication delay in the network, and then establishes the corresponding filtering error system based on a kind of network control system described by T-S fuzzy model while taking into consideration the random delay. Based on Lyapunov stability theory and LMI technique, this paper proposes a robust $L_1$ filter design method with time-delay correlation and fuzzy dependence. The designed fuzzy filter can ensure that the filter error system is asymptotically stable while satisfying $L_1$ noise suppression level. The effectiveness of the design is verified through stimulation curves.

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