Received: 30 July 2020 | Revised: 10 December 2020 | Accepted: 22 February 2021

DOI: 10.1002/rnc.5490

RESEARCH ARTICLE

WILEY

A discretization approach to sampled-data stabilization of networked systems with successive packet losses

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 61733008, 61873099, 61873170, 62003204, 62073144, U1813225; Shantou University Scientific Research Foundation for Talents, Grant/Award Number: NTF19031; Natural Science Foundation of Guangdong Province, Grant/Award Number: 2020A1515010441; Science and Technology Development Foundation of the Shenzhen Government, Grant/Award Number: JCYJ20190808144607400; Guangzhou Science and Technology Planning Project, Grant/Award Numbers: 202002030158, 202002030389

Abstract

This article is concerned with the stabilization problem for a class of networked systems subject to successive packet losses. Different from the input delay approach used in some existing literature, the continuous-time system under consideration is first converted into a discrete-time stochastic system with system matrices subject to stochastic characteristic. In order to deal with the difficulties in the calculations of mathematical expectations of both matrix exponential and integral of matrix exponential function, the upper bound of successive packet losses and packet drop rate are assumed to be known and then the probabilities of the number of successive packet losses taking each value in a bounded set are calculated. Based on this, stability criteria are derived by recurring to the law of total expectation, which guarantee the exponential mean-square stability of resulting closed-loop discrete-time stochastic system with a prescribed H_∞ performance. Moreover, a controller design procedure is then proposed. Finally, to verify the analysis results and testify the effectiveness and applicability of the designed algorithm, a numerical simulation example is given.

KEYWORDS

discretization approach, networked sampled-data systems, stochastic systems, successive packet losses

1 INTRODUCTION

With the rise of 5G communication technology and industry 4.0, the networked systems integrating mathematics, physics, control science, sensing technology, and computer are in the ascendant. The networked systems, which connect the controlled objects, sensors, controllers, and actuators in different geographical locations through the communication networks, have garnered particular attention due to its advantages of high flexibility, strong reliability, easy maintenance, and convenient installation.[1-8] In the process of the development of the real economy, networked control is a good choice for the deep integration of communication technology and real economy, and is increasingly widely used in the fields such as intelligent manufacturing, aerospace, UAV formation, and industrial network,[9,10] and so forth. Because of its important theoretical value and engineering practicability, it is of far-reaching significance to study the stability analysis and synthesis of networked systems.

In networked systems, the increase of network communication burden and computation may lead to uncertainties and even instability of closed-loop system. Based on this fact, there is no need to constantly exchange information and update control signals in real time. Therefore, the sampled-data control strategy has received constant research interests on the stability analysis and stabilization of networked systems because of the inherent properties of digital control systems, for example, the network congestion and controller update frequency can be effectively reduced. Accordingly, fruitful research results have been achieved.[11-15] Besides that, although networked systems have received increasing attention since their extensive applications in many practical systems, the introduction of communication network also creates new challenges to the control of networked systems. For examples, the packets in network environment may be lost due to the congestions of network traffic, actuator suspension, and denial-of-service attacks[16,17] occurring in the unreliable wireless communication networks. Accordingly, packet loss is one of the major ingredients that weaken the stability performance or even cause the instability of networked systems. Therefore, the research of the sampled-data control problems of networked systems subject to successive packet losses has great significance.

Traditionally, for the stabilization of networked sampled-data systems with successive packet losses, the successive packet losses are usually regarded as a delayed input and then the probability characteristic of successive packet losses is fully utilized to the modeling of the networked sampled-data systems. For example, the robust sampled-data control problem has been studied for uncertain systems with successive packet losses in Reference 18, where the sampling interval is supposed to be a constant and input delay approach is used to model the networked systems with successive packet losses. In the presence of successive packet losses and disturbances, the authors in Reference 19 have investigated the periodic sampled-data fuzzy control problem of nonlinear systems. In the work of Reference 20, the robust exponential stability has been studied for a class of uncertain stochastic networked systems with successive packet losses and stability criteria with less conservative results have been obtained. It is worth noting that in References 18-20, the input delay induced by consecutive packet dropouts would be characterized by randomness. Although the probability characteristic of the stochastic input delay can be fully considered by introducing some indicator functions, the stochastic characteristic of the state delay of the resulting delay system is not changed. In view of such a difficult problem, most of the existing literature are based on the indirect research methods that are proposed in References 21,22 and there are few direct research methods for delay systems with state delays that are characterized by randomness. As a result, a preferred approach would be to convert the networked sampled-data systems with successive packet losses to their equivalent discrete models. It needs to be emphasized that, up to now, little work has focused on the stabilization of networked sampled-data systems with successive packet losses by discretization approach. Therefore, the first motivation in this study is to establish a unified framework by discretization approach under which the sampled-data stabilization problem is investigated for a class of networked systems with successive packet losses.

By discrete-time system approach, the equivalent discrete system will be characterized by randomness with respect to the number of successive packet losses, which leads to difficulties in the stabilization of the networked sampled-data system. The difficulties are mainly manifested in the following aspects: (1) Since the number of successive packet losses is a discrete random variable, how can we obtain the probability characteristic of the discrete random variable before stability criteria are derived? (2) In the stabilization of the discrete stochastic system, how can we develop a new approach to calculate the mathematical expectations of both matrix exponential and integral of matrix exponential function involving the number of successive packet losses? Therefore, the second motivation in this study is to provide a favorable answer to the aforementioned issues.

Inspired by the theoretical analyses mentioned previously, the authors are devoted to studying the stabilization of networked sampled-data systems with successive packet losses. The key contributions can be stated as follows:

(1) A new sampled-data stabilization issue is settled for a class of networked systems with successive packet losses, where the discretization approach is introduced to the modeling of successive packet losses, which is not the same as the input delay approach used in References 18-20.
(2) By the law of total expectation, the mathematical expectations of both matrix exponential and integral of matrix exponential function are calculated and then an H_∞ stabilization controller is designed.

Finally, to verify the analysis results and testify the effectiveness and applicability of the designed algorithm, a numerical simulation example is given.

Notation: Denote $\mathbb{N}_0$ as the set of nonnegative integers. The space of square-integrable vector functions over $[0,\infty)$ is denoted by $\mathcal{L}_2[0,\infty)$. For $v=\{v(k)\}\in l_2[0,\infty)$, $\sum_{k=0}^{\infty}\|v(k)\|^2<\infty$ and the l_2 norm is given by $|v|_2=\sqrt{\sum_{k=0}^{\infty}\|v(k)\|^2}$.

2 | PRELIMINARIES AND PROBLEM FORMULATION

Let us consider the following continuous-time networked system with successive packet losses:

$$\begin{cases}\dot{x}(t)=Ax(t)+Bu(t)+Ew(t),\\ y(t)=Cx(t)+Dw(t),\end{cases} \tag{1}$$

where $x(t)\in\mathbb{R}^n$ is the state vector, $u(t)\in\mathbb{R}^m$ is the control input, $y(t)\in\mathbb{R}^p$ is controlled output, and $w(t)\in\mathcal{L}_2[0,\infty)$ is disturbance input vector. A, B, C, D, E are constant matrices with appropriate dimensions.

In order to simplify the problem on the basis of rationality, we only consider the successive packet losses occurring in the sampler-controller channel. The system's state of (1) is periodically sampled. Denote by $\{kh\}_{k=0}^{\infty}$ the sampling sequence and $\{t_j\}_{j=0}^{\infty}$ those sequence transmitted to controller successfully, where $t_0=0$. Then, for state-feedback control with zero-order hold, $u(t)$ can be represented as:

$$u(t)=Kx(t_j),\, t_j\le t<t_{j+1}, \tag{2}$$

where K is the gain matrix, which will be designed later. Combining (1) with (2), the closed-loop system can be obtained as follows:

$$\begin{cases}\dot{x}(t)=Ax(t)+BKx(t_j)+Ew(t),\\ y(t)=Cx(t)+Dw(t),\, t_j\le t<t_{j+1}.\end{cases} \tag{3}$$

In order to develop our main results in sequel, the following assumption is imposed for closed-loop system (3).

Assumption 1. The number of successive packet losses $n_j^{j+1}\in\mathbb{N}_0$ that might occur in the interval $[t_j,t_{j+1})$ is upper bounded by N, where $N\in\mathbb{N}_0$ represents the maximum allowable number of successive packet losses.

Under the Assumption 1, the relationship between two consecutive update times of zero-order hold is $t_{j+1}-t_j=(n_j^{j+1}+1)h$. Integrating equation (3) from t_j to t_{j+1} and note that $t_{j+1}-t_j=(n_j^{j+1}+1)h$, one has

$$\begin{cases}x(t_{j+1})=\left(e^{A(n_j^{j+1}+1)h}+\int_0^{(n_j^{j+1}+1)h}e^{As}dsBK\right)x(t_j)+\int_0^{(n_j^{j+1}+1)h}e^{As}dsEw(t_j),\\ y(t_j)=Cx(t_j)+Dw(t_j).\end{cases} \tag{4}$$

Remark 1. In Reference 18-20, the control problems of periodic sampled-data systems with successive packet losses are investigated. Different from the input delay method used in References 18-20, we use the discrete-time approach to model the networked systems subject to successive packet losses. Note that n_j^{j+1} in (4) is a stochastic variable since n_j^{j+1} can take values in set $\{0,1,2,\dots,N\}$ randomly. Thus, how to deal with the difficulty caused by n_j^{j+1} is a crucial issue to be solved in this article.

Notice that system (4) is a discrete-time stochastic system because of the existence of stochastic variable n_j^{j+1}. In this article, our goal is to design (2) such that the exponential mean-square stability of stochastic system (4) is guaranteed with a prescribed H_∞ performance:

(1) Stochastic system (4) with $w(t_j) = 0$ is said to be exponentially mean-square stable, that is, there exist $\omega > 0$ and $\mu \in (0, 1)$ such that

$$\mathbb{E}\{\|x(t_j)\|^2\} \leq \omega\mu^k\mathbb{E}\{\|x(0)\|^2\},$$

holds for all $x(0) \in \mathbb{R}^n$ and $k > \kappa$, where κ is a sufficiently large positive integer;

(2) Under the assumption of zero initial condition, $y(t_j)$ satisfies

$$\mathbb{E}\left\{\sum_{j=0}^{\infty}\|y(t_j)\|^2\right\} < \gamma^2\mathbb{E}\left\{\sum_{j=0}^{\infty}\|w(t_j)\|^2\right\}$$

for any nonzero $w(t_j) \in l_2[0, \infty)$.

Due to the existence of stochastic variable n_j^{j+1}, it brings difficulties to the calculation of resulting mathematical expectation. To reduce the complexity of analyzing stochastic system (4), we first let

$$\hat{A} = e^{Ah}, \hat{B} = \int_0^h e^{As}dsB, \hat{C} = \hat{A}B, \overline{B} = \int_0^h e^{As}dsE, \overline{C} = \hat{A}E, \Delta = \int_0^{n_j^{j+1}h} e^{As}ds,$$

then, we have

$$e^{A(n_j^{j+1}+1)h} = e^{n_j^{j+1}Ah}\hat{A}, \int_0^{(n_j^{j+1}+1)h} e^{As}dsB = \hat{B} + \Delta\hat{C}$$

and

$$\int_0^{(n_j^{j+1}+1)h} e^{As}dsE = \overline{B} + \Delta\overline{C}, e^{A(n_j^{j+1}+1)h} + \int_0^{(n_j^{j+1}+1)h} e^{As}dsBK = e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K.$$

Thus, stochastic system (4) can be equivalently rewritten as follows:

$$\begin{cases} x(t_{j+1}) = (e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K)x(t_j) + (\overline{B} + \Delta\overline{C})w(t_j), \\ y(t_j) = Cx(t_j) + Dw(t_j). \end{cases} \tag{5}$$

In order to design a controller such that the exponential mean-square stability of stochastic system (5) is guaranteed with a prescribed H_∞ performance, the following lemmas are introduced, which help to clarify the issue to be studied.

Lemma 1. *Assume that the packet transmitted in sampler-controller channel has a packet loss rate ϑ ($0 \leq \vartheta < 1$), then*

$$\begin{cases} \mathscr{P}\{n_j^{j+1} = s\} = \vartheta^s(1-\vartheta), s = 0, 1, 2, \ldots, N-1, \\ \mathscr{P}\{n_j^{j+1} = N\} = \vartheta^N. \end{cases}$$

Proof. First, for any $kh \in [t_j, t_{j+1}), j \in \mathbb{N}_0$, we introduce stochastic variable $\alpha(kh)$. If the packet in sampler-controller channel is transmitted successfully at time kh, $\alpha(kh) = 0$; otherwise, $\alpha(kh) = 1$. Since ϑ is the packet loss rate, stochastic sequence $\{\alpha(kh)\}_{k\in\mathbb{N}_0}$ satisfies Bernoulli distribution with $\mathscr{P}\{\alpha(kh) = 1\} = \vartheta$ and $\mathscr{P}\{\alpha(kh) = 0\} = 1 - \vartheta$. Second, for $s = 0, 1, 2, \ldots, N$, the following stochastic variables $\zeta_s(j)$ defined in the interval $[t_j, t_{j+1})$ are introduced:

$$\zeta_s(j) = \begin{cases} 1 & n_j^{j+1} = s, \\ 0 & \text{otherwise}, \end{cases} \quad s = 0, 1, 2, \ldots, N.$$

Accordingly, the relationship between n_j^{j+1} and $\zeta_s(j)$ can be obtained in Table 1.

TABLE 1 A one-to-one correspondence between n_j^{j+1} and $\zeta_s(j)$

n_j^{j+1}	Stochastic variables $\zeta_s(j), s = 0, 1, 2, \dots, N$
$n_j^{j+1} = 0$	$\zeta_0(j) = 1 - \alpha(t_{j+1}) = 1$
$n_j^{j+1} = 1$	$\zeta_1(j) = \alpha(t_j + h)[1 - \alpha(t_{j+1})] = 1$
$\vdots$	$\vdots$
$n_j^{j+1} = N - 1$	$\zeta_{N-1}(j) = \alpha(t_j + h)\alpha(t_j + 2h) \times \dots \times \alpha(t_{j+1} - h) \times [1 - \alpha(t_{j+1})] = 1$
$n_j^{j+1} = N$	$\zeta_N(j) = \alpha(t_j + h)\alpha(t_j + 2h) \times \dots \times \alpha(t_{j+1} - h) = 1$

From Table 1, we have

$$\begin{cases} \mathscr{P}\ \{n_j^{j+1} = s\} \\ = \mathscr{P}\ \{\zeta_s(j) = 1\} \\ = \mathscr{P}\ \{\alpha(t_j + h)\alpha(t_j + 2h)\ \dots\ \alpha(t_j + sh)[1 - \alpha(t_{j+1})] = 1\} \\ = \mathscr{P}\ \{\alpha(t_j + h) = 1\} \times \mathscr{P}\ \{\alpha(t_j + 2h) = 1\} \times\ \dots\ \times \mathscr{P}\ \{\alpha(t_j + sh) = 1\} \times \mathscr{P}\ \{\alpha(t_{j+1}) = 0\} \\ = \vartheta^s(1 - \vartheta), s = 0, 1, 2, \dots, N - 1; \\ \mathscr{P}\ \{n_j^{j+1} = N\} \\ = \mathscr{P}\ \{\zeta_N(j) = 1\} \\ = \mathscr{P}\ \{\alpha(t_j + h)\alpha(t_j + 2h)\ \dots\ \alpha(t_{j+1} - h) = 1\} \\ = \mathscr{P}\ \{\alpha(t_j + h) = 1\} \times \mathscr{P}\ \{\alpha(t_j + 2h) = 1\} \times\ \dots\ \times \mathscr{P}\ \{\alpha(t_{j+1} - h) = 1\} \\ = \vartheta^N. \end{cases} \tag{6}$$

Then, we have by (6) that

$$\mathscr{P}\ \{n_j^{j+1} = s\} = \vartheta^s(1 - \vartheta), s = 0, 1, 2, \dots, N - 1; \mathscr{P}\ \{n_j^{j+1} = N\} = \vartheta^N.$$

The proof is complete. ■

Lemma 2. 23,24 *If there exist positive real constants υ_1 and υ_2, $\sigma \geq 0$ and $\varphi \in (0, 1]$ such that the following conditions*

$$\upsilon_1 \left\| x(t_j) \right\|^2 \leq V(x(t_j)) \leq \upsilon_2 \left\| x(t_j) \right\|^2$$

and

$$\mathbb{E}\left\{ \mathbb{E}\{V(x(t_{j+1})) \left| x(t_j) \right.\} - V(x(t_j)) \right\} \leq \sigma - \varphi \mathbb{E}\left\{ V(x(t_j)) \right\}$$

hold, where $V(x(t_j))$ is a Lyapunov function. Then, one has

$$\mathbb{E}\left\{ \left\| x(t_j) \right\|^2 \right\} \leq \frac{\upsilon_2}{\upsilon_1} \mathbb{E}\left\{ \|x(0)\|^2 \right\} (1 - \varphi)^k + \frac{\sigma}{\upsilon_1 \varphi}.$$

3 | MAIN RESULTS

In the presence of successive packet losses, the sampled-data stabilization problem of networked systems is considered in this section.

Theorem 1. *Given the packet drop rate ϑ and controller gain matrix K, stochastic system (5) with $w(t_j) = 0$ is exponentially mean-square stable if there exists $P > 0$ such that (7) holds:*

$$-P + (\Pi_1 + \Pi_2 + \Pi_3)^T (I \otimes P)(\Pi_1 + \Pi_2 + \Pi_3) < 0, \tag{7}$$

where Π_1, Π_2, *and* Π_3 *are*

$$
\begin{aligned}
\Pi_1^T &= \begin{bmatrix} \theta_0 \hat{A}^T & \theta_1 \hat{A}^T e^{A^T h} & \dots & \theta_N \hat{A}^T e^{NA^T h} \end{bmatrix} \\
\Pi_2^T &= K^T \hat{C}^T \begin{bmatrix} 0 & \theta_1 \int_0^h e^{A^T s} ds & \dots & \theta_N \int_0^{Nh} e^{A^T s} ds \end{bmatrix} \\
\Pi_3^T &= \begin{bmatrix} \theta_0 K^T \hat{B}^T & \theta_1 K^T \hat{B}^T & \dots & \theta_N K^T \hat{B}^T \end{bmatrix}
\end{aligned}
$$

with $\theta_i = \sqrt{\vartheta^i(1-\vartheta)}, i = 0, 1, 2, \dots, N-1$ *and* $\theta_N = \sqrt{\vartheta^N}$.

Proof. First, the Lyapunov function is constructed as follows:

$$
V(x(t_j)) = x^T(t_j) P x(t_j), \tag{8}
$$

where $P > 0$. Second, the difference of the Lyapunov function (8) is defined as

$$
\Delta V(x(t_j)) = \mathbb{E}\{V(x(t_{j+1})) \left| x(t_j) \right. \} - V(x(t_j)). \tag{9}
$$

When $w(t_j) = 0$, calculating (9) along system (5), it yields

$$
\begin{aligned}
\mathbb{E}\{\Delta V(x(t_j))\} &= \mathbb{E}\left\{ x^T(t_j) \left[\left(e^{n_j^{j+1} Ah} \hat{A} + \hat{B}K + \Delta \hat{C} K \right)^T P \left(e^{n_j^{j+1} Ah} \hat{A} + \hat{B}K + \Delta \hat{C} K \right) - P \right] x(t_j) \right\} \\
&= \mathbb{E}\left\{ x^T(t_j) \left(\hat{A}^T e^{n_j^{j+1} A^T h} P e^{n_j^{j+1} Ah} \hat{A} + \hat{A}^T e^{n_j^{j+1} A^T h} P \hat{B} K + \hat{A}^T e^{n_j^{j+1} A^T h} P \Delta \hat{C} K \right. \right. \\
&\quad + K^T \hat{B}^T P e^{n_j^{j+1} Ah} \hat{A} + K^T \hat{B}^T P \hat{B} K + K^T \hat{B}^T P \Delta \hat{C} K + K^T \hat{C}^T \Delta^T P e^{n_j^{j+1} Ah} \hat{A} \\
&\quad \left. \left. + K^T \hat{C}^T \Delta^T P \hat{B} K + K^T \hat{C}^T \Delta^T P \Delta \hat{C} K - P \right) x(t_j) \right\}.
\end{aligned} \tag{10}
$$

By Lemma 1 and the law of total expectation, we have

$$
\mathbb{E}\left\{ e^{n_j^{j+1} A^T h} \right\} = \vartheta^N e^{NA^T h} + \sum_{i=0}^{N-1} \vartheta^i (1-\vartheta) e^{iA^T h} \tag{11}
$$

and

$$
\mathbb{E}\left\{ \int_0^{n_j^{j+1} h} e^{As} ds \right\} = \vartheta^N \int_0^{Nh} e^{As} ds + \sum_{i=1}^{N-1} \vartheta^i (1-\vartheta) \int_0^{ih} e^{As} ds. \tag{12}
$$

For the term $\mathbb{E}\left\{ \hat{A}^T e^{n_j^{j+1} A^T h} P e^{n_j^{j+1} Ah} \hat{A} \right\}$, we have

$$
\begin{aligned}
\mathbb{E}\left\{ e^{n_j^{j+1} A^T h} P e^{n_j^{j+1} Ah} \right\} &= \sum_{i=0}^{N} \mathbb{E}\left\{ e^{n_j^{j+1} A^T h} P e^{n_j^{j+1} Ah} \left| n_j^{j+1} = i \right. \right\} \times \mathscr{P}\left\{ n_j^{j+1} = i \right\} \\
&= \vartheta^N e^{NA^T h} P e^{NAh} + \sum_{i=0}^{N-1} \vartheta^i (1-\vartheta) e^{iA^T h} P e^{iAh}.
\end{aligned} \tag{13}
$$

For the term $\mathbb{E}\left\{ K^T \hat{C}^T \Delta^T P \Delta \hat{C} K \right\}$, we can also have by Lemma 1 and the law of total expectation that

$$
\mathbb{E}\left\{ \Delta^T P \Delta \right\} = \vartheta^N \left(\int_0^{Nh} e^{As} ds \right)^T P \left(\int_0^{Nh} e^{As} ds \right) + \sum_{i=1}^{N-1} \vartheta^i (1-\vartheta) \left(\int_0^{ih} e^{As} ds \right)^T P \left(\int_0^{ih} e^{As} ds \right) \tag{14}
$$

and for the term $\mathbb{E}\left\{ \hat{A}^T e^{n_j^{j+1} A^T h} P \Delta \hat{C} K \right\}$, one has

$$
\begin{aligned}
\mathbb{E}\left\{e^{n_j^{j+1}A^T h}P\Delta\right\} &= \mathbb{E}\left\{\left(e^{n_j^{j+1}A^T h}\right)P\left(\int_0^{n_j^{j+1}h} e^{As}ds\right)\right\} \\
&= \vartheta^N\left(e^{NA^T h}\right)P\left(\int_0^{Nh} e^{As}ds\right) + \sum_{i=1}^{N-1}\vartheta^i(1-\vartheta)\left(e^{iA^T h}\right)P\left(\int_0^{ih} e^{As}ds\right).
\end{aligned} \tag{15}
$$

By using the (11–15) and note that $K^T\hat{B}^T P\hat{B}K = \Pi_3^T(I\otimes P)\Pi_3$, we have by (10) that

$$
\begin{aligned}
\mathbb{E}\{\Delta V(x(t_j))\} = \mathbb{E}\{x^T(t_j)\big(&-P + \Pi_1^T(I\otimes P)\Pi_1 + \Pi_2^T(I\otimes P)\Pi_2 \\
&+ \Pi_3^T(I\otimes P)\Pi_3 + \Pi_1^T(I\otimes P)\Pi_3 + \Pi_3^T(I\otimes P)\Pi_1 + \Pi_1^T(I\otimes P)\Pi_2 \\
&+ \Pi_2^T(I\otimes P)\Pi_1 + \Pi_3^T(I\otimes P)\Pi_2 + \Pi_2^T(I\otimes P)\Pi_3\big)x(t_j)\} \\
= \mathbb{E}\{x^T(t_j)\big(&-P + (\Pi_1+\Pi_2+\Pi_3)^T(I\otimes P)(\Pi_1+\Pi_2+\Pi_3)\big)x(t_j)\}.
\end{aligned} \tag{16}
$$

Let $\Pi = -P + (\Pi_1+\Pi_2+\Pi_3)^T(I\otimes P)(\Pi_1+\Pi_2+\Pi_3)$. From inequality (7), it follows that $\Pi < 0$. Hence, one has $\mathbb{E}\{\Delta V(x(t_j))\} \le E\{x^T(t_j)\Pi x(t_j)\} \le -\lambda_{\min}(-\Pi)\mathbb{E}\{x^T(t_j)x(t_j)\} \le \frac{-\lambda_{\min}(-\Pi)}{\lambda_{\max}(P)}\mathbb{E}\{V(x(t_j))\}$. By defining $\varpi = \min\{\lambda_{\min}(-\Pi), \lambda_{\max}(P)\}$, it yields

$$
\mathbb{E}\{\Delta V(x(t_j))\} \le -\frac{\varpi}{\lambda_{\max}(P)}\mathbb{E}\{V(x(t_j))\}. \tag{17}
$$

From (8), one has

$$
\lambda_{\min}(P)\|x(t_j)\|^2 \le V(x(t_j)) \le \lambda_{\max}(P)\|x(t_j)\|^2. \tag{18}
$$

Then, combine (17) with (18), we have by Lemma 2 that

$$
\mathbb{E}\left\{\|x(t_j)\|^2\right\} \le \omega\mu^k\mathbb{E}\left\{\|x(0)\|^2\right\}.
$$

where $\omega = \frac{\lambda_{\max}(P)}{\lambda_{\min}(P)}$ and $\mu = 1 - \frac{\varpi}{\lambda_{\max}(P)} \in (0,1]$. Therefore, the stochastic system (5) with $w(t_j)=0$ is exponentially mean-square stable. We complete the proof. ■

In the following analysis, the H_∞ performance of stochastic system (5) is discussed. Choosing the same Lyapunov function candidate as (8). Then, for any nonzero $w(t_j) \in l_2[0,\infty)$, calculating (9) alone (5) and taking mathematical expectation, we have by similar techniques as those in the above that

$$
\begin{aligned}
\mathbb{E}\{\Delta V(x(t_j)) + \|y(t_j)\|^2 - \gamma^2\|w(t_j)\|^2\} = \mathbb{E}\Big\{x^T(t_j)\Big[&(e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K)^T P(e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K) \\
&- P + C^T C\Big]x(t_j) + x^T(t_j)(e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K)^T P(\overline{B} + \Delta\overline{C})w(t_j) \\
&+ w^T(t_j)(\overline{B} + \Delta\overline{C})^T P(e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K)x(t_j) + x^T(t_j)C^T Dw(t_j) \\
&+ w^T(t_j)D^T Cx(t_j) + w^T(t_j)\Big[(\overline{B} + \Delta\overline{C})^T P(\overline{B} + \Delta\overline{C}) + D^T D - \gamma^2 I\Big]w(t_j)\Big\}.
\end{aligned} \tag{19}
$$

By the law of total expectation and Lemma 1, we have $\mathbb{E}\left\{\hat{A}^T e^{n_j^{j+1}A^T h}P\overline{B}\right\} = \Pi_1^T(I\otimes P)\Pi_4$ with $\Pi_4^T = \begin{bmatrix}\theta_0\overline{B}^T & \theta_1\overline{B}^T & \dots & \theta_N\overline{B}^T\end{bmatrix}$, and $\mathbb{E}\left\{\hat{A}^T e^{n_j^{j+1}A^T h}P\Delta\overline{C}\right\} = \Pi_1^T(I\otimes P)\Pi_5$ with $\Pi_5^T = \overline{C}^T\begin{bmatrix}0 & \theta_1\int_0^h e^{A^T s}ds & \dots & \theta_N\int_0^{Nh} e^{A^T s}ds\end{bmatrix}$.

Using the same method, we can get $\mathbb{E}\left\{K^T\hat{B}^T P\Delta\overline{C}\right\} = \Pi_3^T(I\otimes P)\Pi_5$, $\mathbb{E}\left\{K^T\hat{C}^T\Delta^T P\overline{B}\right\} = \Pi_2^T(I\otimes P)\Pi_4$, and $\mathbb{E}\left\{K^T\hat{C}^T\Delta^T P\Delta\overline{C}\right\} = \Pi_2^T(I\otimes P)\Pi_5$. Note that $K^T\hat{B}^T P\overline{B} = \Pi_3^T(I\otimes P)\Pi_4$, we have

$$
\mathbb{E}\left\{\left(e^{n_j^{j+1}Ah}\hat{A} + \hat{B}K + \Delta\hat{C}K\right)^T P(\overline{B} + \Delta\overline{C})\right\} = (\Pi_1+\Pi_2+\Pi_3)^T(I\otimes P)(\Pi_4+\Pi_5), \tag{20}
$$

where Π_1, Π_2, and Π_3 are defined in Theorem 1.

Similarly, for the term $\mathbb{E}\left\{(\overline{B}+\Delta\overline{C})^T P(\overline{B}+\Delta\overline{C})\right\}$, one has

$$\mathbb{E}\left\{(\overline{B}+\Delta\overline{C})^T P(\overline{B}+\Delta\overline{C})\right\} = (\Pi_4+\Pi_5)^T(I\otimes P)(\Pi_4+\Pi_5). \tag{21}$$

Denote by $\zeta(t_j) = \begin{bmatrix} x^T(t_j) & w^T(t_j)\end{bmatrix}^T$. Then, substituting (20) and (21) into (19) yields

$$\mathbb{E}\{\Delta V(x(t_j)) + \|y(t_j)\|^2 - \gamma^2\|w(t_j)\|^2\} = \mathbb{E}\left\{\zeta^T(t_j)\begin{bmatrix}\Pi + C^TC & \Pi_{12}+C^TD\\ * & \Pi_{22}+D^TD-\gamma^2 I\end{bmatrix}\zeta(t_j)\right\},$$

where $\Pi_{12} = (\Pi_1+\Pi_2+\Pi_3)^T(I\otimes P)(\Pi_4+\Pi_5)$ and $\Pi_{22} = (\Pi_4+\Pi_5)^T(I\otimes P)(\Pi_4+\Pi_5)$. By the Schur complement formula, the following inequality

$$\begin{bmatrix}\Pi + C^TC & \Pi_{12}+C^TD\\ * & \Pi_{22}+D^TD-\gamma^2 I\end{bmatrix} < 0$$

holds if and only if

$$\hat{\Pi} = \begin{bmatrix} -P & 0 & (\Pi_1+\Pi_2+\Pi_3)^T & C^T\\ * & -\gamma^2 I & (\Pi_4+\Pi_5)^T & D\\ * & * & -(I\otimes P)^{-1} & 0\\ * & * & * & -I\end{bmatrix} < 0$$

If $\hat{\Pi} < 0$, we can conclude that

$$\mathbb{E}\{\Delta V(x(t_j)) + \|y(t_j)\|^2 - \gamma^2\|w(t_j)\|^2\} < 0. \tag{22}$$

For all $j \in \mathbb{N}_0$, we have by summing up (22) that

$$\mathbb{E}\left\{\sum_{j=0}^{\infty}\|y(t_j)\|^2\right\} - \gamma^2 E\left\{\sum_{j=0}^{\infty}\|w(t_j)\|^2\right\} \le \mathbb{E}\{x^T(0)Px(0)\} - \mathbb{E}\{x^T(\infty)Px(\infty)\}. \tag{23}$$

Notice that $\mathbb{E}\{x^T(\infty)Px(\infty)\} > 0$, under zero initial condition and according to (23), one has

$$\mathbb{E}\left\{\sum_{j=0}^{\infty}\|y(t_j)\|^2\right\} < \gamma^2\mathbb{E}\left\{\sum_{j=0}^{\infty}\|w(t_j)\|^2\right\}$$

holds for any nonzero $w(t_j) \in l_2[0,\infty)$.

In addition, noticing that inequality (7) holds when $\hat{\Pi} < 0$ holds, thus, stochastic system (5) with $w(t_j) = 0$ is also exponentially stable in the mean square sense when $\hat{\Pi} < 0$ holds. Now, we get the following theorem.

Theorem 2. *Let packet drop rate ϑ, controller gain matrix K and $\gamma > 0$ be given. The stochastic system (5) is exponentially stable in the mean square sense and achieves a prescribed H_∞ performance γ if there exists $P > 0$ with appropriate dimensions, such that (24) holds:*

$$\begin{bmatrix} -P & 0 & (\Pi_1+\Pi_2+\Pi_3)^T & C^T\\ * & -\gamma^2 I & (\Pi_4+\Pi_5)^T & D\\ * & * & -(I\otimes P)^{-1} & 0\\ * & * & * & -I\end{bmatrix} < 0, \tag{24}$$

where Π_4 and Π_5 are

$$\Pi_4^T = \begin{bmatrix} \theta_0 \overline{B}^T & \theta_1 \overline{B}^T & \dots & \theta_N \overline{B}^T \end{bmatrix}, \Pi_5^T = \overline{C}^T \begin{bmatrix} 0 & \theta_1 \int_0^h e^{A^T s} ds & \dots & \theta_N \int_0^{Nh} e^{A^T s} ds \end{bmatrix}$$

and Π_1, Π_2, Π_3 *are defined in Theorem 1 with* $\theta_i = \sqrt{\vartheta^i(1-\vartheta)}, i = 0, 1, 2, \dots, N-1$ *and* $\theta_N = \sqrt{\vartheta^N}$.

Based on Theorem 2, the design problem of H_∞ controller is given in the following theorem.

Theorem 3. *Let packet drop rate* ϑ *and* $\gamma > 0$ *be given. For stochastic system (4) with* $u(t)$ *given by (2), discrete-time stochastic system (5) is exponentially stable in the mean square sense and achieves a prescribed* H_∞ *performance* γ*, if there exist* $Q > 0$ *and* $\overline{K}$ *such that (25) holds:*

$$\begin{bmatrix} -Q & 0 & Q\Pi_1^T + \overline{K}\hat{\Pi}_2^T + \overline{K}\hat{\Pi}_3^T & QC^T \\ * & -\gamma^2 I & (\Pi_4^T + \Pi_5^T) & D \\ * & * & -(I \otimes Q) & 0 \\ * & * & * & -I \end{bmatrix} < 0, \tag{25}$$

where

$$\Pi_1^T = \begin{bmatrix} \theta_0 \hat{A}^T & \theta_1 \hat{A}^T e^{A^T h} & \dots & \theta_N \hat{A}^T e^{NA^T h} \end{bmatrix},$$
$$\hat{\Pi}_2^T = \begin{bmatrix} 0 & \theta_1 \hat{C}^T \int_0^h e^{A^T s} ds & \dots & \theta_N \hat{C}^T \int_0^{Nh} e^{A^T s} ds \end{bmatrix},$$
$$\hat{\Pi}_3^T = \begin{bmatrix} \theta_0 \hat{B}^T & \theta_1 \hat{B}^T & \dots & \theta_N \hat{B}^T \end{bmatrix}.$$

with $\theta_i = \sqrt{\vartheta^i(1-\vartheta)}, i = 0, 1, 2, \dots, N-1$ *and* $\theta_N = \sqrt{\vartheta^N}$*. Moreover, if (25) is feasible, the desired controller gain can be obtained as follows*

$$K = \overline{K}^T Q^{-1}.$$

Proof. By performing a congruence transformation of diag$\{P^{-1}, I, I \otimes I, I\}$ on (24), we have

$$\begin{bmatrix} -P^{-1} & 0 & P^{-1}(\Pi_1^T + \Pi_2^T + \Pi_3^T) & P^{-1}C^T \\ * & -\gamma^2 I & \Pi_4^T + \Pi_5^T & D \\ * & * & -(I \otimes P)^{-1} & 0 \\ * & * & * & -I \end{bmatrix} < 0$$

Let $Q = P^{-1}$ and $\overline{K} = P^{-1}K^T$, inequality (25) holds immediately. Thus, (25) implies (24) and then the exponential mean-square stability of stochastic system (5) can be guaranteed with a prescribed γ by following the same route as Theorem 2. ∎

Remark 2. About the feasibility of inequality (7) in Theorem 1, given h, ϑ, and N, we need to choose a proper K such that $\Pi_1 + \Pi_2 + \Pi_3$ is a Schur matrix implying that all its eigenvalues are inside of the unit circle. If inequality (7) in Theorem 1 is feasible, then (24) in Theorem 2 is also feasible for small enough $\frac{1}{\gamma} > 0$ and $||C||$. Different from the previous, when checking the feasibility of (25) in Theorem 3, one need only to choose h, ϑ, and N. If not feasible, rechoose h, ϑ, and N until (25) in Theorem 3 to be feasible. The latter leads to control gain, see, for example, Section 4.

4 | APPLICATION TO AIRCRAFT FLIGHT CONTROL SYSTEM

In this section, flight control system in Reference 25 is used to verify the analysis results and testify the effectiveness and applicability of the designed algorithm and the continuous-time dynamic equations are as follows:

$$
\begin{cases}
\dot{V} = \frac{F_{wx} g \sin \gamma}{m} \\
\dot{\alpha} = q_b - \frac{q_w}{\cos \beta} - p_b \cos \alpha \tan \beta - r_b \sin \alpha \tan \beta \\
\dot{\beta} = r_w + p_b \sin \alpha - r_b \cos \alpha \\
\dot{\gamma} = q_w \cos \varphi - r_w \sin \varphi \\
\dot{\varphi} = p_w + (q_w \sin \varphi - r_w \cos \varphi) \tan \gamma \\
\dot{\psi} = \frac{(q_w \sin \varphi - r_w \cos \varphi) \tan \gamma}{\cos \gamma} \\
\dot{q}_b = \frac{1}{I_x} [M_b + I_{xz}(r_b^2 - p_b^2) + (I_z - I_x) r_b p_b]
\end{cases}
\tag{26}
$$

with p_b and r_b satisfying

$$
\begin{bmatrix} \dot{p}_b \\ \dot{r}_b \end{bmatrix} = \begin{bmatrix} I_x & -I_{xz} \\ -I_{xz} & I_z \end{bmatrix}^{-1} \begin{bmatrix} L_b + I_{xz} p_b q_b + (I_z - I_x) q_b r_b \\ N_b + I_{xz} q_b r_b + (I_x - I_y) p_b q_b \end{bmatrix}
$$

where V represents the flight path velocity; F_{wx} stands for the wind-axis total force with respect to x-body axis; g is the gravity acceleration and m is the mass; α represents the angle of attack and β is the angle of sideslip; the body-axis angular rates are, respectively, denoted as p_b, q_b, and r_b; the wind-axis Euler angles are, respectively, characterized by γ, φ, and ψ; the wind-axis angular rates are, respectively, denoted as p_w, q_w, and r_w; the body axis total rolling, pitching, and yawing moments are, respectively, denoted as L_b, M_b, and N_b; the moments of inertia with respect to x-, y-, and z- body axes are, respectively, characterized by I_x, I_y, and I_z; the crossproduct of inertia with respect to x- and z- body axes is denoted as I_{xz}.

Suppose that V is constant and by linearization on the equilibrium point, one can decouple (26) and then the longitudinal state-space model is obtained as follows:

$$
\dot{x}(t) = Ax(t) + Bu(t) + Ew(t), \tag{27}
$$

where $x(t) = \begin{bmatrix} \alpha & q_b & \theta \end{bmatrix}^T$, $u(t)$ and $w(t)$ are, respectively, denoted as the longitudinal motion of a state vector, the elevator deflection and the disturbance input vector with θ represents the pitch angle. A and B are constant matrices with appropriate dimensions and E stands for the influence of disturbance on system matrices:

$$
A = \begin{bmatrix} Z_\alpha & 1 & -g \sin\left(\frac{\mu_*}{V_*}\right) \\ M_\alpha & M_q & 0 \\ 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} Z_{\delta_z} \\ M_{\delta_z} \\ 0 \end{bmatrix}, E = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \tag{28}
$$

where μ_* and V_* are, respectively, the flight-path angle and the velocity on the equilibrium point; δ_z stands for the equivalent elevator deflection; the parameters Z_α, M_α, M_q, Z_{δ_z}, and M_{δ_z} represent the force and moment dimensional derivatives.

According to the work of Reference 25, the parameter values in (28) are given as follows:

$$
A = \begin{bmatrix} -0.5427 & 1 & 0 \\ -1.069 & -0.4134 & 0 \\ 0 & 1 & 0 \end{bmatrix}, B = \begin{bmatrix} -0.113 \\ -3.259 \\ 0 \end{bmatrix}, E = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}.
$$

The controlled output $y(t)$ has the form

$$
y(t) = Cx(t), \quad C = \begin{bmatrix} 0.01 & 0 & 0 \end{bmatrix}.
$$

Consider the aircraft flight control system (27) over a communication network. Assume that the packet losses occur with the probability $\vartheta = 0.3$, and the number of consecutive packet losses is $N = 5$. Let the sampling period be $h = 0.2$. By solving Theorem 3, we find that the minimum value of H_∞ performance level is $\gamma_{\min} = 0.0198$. Meanwhile,

$$Q = 10^3 \times \begin{bmatrix} 1.1641 & -0.1036 & -0.1620 \\ -0.1036 & 0.7429 & -0.1383 \\ -0.1620 & -0.1383 & 0.7254 \end{bmatrix}$$

and

$$\overline{K} = \begin{bmatrix} -273.2721 & 572.3051 & 150.9016 \end{bmatrix}^T,$$

which gives the matrix K as follows

$$K = \begin{bmatrix} -0.1149 & 0.8172 & 0.3381 \end{bmatrix}.$$

Then, the state responses of the closed-loop system (5) are depicted in Figure 1, where the initial condition and disturbance input are given by $x(0) = [-0.2, 0.5, 0.1]^T$ and $w(t) = \sin(0.1t)e^{-0.1t}$, respectively. The corresponding packet transmissions in the communication network are depicted in Figure 2. From the simulation results, one can see that the

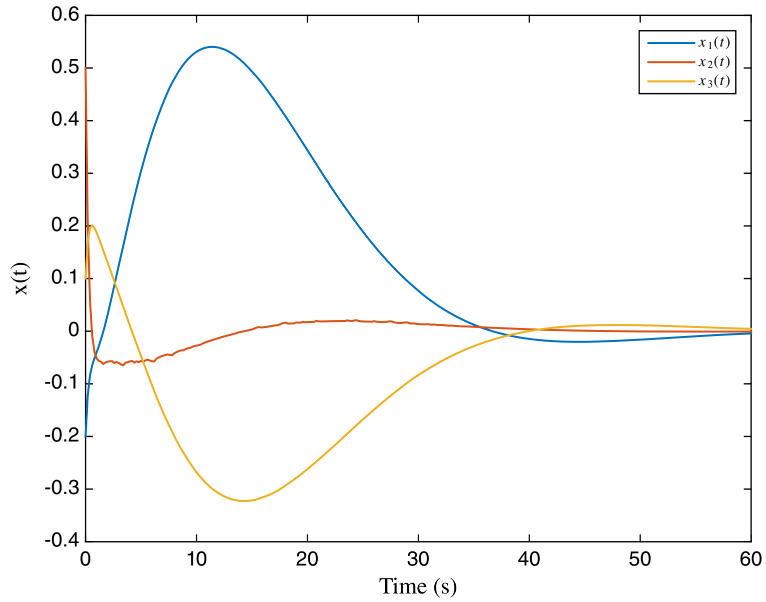

FIGURE 1 State responses of closed-loop system (5) subject to randomly occurring packet losses [Colour figure can be viewed at wileyonlinelibrary.com]

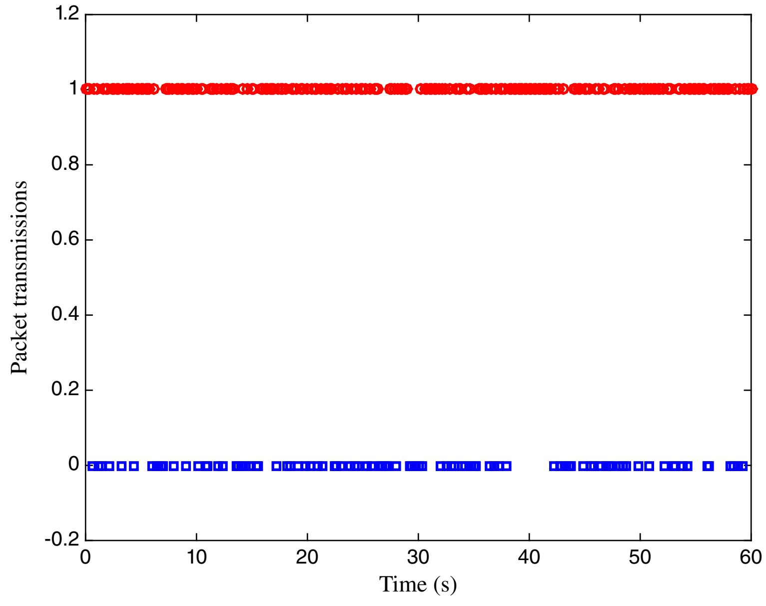

FIGURE 2 Packet transmissions in the communication network (○: successfully transmitted and □: unsuccessfully transmitted) [Colour figure can be viewed at wileyonlinelibrary.com]

proposed designed algorithm effectively overcomes the presence of randomly occurring packet losses while ensuring the system's performance. By calculation, $|w|_2 = 4.0748$ and $|y|_2 = 0.0014$, which yields $\frac{|y|_2}{|w|_2} = 0.0183 < 0.0198$ and then also the effectiveness of the H_∞ controller design is shown.

5 | CONCLUSIONS

In this article, the sampled-data stabilization problem has been studied for a class of networked systems with successive packet losses. We have first established a relationship between two consecutive update times of zero-order hold and then set up an equivalent stochastic system with system matrices subject to stochastic characteristic by discrete-time system approach. By calculating the probabilities of the number of successive packet losses taking each value in a bounded set and recurring to the law of total expectation, stochastic stability criteria have been derived and thus an H_∞ controller design procedure has been proposed. Finally, to verify the analysis results and testify the effectiveness and applicability of the designed algorithm, a numerical simulation example has been given. In the future research, the authors will be devoted to the stabilization problem or adaptive control problem[26,27] of linear networked systems with delays or consecutive packet losses subject to noisy sampling intervals[28,29] by discrete-time system approach.

ACKNOWLEDGMENTS

This work was partially supported by the National Natural Science Foundation of China under Grants 62003204, 62073144, 61873099, 61733008, 61873170, and U1813225, in part by Shantou University Scientific Research Foundation for Talents under Grant NTF19031, in part by the Natural Science Foundation of Guangdong Province Under Grant 2020A1515010441, in part by the Science and Technology Development Foundation of the Shenzhen Government under Grant JCYJ20190808144607400, in part by the Guangzhou Science and Technology Planning Project Under Grants 202002030158 and 202002030389.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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How to cite this article: Hu Z, Zhang J, Deng F, Fan Z, Qiu L. A discretization approach to sampled-data stabilization of networked systems with successive packet losses. *Int J Robust Nonlinear Control*. 2021;1–13. https://doi.org/10.1002/rnc.5490