Performance limitation of networked control systems with networked delay and two-channel noises constraints

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ABSTRACT
The performance limitation of networked control systems (NCSs) with networked delay and two-channel noises constraints are studied in this paper. The networked parameters mainly consider the networked delay in the forward channel and white Gaussian noise constraint existing in forward channel and feedback channel. The tracking performance limitation expression is achieved by using the spectral decomposition technique and selecting the optimal one-parameter structure. The obtained result shows that the tracking performance limitation of NCSs is related to the position of the non-minimum phase zeroes, the position of the unstable poles, networked delay, two-channel noises and input signal. We can also know that the networked delay and white Gaussian noise have influence on the tracking performance limitation of NCSs. Finally, a simulation example is given to demonstrate effectiveness of the theoretical results.

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KEYWORDS
Networked control systems; performance limitation; networked delay; unstable poles

1. Introduction
With the development of internet and computer technology, the traditional control system can’t adapt to the needs of daily life. We know that the internet has been inextricably linked to us, so it is a development trend to use the network for traditional control systems. The networked control systems (NCSs) emerge as the times require. And then, it has developed rapidly. Until now it is still an important research issue (Almakhles, Swain, Nasiri, & Patel, 2017; Zhang, Shi, Wang, & Yu, 2017; Zhang, Yan, Yang, & Chen, 2011; Zhang, Han, & Yu, 2016). The NCSs have many advantages like: flexibility; low cost; simple installation and maintenance; reduced weight and power requirement, etc. In recent years, much research works have been investigated about the stability analysis of NCSs with communication constraints, e.g. quantization (Fu & Xie, 2005; Xiao, Xie, & Fu, 2010; Yuan, Yuan, Wang, Guo, & Yang, 2017), time delay (Liu, 2010; Luan, Shi, & Liu, 2011), bandwidth (Rojas, Braslavsky, & Middleton, 2008) and packet loss (Chen, Gao, Shi, & Lu, 2016; Pang, Liu, Zhou, & Sun, 2016) etc. The research progress of NCSs from several aspects was summarized in Mahmoud (2016). The stability of quantitative in feedback control system based on event trigger was considered in Boukens, Boukabou, and Chadli (2017). The sufficient conditions to ensure the stability and dissipativity of the filtering error system by establishing the mode-dependent periodic Lyapunov function was proposed in Lu et al. (2018). The stability analysis of sampling system by a new time-based discontinuous Lyapunov function was studied in Shao, Han, Zhao, and Zhang (2017). In NCSs, the network delay is time-varying or random (Gao, Jiang, & Pan, 2018; Su & Chesi, 2017; Tao, Wu, Su, Wu, & Zhang, 2018; Zhang, Wu, Shi, & Zhao, 2015). A new Lyapunov function and stability results are dependent on both the data packet dropouts and the time delay was proposed in Tao, Lu, and Wu (2017). The stability of time delay of NCSs was studied in Liu, Zhang, and Xie (2017). The problem of output feedback delay compensation controller for NCSs with random network delay was discussed in Zhang, Lam, and Xia (2014). But sometimes, the authors study the determined time delay to reduce the difficult of a problem. The problem of stability for switched positive linear systems with constant time delay was studied in Zhao, Zhang, and Shi (2013). The authors focused on the problems of robust stabilization and robust $H_{\infty}$ control for linear systems with a constant time delay in De Souza and Xi (1999).

In nowadays research, more and more researchers are interested in the performance study of the control system in the control community, see Wu, Zhan, Zhang, Jiang, and Han (2017); Wu, Zhou, Zhan, Yan, and Ge (2017); Zhan, Guan, Zhang, and Yuan (2013); Zhan,
given plant, a tracking error of the NCSs is defined as the design of the NCSs. The relationship between bandwidth constraint and optimal modified tracking performance of MIMO NCSs was studied in Sun, Wu, Zhan, and Han (2016). The authors Guan, Chen, Feng, and Li (2013) investigated the tracking performance limitation for MIMO LTI systems with coloured channel noise and limited bandwidth channel. The above results only consider one-way channel constraint. However, the networked delay often appears, the time delay can result in the performance degradation of control systems and even worse cause a system to become unstable. The communication channel constraint both in forward and feedback channels often exist, the tracking performance limitation of NCSs with two-way channel constraints is more difficult to study. It is necessary and important to study the performance limitation of the NCSs with networked delay and two-channel noises constraints.

The main contributions of this paper are as follows. This paper introduces a model for the NCSs, the networked control systems with networked delay and two-channel noises. Figure 1, the signal \( r \) is a random reference signal, the variance of \( r \) is \( \sigma_r^2 \). \( K \) denotes the one-parameter compensator. \( G \) denotes the plant model, \( \tau \) is the networked delay, the signal \( y \) is the systems output and \( n_1, n_2 \) are white Gaussian noise and variance are \( \sigma_n^2 \) and \( \sigma_n^2 \). For a given plant, a tracking error of the NCSs is defined as \( e = r - y \).

According to Figure 1, we have

\[
y = e^{-\tau s}KGr - e^{-\tau s}KGY - e^{-\tau s}KGn_1 + n_2 e^{-\tau s}G. \tag{1}
\]

Then

\[
y = \frac{e^{-\tau s}KGr}{1 + e^{-\tau s}KG} - \frac{e^{-\tau s}n_1 KG}{1 + e^{-\tau s}KG} + \frac{e^{-\tau s}n_2 G}{1 + e^{-\tau s}KG}. \tag{2}
\]

The tracking error is obtained by

\[
e = r - y = T_1 r + T_2 n_1 - T_3 n_2, \tag{3}
\]

where

\[
T_1 = \frac{1}{1 + e^{-\tau s}KG}, \quad T_2 = \frac{e^{-\tau s}KG}{1 + e^{-\tau s}KG}, \quad T_3 = \frac{e^{-\tau s}G}{1 + e^{-\tau s}KG}. \tag{4}
\]

It is clearly that the rational transfer function \( G \) can be given by:

\[
G = \frac{N}{M}, \tag{5}
\]

where, \( N, M \in \mathcal{RH}_\infty \), and satisfied the Bezout identity

\[
MX + e^{-\tau s}NY = 1, \tag{6}
\]

where, \( X, Y \in \mathcal{RH}_\infty \). All the compensators which can make the system become stable can be characterized by Youl parameterization

\[
\mathcal{K} = \left\{ K : K = \frac{(Y + MQ)}{X - e^{-\tau s}NQ}, Q \in \mathcal{RH}_\infty \right\}. \tag{7}
\]

It is well known that a non-minimum phase transfer function could factorize a minimum phase part and an all-pass factor

\[
N = B_2 N_n, \quad M = B_p M_m, \tag{8}
\]

where \( N_n \) and \( M_m \) are the minimum phase part \( B_2 \) and \( B_p \) are the all-pass factor \( B_2 \) includes all non-minimum phase zeros \( z_i \in C_+, i = 1, \ldots, n \), \( B_p \) includes all the unstable poles of the given plant \( p_j \in C_+, j = 1, \ldots, m \), \( B_2 \) and

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Networked control systems with networked delay and two-channel noises.}
\end{figure}
$B_p$ can be represented as

$$B_z(s) = \prod_{i=1}^{n} \frac{s - z_i}{s + z_i}, \quad B_p(s) = \prod_{j=1}^{m} \frac{s - p_j}{s + p_j}. \quad (9)$$

The tracking performance of NCSs is defined as

$$J := E \left\{ \| e \|_2^2 \right\} = E \left\{ r - y \|_2^2 \right\}. \quad (10)$$

3. Performance limitations of the NCSs with the networked delay and two-channel noises

The tracking performance limitation of NCSs is measured by the possible minimal tracking error achievable by all possible linear stabilizing controllers (denote by $\mathcal{K}$), determined as

$$J^* = \inf_{K \in \mathcal{K}} J. \quad (11)$$

Assuming the input signal has no connection with white Gaussian noise $n_1, n_2$, then the tracking performance can be shown as

$$J = \| T_1 \|_2^2 \psi_1^2 + \| T_2 \|_2^2 \psi_2^2 + \| T_3 \|_2^2 \psi_3^2. \quad (12)$$

According to (3), (4), (5), (11) and (12), we can obtain

$$J^* = \inf_{Q \in \mathcal{RH}_\infty} \left\{ \| (X - e^{-ts}NQ)M \|_2^2 \psi_1^2 + \| (Y + MQ)N e^{-ts} \|_2^2 \psi_2^2 + \| e^{-ts}N(X - e^{-ts}NQ) \|_2^2 \psi_3^2 \right\}. \quad (13)$$

**Theorem 3.1:** Assume that a given system has many unstable poles $z_i \in \mathbb{C}_+$, $i = 1, \ldots, n$, and NMP zeros $p_j \in \mathbb{C}_+$, $j = 1, \ldots, m$ with the networked delay and two-channel noises constraints, the tracking performance limitation of the NCSs be shown as

$$J^* \geq \sum_{i=1}^{n} 2\text{Re}(z_i)\psi_1^2 + \sum_{j \in N} 4\text{Re}(p_j)\text{Re}(p_j) \frac{(1 - B_z^{-1}(p_i))(1 - B_z^{-1}(p_j))}{(p_i + p_j)p_i} b_j, b_j + \sum_{j \in N} 4\text{Re}(p_j)\text{Re}(p_j) \frac{B_z^{-1}(p_i)B_z^{-1}(p_j) e^{(p_i + p_j)}}{b_j} + \sum_{j \in N} 4\text{Re}(z_j)\text{Re}(z_j) \frac{N_n(z_j)N_n(z_j) e^{(z_j + z_j)}}{M(z_j)M(z_j)l_j} \psi_3^2$$

where $b_j = \prod_{i \neq j}^{m} (p_i - p_j)/(p_i + p_j), \quad l_j = \prod_{i \neq j}^{m} (z_i - z_j)/(z_i + z_j)$.

**Proof:** According to (7) and (13), we can obtain

$$J^* = \inf_{Q \in \mathcal{RH}_\infty} \left\{ \| (X - e^{-ts}NQ)M \|_2^2 \psi_1^2 + \| (Y + MQ)N e^{-ts} \|_2^2 \psi_2^2 + \| e^{-ts}(B_zN_nX - e^{-ts}B_zN_nQ) \|_2^2 \psi_3^2 \right\}. \quad (14)$$

According to (8) and (14), we can obtain

$$J^* = \inf_{Q \in \mathcal{RH}_\infty} \left\{ \| (X - e^{-ts}NQ)M \|_2^2 \psi_1^2 + \| (Y + MQ)N e^{-ts} \|_2^2 \psi_2^2 + \| e^{-ts}(B_zN_nX - e^{-ts}B_zN_nQ) \|_2^2 \psi_3^2 \right\}. \quad (15)$$

According to (6), we can obtain

$$MX - 1 = -e^{-ts}NY \quad (16)$$

Then we define

$$B_z^{-1}MX - B_z^{-1} = -e^{-ts}N_nY \quad (17)$$

According to (15) and (17), we can obtain

$$J^* = \inf_{Q \in \mathcal{RH}_\infty} \left\{ \| (B_z^{-1}N_nY - N_nQB_pM_m) e^{-ts} \|_2^2 \psi_2^2 + \| (YN_n + N_nQB_pM_m) e^{-ts} \|_2^2 \psi_3^2 + \| e^{-ts}(B_z^{-1}N_nX - e^{-ts}N_nQ) \|_2^2 \psi_3^2 \right\}. \quad (18)$$

Because $(B_z^{-1} - 1) \in H_2, \quad (1 - e^{-ts}N_nY - e^{-ts}N_nQM) \in H_2$, we can obtain

$$J^* = \| (B_z^{-1} - 1) \|_2^2 \psi_1^2 + \inf_{Q \in \mathcal{RH}_\infty} \left\{ \| e^{-ts} - N_nY - N_nQB_pM_m \|_2^2 \psi_1^2 + \| (YN_n + N_nQB_pM_m) e^{-ts} \|_2^2 \psi_1^2 + \| e^{-ts}(B_z^{-1}N_nX - e^{-ts}N_nQ) \|_2^2 \psi_3^2 \right\}. \quad (19)$$
Because of the $B_p$ and $e^{-rs}$ are the all-pass factors, it follows that

$$J^* = \left\| (B_z^{-1} - 1)^2 \right\|_2^2 \psi_1^2 + \inf_{Q \in \mathcal{RH}_\infty} \left\{ \left\| \frac{e^{rs} - N_n Y}{B_p} - N_n Q M_m \right\|_2^2 \psi_1^2 + \left\| \frac{YN_n}{B_p} + N_n Q M_m \right\|_2^2 \psi_2^2 + \left\| \frac{N_n X e^{rs}}{B_z} - N_n N_n Q \right\|_2^2 \psi_3^2 \right\}$$

(20)

Based on a partial fraction procedure, we can obtain

$$\frac{e^{rs} - N_n Y}{B_p} = \sum_{j \in N} \frac{s + \tilde{p}_j}{s - p_j} e^{r_j p_j} - \frac{N_n(p_j) Y(p_j)}{b_j} + \vartheta_1$$

$$\frac{YN_n}{B_p} = \sum_{j \in N} \frac{s + \tilde{p}_j}{s - p_j} Y(p_j) N_n(p_j) + \vartheta_2$$

$$\frac{N_n X e^{rs}}{B_z} = \sum_{j \in N} \frac{s + z_j}{s - z_j} \frac{N_n(z_j) X(z_j) e^{rz_j}}{l_j} + \vartheta_3,$$  

where $\vartheta_1(s), \vartheta_2(s), \vartheta_3(s) \in \mathcal{RH}_\infty, b_j = \prod_{i \neq j} N_n(p_i - p_j)/ (\tilde{p}_j + p_j), l_j = \prod_{i \neq j} (z_i - z_j)/(\tilde{z}_i + z_j)$.

According to (9), we can obtain $M(p_j) = B_p(p_j)M_m = 0$, then

$$Y(p_j) N_n(p_j) = B_z^{-1}(p_j) e^{r_j p_j}, \quad N_n(z_j)X(z_j) = N_n(z_j) M^{-1}(z_j).$$

(21)

Then

$$\frac{e^{rs} - N_n Y}{B_p} = \sum_{j \in N} \frac{s + \tilde{p}_j}{s - p_j} \frac{e^{r_j p_j}(1 - B_z^{-1}(p_j))}{b_j} + \vartheta_1$$

$$\frac{YN_n}{B_p} = \sum_{j \in N} \frac{s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j}}{b_j} + \vartheta_2$$

$$\frac{N_n X e^{rs}}{B_z} = \sum_{j \in N} \frac{s + z_j}{s - z_j} \frac{N_n(z_j) M^{-1}(z_j) e^{rz_j}}{l_j} + \vartheta_3.$$  

Therefore, we have

$$J^* = \left\| (B_z^{-1} - 1)^2 \right\|_2^2 \psi_1^2 + \inf_{Q \in \mathcal{RH}_\infty} \left\{ \left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_1 - N_n Q M_m}{b_j} \right\|_2^2 \psi_1^2 + \left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_1 + N_n Q M_m}{b_j} \right\|_2^2 \psi_1^2 + \left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_2 + N_n Q M_m}{b_j} \right\|_2^2 \psi_2^2 \right\}$$

(23)

Because of $N_n$ and $M_m$ are the minimum phase part, we can choose a suitable $Q$ to derive

$$\left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_1 + N_n Q M_m}{b_j} \right\|_2^2 \psi_1^2 = 0$$

$$\left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_2 + N_n Q M_m}{b_j} \right\|_2^2 \psi_2^2 = 0$$

$$\left\| \frac{\sum_{j \in N} (s + \tilde{p}_j}{s - p_j} \frac{B_z^{-1}(p_j) e^{r_j p_j} + \vartheta_3 + N_n(z_j) M^{-1}(z_j) e^{rz_j}}{l_j} - N_n N_n Q \right\|_2^2 \psi_3^2 = 0.$$
Then we can have
\[ J^* \geq \left\| (B^{-1}_z - 1) \right\|_2^2 \varphi_1^2 \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \frac{e^{\tau_{pj}}(1 - B^{-1}_z(p_j))}{b_j} \left\| \varphi_2^2 \right\|_2 \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \left\| (B^{-1}_z(1 - B^{-1}_z(p_j)))^H \right\|_2 \]
\[ + \sum_{j \in \mathds{N}} \left| \frac{\text{Re}(z_j) Re(z_j) - \text{Re}(p_j) - \text{Re}(p_j)}{b_j} \right| \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \left( \frac{\text{Re}(z_j) M^{-1}(z_j) e^{\tau_{z_j}}}{l_j} \right) \]
\[ \left\| \varphi_3^2 \right\|_2. \] 

According to Toker, Chen, and Qiu (2002)
\[ \left\| (B^{-1}_z - 1) \right\|_2^2 \varphi_1^2 = \sum_{j=1}^{n} 2 \text{Re}(z_j) \varphi_1^2. \] 

Then
\[ J^* \geq \sum_{j=1}^{n} 2 \text{Re}(z_j) \varphi_1^2 \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \frac{e^{\tau_{pj}}(1 - B^{-1}_z(p_j))}{b_jb_j} \left\| \varphi_2^2 \right\|_2 \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \frac{\text{Re}(z_j) Re(z_j) - \text{Re}(p_j) + \text{Re}(p_j)}{b_jb_j} \]
\[ + \sum_{j \in \mathds{N}} \left( \frac{s + \bar{p}_j}{s - p_j} - 1 \right) \left( \frac{\text{Re}(z_j) M^{-1}(z_j) e^{\tau_{z_j}}}{l_j} \right) \]
\[ \left\| \varphi_3^2 \right\|_2, \]

where \( b_j = \prod_{i \in j} (p_i - p_j)/(\bar{p}_j + p_j), \) \( l_j = \prod_{i \in j} (z_i - z_j)/(z_i + z_j). \)

This completes the proof.

4. Illustrative examples

In this section, the obtained result is illustrated by a classical example. The transfer function of the given plant is
\[ G = \frac{s - k}{(s - 3)(s + 5)}. \]

For \( k > 0, \) we may see that NMP zeros is located at \( z_i = k, \) the unstable pole is located at \( p_j = 3. \) Supposing the networked delay is \( \tau = 0.3, \) the input signal is \( \varphi_1^2 = 1, k = 1, \) according to Theorem 3.1, we have
\[ J_1^* = 2 + \frac{2}{3} e^{1.8} + \frac{4}{3} e^{1.8} e_j^2 + e^{0.6} \varphi_3^2. \]

The tracking performances limitation of the NCSs with different two-channel noises are shown in Figure 2. In Figure 2, the two-channel noises affect the tracking performance limitation of the NCSs, when the two-channel noises become big, the tracking performances limitation of NCSs become bad.

The influence of the networked delay is also existing in the NCSs. Thus, the simulation about the influence of the networked delay to the NCSs is necessary. In Zhan, Guan, and Wu (2010), the performance limitation of networked control systems with networked induce-delay is discussed. In this paper we consider about the NMP zeros, the unstable poles and the input signal. The choice of date is the same in previous example, the networked delay is \( \tau = 0.3, \varphi_1^2 = 1, \varphi_2^3 = 2 \) and \( \varphi_3^2 = 3, \) according to the Theorem, we can obtain \( J_1^* \)
\[ J_1^* = 2k + \frac{2}{3} e^{1.8} \left( \frac{-2k}{3 - k} \right) + \frac{4}{3} e^{1.8} \left( \frac{3 + k}{3 - k} \right) \]
\[ + 6k e^{0.6k} \left( \frac{1}{k - 3} \right). \]

Figure 2. Performance limitation of white Gaussian noise.
According to Zhan et al. (2010), we can obtain $J^*_2$:

$$J^*_2 = \frac{2}{k} + \frac{2}{3} e^{1.8} \left( -\frac{2k}{3-k} \right).$$

The tracking performance limitation of the NCSs with different NMP zeros is shown in Figure 3. Figure 3 reveals that the tracking performance limitation of the NCSs is based on the NMP zeros and unstable poles of the given plant. When the NMP zeros move closer to the unstable poles, the tracking performance limitation of the NCSs tends to the infinity. By comparing $J^*_1$ and $J^*_2$, we can know that the noise exists in the communication channel will make the performance limitation of NCSs become worse.

According to the research before, there are a few articles talk about noise in both forward and feedback channel, so it is valuable to talk about the difference of tracking performance limitation by the effect of noise in forward and feedback channel. Assuming that the networked delay is $\tau = 0.3$, the input signal is $\varphi_2^2 = 1, k = 1$, according to Theorem,

Supposing there is no noise in the forward channel,

$$\varphi_3^2 = 0, J_1^* = 2 + \frac{2}{3} e^{1.8} + e^{0.6} \varphi_3^2.$$

Supposing there is no noise in the feedback channel,

$$\varphi_3^2 = 0, J_2^* = 2 + \frac{2}{3} e^{1.8} + \frac{2}{3} e^{1.8} \varphi_2^2.$$

When the noise in the forward channel, $\varphi_3^2 = 0.5$, $J_1^* = 2 + \frac{2}{3} e^{1.8} + \frac{2}{3} e^{1.8} + e^{0.6} \varphi_3^2.$

When the noise in the feedback channel, $\varphi_3^2 = 0.5$, $J_2^* = 2 + \frac{2}{3} e^{1.8} + \frac{2}{3} e^{1.8} \varphi_2^2 + \frac{1}{2} e^{0.6}$.

Figure 4 shows the tracking performance limitation of the NCSs is effect by the noise, no matter the noise appears in the forward channel or in the feedback channel. According to Figure 4, we can know the degree of impact of noise in the forward channel or in the feedback channel are different. Also, Figure 4 indicates the tracking performance limitation is more affected by the noise in the forward channel. Form Figure 5, we can find the tracking performance limitation will intersect in somewhere (defined as P), before point P, noise in the forward channel has a greater impact on the tracking performance limitation of the NCSs; after point P, noise in the feedback channel has a greater impact on the tracking performance limitation of the NCSs.

5. Conclusion

In this paper, we explore the tracking performance limitation of NCSs with the two-channel noises. The proposed model takes into consideration the channel noise in the feedback channel and the networked delay in the forward path. The analytical expression of the tracking performance limitation is derived by using the method of $H_2$-norm and spectral factorizations. The obtained results...
show that the tracking performance limitation mainly depends on the position of the non-minimum phase zeros, position of the unstable poles, networked delay and two-channel noises. An illustrative example is analysed to demonstrate the effectiveness of the proposed method.

Possible future extensions to this work include study of more general plants such as multiple-input multiple-output nonlinear NCSs, more complex channel models such as the fading channel, and more parameters of communication channel constraints such as quantization effect, bandwidth, time-varying delay and signal-to-noise ratio.

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No potential conflict of interest was reported by the authors.

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