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Stabilization for Networked Control System With Time-Delay and Packet Loss in Both S-C Side and C-A Side

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ABSTRACT The stabilization problem for a class of discrete network control system with time-delay and packet loss in both S-C side and C-A side is researched in this paper. Firstly, two independent discrete Markov chains are used to describe the network time-delay from sensor to controller and the network time-delay from controller to actuator. Two random variables obeying the Bernoulli distribution are employed to describe the packet loss between the sensor and the controller and the packet loss between the controller and the actuator. Secondly, a mathematical model for closed-loop system is established. By constructing the appropriate Lyapunov-Krasovskii functional, the sufficient conditions for the existence of the controller and observer gain matrix are obtained under the condition that the transition probabilities of S-C time-delay and C-A time-delay are both partly unknown. Finally, two examples are exploited to illustrate the effectiveness of the proposed method.

INDEX TERMS Time-delay, packet loss, observer, stabilization, networked control system, Lyapunov–Krasovskii functional.

I. INTRODUCTION

Networked control system (NCS) has a great many advantages, such as easy expansion, easy diagnosis and low cost, and it is widely used in industrial control, environmental monitoring, military and other fields [1]–[3]. However, the introduction of the network inevitably produces the time-delay, packet loss and other problems [4]–[6], which makes the performance of the control system degraded and may even lead to system instability. How to design the controller for NCS with time-delay and packet loss has attracted the attention of many scholars and a lot of research results have appeared [7]–[11].

The network of the NCS exists not only between the sensor and the controller (sensor to controller, S-C) but also between the controller and the actuator (controller to actuator, C-A), and both networks will experience time-delay and packet loss. However, among the existing literatures on stabilization controller design for NCS, some literatures only considered the time-delay of two networks, and some literatures only

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considered the packet loss of two networks, and some literatures only consider the time-delay and packet loss of S-C side or C-A side. The existing literatures on controller design for NCS can be divided into the following three types:

The first type of literatures only considered time-delay. The S-C time-delay was described by a finite-state discrete Markov chain, and the closed-loop NCS was modelled as a Markov jump linear system [12]. Two independent discrete Markov chains were employed to describe the S-C time-delay σ_k and C-A time-delay ϕ_k respectively, and the mathematical model of the closed-loop system was established by the method of state augmentation. The necessary and sufficient conditions for the stochastic stability of the closed-loop system were obtained, and the solution method of the state feedback controller was proposed [13]. Considering S-C time-delay σ_k and C-A time-delay ϕ_k, the $\mathcal{H}_2/\mathcal{H}_\infty$ control problem for a class of discrete-time NCS was investigated. Two independent Markov chains were exploited to model the time-delay in S-C side and C-A side. The resulting closed-loop system was a jump linear time-delay induced by two Markov chains. Sufficient conditions for existence of $\mathcal{H}_2/\mathcal{H}_\infty$ controller were established based on the free weight matrix method [14]. The robust $\mathcal{H}_\infty$ fault detection problem was investigated for the discrete NCS with time-delay on condition that the transition probabilities of time-delay were partly unknown. The closed-loop NCS was molded as a control system which contained two Markov chains, and the relationship between transition probabilities and the minimum $\mathcal{H}_\infty$ attenuation level was also obtained [15].

The second type of literatures only considered packet loss. Considering the S-C packet loss and C-A packet loss, the observer-based stabilization controller design problem was researched for a class of nonlinear NCS. The S-C packet loss and C-A packet loss were described by two random variables obeying the Bernoulli distribution. The controller that made the closed-loop system stochastically mean square stable and meet certain $\mathcal{H}_\infty$ performance was designed [16]. For a class of nonlinear NCS with S-C packet loss and C-A packet loss, the $\mathcal{H}_\infty$ controller was designed as an observer-based dynamic, such that the closed-loop system was exponentially mean square stable and the effect of the disturbance input on the controlled output was less than a minimum level γ for all admissible uncertainties [17].

The third type of literatures only considered time-delay and packet loss in S-C side or time-delay and packet loss in C-A side. The dynamic output feedback controller was designed for nonlinear NCS with time-delay and packet loss in S-C side. The time-delay and packet loss were modeled as two independent random variables. An observer-based dynamic output feedback controller was designed based upon the Lyapunov theory.The quantitative relationship between the packet loss rate and nonlinear level was derived by solving a set of linear matrix inequalities (LMIs) [18]. For the NCS with time-delay and packet loss, the sufficient conditions for the existence of the fault detection filter which made the closed-loop system stable and achieve given $\mathcal{H}_\infty$ attenuation performance were established. Although the time-delay in S-C side and C-A side were considered, but the packet loss in C-A side was ignored [19].

Due to the limitation of environmental or economic conditions, it is usually difficult to measure the entire states of the controlled plant, which makes state feedback difficult to achieve. Hence, the state observer needs to be designed, and the state of the controlled plant can be reconstructed through the observer to achieve the required feedback. Therefore, it is of great practical significance to research the observer-based stabilization for NCS [20].

In summary, the current research on the controller design of NCS is not sufficient. To the best of our knowledge, for NCS with time-delay and packet loss in both S-C side and C-A side, the stabilization problem under the condition that the transition probabilities of S-C time-delay and C-A time-delay are both partly unknown has not been researched, which motivates our investigation. Compared to the previous relevant literatures, the main contribution of this paper is that a mathematical model of NCS with time-delay and packet loss in both S-C side and C-A side has been proposed. By constructing proper Lyapunov-Krasovskii functional, and separating unknown probabilities from the known ones, the proposed controller design method is applicable not only to the case that the transition probabilities of the time-delay are partially unknown, but also to the case where the transition probabilities of the time-delay are known, which is less conservative than the existing literatures.

The rest of this paper is organized as follows. The mathematical model of NCS with time-delay and packet loss in both S-C side and C-A side is obtained in Section II. The main results are provided in Section III. Section IV presents a simulation example, and the conclusions are given in Section V.

Notations: Throughout the paper, $\Pr\{\cdot\}$ means mathematical probability, $E\{\cdot\}$ stands for mathematical expectation and $\mathrm{Var}\{\cdot\}$ denotes variance. The superscript "T" and "-1" stands for the transpose and inverse of a matrix, respectively. $\mathrm{Diag}\{\cdots\}$ stands for a block-diagonal matrix. The symbol "*" denotes the symmetric part in a symmetric matrix. $P > 0$ denotes a positive definite matrix.

II. PROBLEM FORMULATION AND PRELIMINARIES

The structure of the NCS considered in this paper is shown in Figure 1, where the switch closure indicates that the packet transmission is successful, and the switch open indicates that a packet loss has occurred. σ_k and ϕ_k denotes the time-delay in S-C side and C-A side and takes value from $\Omega = \{0, \cdots, \sigma_M\}$ and $\Xi = \{0, \cdots, \phi_M\}$, respectively. The transition probability matrix of σ_k and ϕ_k is $\Pi = [\mu_{ab}]$, $\Theta = [\nu_{mn}]$, respectively, where μ_{ab} and ν_{mn} is defined as $\mu_{ab} = \Pr\{\mu_{k+1} = b|\mu_k = a\}$, $\nu_{mn} = \Pr\{\nu_{k+1} = n|\nu_k = m\}$, respectively, where $\mu_{ab} \geq 0$, $\nu_{mn} \geq 0$, $\sum_{b=0}^{\sigma_M} \mu_{ab} = 1$, $\sum_{n=0}^{\phi_M} \nu_{mn} = 1$.

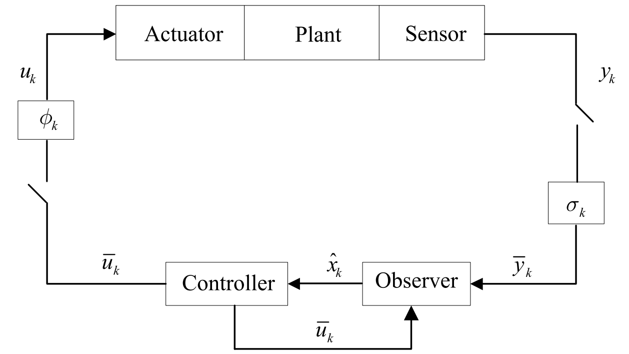

FIGURE 1. **Structure of NCS with time-delay and packet loss.**

It is usually difficult to obtain the all transition probabilities of the time-delay, so it is assumed that there are some unknown elements in the transition probability matrix of the time-delay. For notational clarity, $\forall b \in \Omega$, let $\Omega = \Omega_k^a + \Omega_{uk}^a$ with $\Omega_k^a = \{b : \mu_{ab} \text{ is known}\}$, $\Omega_{uk}^a = \{b : \mu_{ab} \text{ is unknown}\}$. If Ω_k^a is not an empty set, it is further described as $\Omega_k^a = \{\Omega_{k_1^a}, \Omega_{k_2^a}, \cdots, \Omega_{k_p^a}\}$, where $\Phi_{k_p^a}$ represents the pth known element in the ath row of matrix Π with the index $\Phi_{k_p^a}$. Ω_{uk}^a can be described as $\Omega_{uk}^a = \{\Omega_{\bar{k}_1^a}, \Omega_{\bar{k}_2^a}, \cdots, \Omega_{\bar{k}_{\sigma_M - p}^a}\}$, where $\Phi_{\bar{k}_{\sigma_M - p}^a}$ represents the $(\sigma_M - p)$th unknown element in the ath row of matrix Π with the index $\Phi_{\bar{k}_{\sigma_M - p}^a}$.

Similarly, $\forall n \in \Xi$, let $\Xi = \Xi_k^m + \Xi_{uk}^m$ with $\Xi_k^m = \{n : \nu_{mn} \text{ is known}\}$, $\Xi_{uk}^m = \{n : \nu_{mn} \text{ is unknown}\}$. If Ξ_k^m is not an empty set, it is further described as $\Xi_k^m = \{\Xi_{k_1^m}, \Xi_{k_2^m}, \cdots, \Xi_{k_q^m}\}$, where $\Xi_{k_q^m}$ represents the qth known element in the mth row of matrix Θ with the index $\Xi_{k_q^m}$. Ξ_{uk}^m can be described as $\Xi_{uk}^m = \{\Xi_{\bar{k}_1^m}, \Xi_{\bar{k}_2^m}, \cdots, \Xi_{\bar{k}_{\phi_M - q}^m}\}$, where $\Xi_{\bar{k}_{\phi_M - q}^m}$ represents the $(\phi_M - q)$th unknown element in the mth row of matrix Θ with the index $\Xi_{\bar{k}_{\phi_M - q}^m}$.

The random variable α_k, β_k which obeys Bernoulli distribution is used to describe the packet loss in S-C side and C-A side, respectively. When the random variable takes the value of 1, it indicates that the data packet was successfully transmitted. Otherwise, it indicates that the data packet transmission failed. Random variables α_k, β_k satisfy the following characteristics:

$$\begin{aligned}
&\Pr\{\alpha_k = 1\} = E\{\alpha_k\} \triangleq \bar{\alpha}, \\
&\Pr\{\alpha_k = 0\} = 1 - \bar{\alpha}, \\
&\quad \mathrm{Var}\{\alpha_k\} = E\{(\alpha_k - \bar{\alpha})^2\} = (1 - \bar{\alpha})\bar{\alpha} \triangleq \alpha_1^2, \\
&\Pr\{\beta_k = 1\} = E\{\beta_k\} \triangleq \bar{\beta}, \\
&\Pr\{\beta_k = 0\} = 1 - \bar{\beta}, \\
&\quad \mathrm{Var}\{\beta_k\} = E\{(\beta_k - \bar{\beta})^2\} = (1 - \bar{\beta})\bar{\beta} \triangleq \beta_1^2.
\end{aligned}$$

The discrete NCS equation considered in this paper are as follows:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ y_k = Cx_k \end{cases} \tag{1}$$

where x_k is the system state vector, u_k is the control input vector, y_k is the system measurement output vector, A, B, C are known real constant matrices with appropriate dimensions.

The state equation of the observer is as follows:

$$\begin{cases} \hat{x}_{k+1} = A\hat{x}_k + B\bar{u}_k + L(\bar{y}_k - \alpha_k \hat{y}_{k-\sigma_k}) \\ \hat{y}_k = C\hat{x}_k \end{cases} \tag{2}$$

where $\hat{x}_k$ is the state vector of the observer, $\hat{y}_k$ is the out vector of the observer, L is the gain matrix to be determined, $\bar{y}_k$ is the system output received by the observer and $\bar{u}_k$ is the control input of the observer which expressed as

$$\bar{u}_k = K\hat{x}_k \tag{3}$$

Considering the time-delay and packet loss, the system output $\bar{y}_k$ received by the observer and the control input u_k received by the actuator can be expressed as:

$$\bar{y}_k = \alpha_k y_{k-\sigma_k} \tag{4}$$

$$u_k = \beta_k \bar{u}_{k-\phi_k} \tag{5}$$

Define the following state estimation error and augmentation vector:

$$e_k = x_k - \hat{x}_k \tag{6}$$

$$\zeta_k = \begin{bmatrix} x_k^T & e_k^T \end{bmatrix}^T \tag{7}$$

The state equation of the closed-loop system can be obtained from (1)-(7):

$$\begin{aligned} \zeta_{k+1} = (\bar{A} + \bar{B}KE_1)\zeta_k + \alpha_k E_2 L\bar{C}\zeta_{k-\sigma_k} \\ + \beta_k \tilde{B}KE_1\zeta_{k-\phi_k} \end{aligned} \tag{8}$$

where $\bar{A} = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}$, $\bar{B} = \begin{bmatrix} 0 \\ -B \end{bmatrix}$, $\tilde{B} = \begin{bmatrix} B \\ B \end{bmatrix}$, $\bar{C} = \begin{bmatrix} 0 & -C \end{bmatrix}$, $E_1 = \begin{bmatrix} E & -E \end{bmatrix}$, $E_2 = \begin{bmatrix} 0 \\ E \end{bmatrix}$.

In order to deal with the stochastic parameter in closed-loop system (8), it is necessary to introduce the following definition.

Definition 1 [13]: For any initial system state ζ_0 and initial time-delay mode $\sigma_0 \in \Omega$, $\phi_0 \in \Xi$, if there exists a positive definite matrix W , such that

$$E\left\{\sum_{k=0}^{\infty} \| \zeta_k \|^2 | \zeta_0, \sigma_0, \phi_0 \right\} < \zeta_0^T W \zeta_0 \tag{9}$$

the closed-loop system (8) is said to be stochastically stable.

Remark 1: Because of the existence of the time-delay and the packet loss in C-A side, the control input of the observer $\bar{u}_k$ in (3) is different from the control input of the controlled system u_k in (1), which brings difficulties in the controller design.

III. MAIN RESULTS

In this section, the main resuls of this paper are presented. To proceed, the following lemma is needed.

Lemma 1 [21]: For any positive definite matrix H and two scalar θ, θ_0 satisfying $\theta \geq \theta_0 \geq 1$, the following formula always holds:

$$\sum_{\rho=\theta_0}^{\theta} \upsilon_\rho^T H \sum_{\rho=\theta_0}^{\theta} \upsilon_\rho \leq (\theta - \theta_0 + 1) \sum_{\rho=\theta_0}^{\theta} \upsilon_\rho^T H \upsilon_\rho \tag{10}$$

The following theorem presents a sufficient condition on the stochastic stability of the system (8).

Theorem 1: Under the proposed control law (3), the resulting system (8) is stochastically stable if for given scalars $0 \leq \bar{\alpha} \leq 1$, $0 \leq \bar{\beta} \leq 1$, there exist matrices K, L and positive definite matrices $S_{am} > 0$, $S_{bn} > 0$, $P_1 > 0$, $P_2 > 0$, $P_3 > 0$, $P_4 > 0$, $Y_1 > 0$, $Y_2 > 0$ such that the following matrix inequality:

$$\Upsilon \triangleq \begin{bmatrix} \Upsilon_{11} & * & * & * & * \\ \Upsilon_{21} & \Upsilon_{22} & * & * & * \\ \Upsilon_{31} & \Upsilon_{32} & \Upsilon_{33} & * & * \\ 0 & Y_1 & 0 & -P_1 - Y_1 & * \\ 0 & 0 & Y_2 & 0 & -P_2 - Y_2 \end{bmatrix} < 0 \tag{11}$$

where

$$\begin{aligned}
\Upsilon_{11} &= (\bar{A} + \bar{B}KE_1)^T \bar{S}_{bn}(\bar{A} + \bar{B}KE_1) \\
&\quad + \sigma_M^2(\bar{A} + \bar{B}KE_1 - E)^T Y_1(\bar{A} + \bar{B}KE_1 - E) \\
&\quad + \phi_M^2(\bar{A} + \bar{B}KE_1 - E)^T Y_2(\bar{A} + \bar{B}KE_1 - E) \\
&\quad + P_1 + P_2 + (\sigma_M + 1)P_3 + (\phi_M + 1)P_4 \\
&\quad - Y_1 - Y_2 - S_{am}, \\
\Upsilon_{21} &= (\bar{\alpha}E_2L\bar{C})^T \bar{S}_{bn}(\bar{A} + \bar{B}KE_1) \\
&\quad + \sigma_M^2(\bar{\alpha}E_2L\bar{C})^T Y_1(\bar{A} + \bar{B}KE_1 - E) \\
&\quad + \phi_M^2(\bar{\alpha}E_2L\bar{C})^T Y_2(\bar{A} + \bar{B}KE_1 - E) + Y_1, \\
\Upsilon_{22} &= (\bar{\alpha}^2 + \alpha_1^2)(E_2L\bar{C})^T \bar{S}_{bn}E_2L\bar{C} \\
&\quad + \sigma_M^2(\bar{\alpha}^2 + \alpha_1^2)(E_2L\bar{C})^T Y_1E_2L\bar{C} \\
&\quad + \phi_M^2(\bar{\alpha}^2 + \alpha_1^2)(E_2L\bar{C})^T Y_2E_2L\bar{C} - P_3 - 2Y_1, \\
\Upsilon_{31} &= (\bar{\beta}\tilde{B}KE_1)^T \bar{S}_{bn}(\bar{A} + \bar{B}KE_1) \\
&\quad + \sigma_M^2(\bar{\beta}\tilde{B}KE_1)^T Y_1(\bar{A} + \bar{B}KE_1 - E) \\
&\quad + \phi_M^2(\bar{\beta}\tilde{B}KE_1)^T Y_2(\bar{A} + \bar{B}KE_1 - E) + Y_2, \\
\Upsilon_{32} &= (\bar{\beta}\tilde{B}KE_1)^T \bar{S}_{bn}(\bar{\alpha}E_2L\bar{C}) \\
&\quad + \sigma_M^2(\bar{\beta}\tilde{B}KE_1)^T Y_1(\bar{\alpha}E_2L\bar{C}) \\
&\quad + \phi_M^2(\bar{\beta}\tilde{B}KE_1)^T Y_2(\bar{\alpha}E_2L\bar{C}), \\
\Upsilon_{33} &= (\bar{\beta}^2 + \beta_1^2)(\tilde{B}KE_1)^T \bar{S}_{bn}\tilde{B}KE_1 \\
&\quad + \sigma_M^2(\bar{\beta}^2 + \beta_1^2)(\tilde{B}KE_1)^T Y_1\tilde{B}KE_1 \\
&\quad + \phi_M^2(\bar{\beta}^2 + \beta_1^2)(B_2KI_1)^T Y_2B_2KI_1 - 2Y_2 - P_4, \\
\bar{S}_{bn} &= \sum_{b=0}^{\sigma_M}\sum_{n=0}^{\phi_M} \mu_{ab}\nu_{mn}S_{bn},
\end{aligned}$$

holds for all $a, b \in \Omega$, $m, n \in \Xi$. ■

Proof: Let $\xi_k = \zeta_{k+1} - \zeta_k$, and construct the following Lyapunov-Krasovskii functional:

$$V_k = \sum_{l=1}^{4} V_l(\zeta_k, \sigma_k, \phi_k) \triangleq \zeta_k^T \Gamma_{\sigma_k\phi_k}\zeta_k, \tag{12}$$

where

$$\begin{aligned}
V_1(\zeta_k, \sigma_k, \phi_k) &= \zeta_k^T S_{\sigma_k\phi_k}\zeta_k, \\
V_2(\zeta_k, \sigma_k, \phi_k) &= \sum_{\rho=k-\sigma_M}^{k-1} \zeta_\rho^T P_1\zeta_\rho + \sum_{\rho=k-\phi_M}^{k-1} \zeta_\rho^T P_2\zeta_\rho, \\
V_3(\zeta_k, \sigma_k, \phi_k) &= \sum_{j=-\sigma_M+1}^{0}\sum_{i=k+j}^{k-1} \zeta_i^T P_3\zeta_i + \sum_{\rho=k-\sigma_k}^{k-1} \zeta_\rho^T P_3\zeta_\rho \\
&\quad + \sum_{j=-\phi_M+1}^{0}\sum_{i=k+j}^{k-1} \zeta_i^T P_4\zeta_i + \sum_{\rho=k-\phi_k}^{k-1} \zeta_\rho^T P_4\zeta_\rho, \\
V_4(\zeta_k, \sigma_k, \phi_k) &= \sum_{j=-\sigma_M+1}^{0}\sum_{i=k+j}^{k-1} \sigma_M\xi_i^T Y_1\xi_i \\
&\quad + \sum_{j=-\phi_M+1}^{0}\sum_{i=k+j}^{k-1} \phi_M\xi_i^T Y_2\xi_i.
\end{aligned}$$

Obviously, one has $\Gamma_{\sigma_k\phi_k} > 0$.

$$\begin{aligned}
&E\{\Delta V_1(\zeta_k, \sigma_k, \phi_k)\} \\
&= E\{\zeta_{k+1}^T S_{\sigma_{k+1}\phi_{k+1}}\zeta_{k+1} \,|\sigma_k = a, \phi_k = m\} \\
&\quad - \zeta_k^T S_{\sigma_k\phi_k}\zeta_k \\
&= E\{((\bar{A} + \bar{B}KE_1)\zeta_k + \bar{\alpha}E_2L\bar{C}\zeta_{k-\sigma_k} \\
&\quad + (\alpha_k - \bar{\alpha})E_2L\bar{C}\zeta_{k-\sigma_k} + \bar{\beta}\tilde{B}KE_1\zeta_{k-\phi_k} \\
&\quad + (\beta_k - \bar{\beta})\tilde{B}KE_1\zeta_{k-\phi_k})^T \sum_{b=0}^{\sigma_M}\sum_{n=0}^{\phi_M} \mu_{ab}\nu_{mn}S_{bn} \\
&\quad ((\bar{A} + \bar{B}KE_1)\zeta_k + \bar{\alpha}E_2L\bar{C}\zeta_{k-\sigma_k} \\
&\quad + (\alpha_k - \bar{\alpha})E_2L\bar{C}\zeta_{k-\sigma_k} + \bar{\beta}\tilde{B}KE_1\zeta_{k-\phi_k} \\
&\quad + (\beta_k - \bar{\beta})\tilde{B}KE_1\zeta_{k-\phi_k})\} - \zeta_k^T S_{am}\zeta_k \\
&= \zeta_k^T(\bar{A} + \bar{B}KE_1)^T \bar{P}_{bn}(\bar{A} + \bar{B}KE_1)\zeta_k \\
&\quad + \zeta_k^T(\bar{A} + \bar{B}KE_1)^T \bar{P}_{bn}(\bar{\alpha}E_2L\bar{C})\zeta_{k-\sigma_k} \\
&\quad + \zeta_k^T(\bar{A} + \bar{B}KE_1)^T \bar{P}_{bn}(\bar{\beta}\tilde{B}KE_1)\zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\sigma_k}^T(\bar{\alpha}E_2L\bar{C})^T \bar{P}_{bn}(\bar{A} + \bar{B}KE_1)\zeta_k \\
&\quad + \zeta_{k-\sigma_k}^T(\bar{\alpha}E_2L\bar{C})^T \bar{P}_{bn}(\bar{\alpha}E_2L\bar{C})\zeta_{k-\sigma_k} \\
&\quad + \alpha_1^2\zeta_{k-\sigma_k}^T(E_2L\bar{C})^T \bar{P}_{bn}(E_2L\bar{C})\zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\sigma_k}^T(\bar{\alpha}E_2L\bar{C})^T \bar{P}_{bn}(\bar{\beta}\tilde{B}KE_1)\zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\phi_k}^T(\bar{\beta}\tilde{B}KE_1)^T \bar{P}_{bn}(\bar{A} + \bar{B}KE_1)\zeta_k \\
&\quad + \zeta_{k-\phi_k}^T(\bar{\beta}\tilde{B}KE_1)^T \bar{P}_{bn}(\bar{\alpha}E_2L\bar{C})\zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\phi_k}^T(\bar{\beta}\tilde{B}KE_1)^T \bar{P}_{bn}(\bar{\beta}\tilde{B}KE_1)\zeta_{k-\phi_k} \\
&\quad + \beta_1^2\zeta_{k-\phi_k}^T(\tilde{B}KE_1)^T \bar{P}_{bn}\tilde{B}KE_1\zeta_{k-\phi_k} \\
&\quad - \zeta_k^T S_{am}\zeta_k.
\end{aligned} \tag{13}$$

$$\begin{aligned}
&E\{\Delta V_2(\zeta_k, \sigma_k, \phi_k)\} \\
&= \zeta_k^T P_1\zeta_k - \zeta_{k-\sigma_M}^T P_1\zeta_{k-\sigma_M} + \zeta_k^T P_2\zeta_k \\
&\quad - \zeta_{k-\phi_M}^T P_2\zeta_{k-\phi_M}.
\end{aligned} \tag{14}$$

$$\begin{aligned}
&E\{\Delta V_3(\zeta_k, \sigma_k, \phi_k)\} \\
&= \sigma_M\zeta_k^T P_3\zeta_k - \sum_{\rho=k+1-\sigma_M}^{k} \zeta_\rho^T P_3\zeta_\rho + \zeta_k^T P_3\zeta_k \\
&\quad - \zeta_{k-\sigma_k}^T P_3\zeta_{k-\sigma_k} + \sum_{\rho=k+1-\sigma_{k+1}}^{k-1} \zeta_\rho^T P_3\zeta_\rho
\end{aligned}$$

$$
\begin{aligned}
&-\sum_{\rho=k+1-\sigma_k}^{k-1} \zeta_\rho^T P_3 \zeta_\rho + \phi_M \zeta_k^T P_4 \zeta_k \\
&-\sum_{\rho=k+1-\phi_M}^{k} \zeta_k^T P_4 \zeta_k + \zeta_k^T P_4 \zeta_k - \zeta_{k-\phi_k}^T P_4 \zeta_{k-\phi_k} \\
&+\sum_{\rho=k+1-\phi_{k+1}}^{k-1} \zeta_\rho^T P_4 \zeta_\rho - \sum_{\rho=k+1-\phi_k}^{k-1} \zeta_\rho^T P_4 \zeta_\rho \\
=\ & \sigma_M \zeta_k^T P_3 \zeta_k - \sum_{\rho=k+1-\sigma_M}^{k} \zeta_\rho^T P_3 \zeta_\rho + \zeta_k^T P_3 \zeta_k \\
&- \zeta_{k-\sigma_k}^T P_3 \zeta_{k-\sigma_k} + \sum_{\rho=k+1-\sigma_k}^{k-1} \zeta_\rho^T P_3 \zeta_\rho \\
&+ \sum_{\rho=k+1-\sigma_{k+1}}^{k-\sigma_k} \zeta_\rho^T P_3 \zeta_\rho - \sum_{\rho=k+1-\sigma_k}^{k-1} \zeta_\rho^T P_3 \zeta_\rho \\
&+ \phi_M \zeta_k^T P_4 \zeta_k - \sum_{\rho=k+1-\phi_M}^{k} \zeta_k^T P_4 \zeta_k + \zeta_k^T P_4 \zeta_k \\
&- \zeta_{k-\phi_k}^T P_4 \zeta_{k-\phi_k} + \sum_{\rho=k+1-\phi_k}^{k-1} \zeta_\rho^T P_4 \zeta_\rho \\
&+ \sum_{\rho=k+1-\phi_{k+1}}^{k-\phi_k} \zeta_\rho^T P_4 \zeta_\rho - \sum_{\rho=k+1-\phi_k}^{k-1} \zeta_\rho^T P_4 \zeta_\rho \\
\leq\ & \sigma_M \zeta_k^T P_3 \zeta_k - \sum_{\rho=k+1-\sigma_M}^{k} \zeta_\rho^T P_3 \zeta_\rho + \zeta_k^T P_3 \zeta_k \\
&- \zeta_{k-\sigma_k}^T P_3 \zeta_{k-\sigma_k} + \sum_{\rho=k+1-\sigma_k}^{k-1} \zeta_\rho^T P_3 \zeta_\rho \\
&+ \sum_{\rho=k+1-\sigma_M}^{k} \zeta_\rho^T P_3 \zeta_\rho - \sum_{\rho=k+1-\sigma_k}^{k-1} \zeta_\rho^T P_3 \zeta_\rho \\
&+ \phi_M \zeta_k^T P_4 \zeta_k - \sum_{\rho=k+1-\phi_M}^{k} \zeta_k^T P_4 \zeta_k + \zeta_k^T P_4 \zeta_k \\
&- \zeta_{k-\phi_k}^T P_4 \zeta_{k-\phi_k} + \sum_{\rho=k+1-\phi_k}^{k-1} \zeta_\rho^T P_4 \zeta_\rho \\
&+ \sum_{\rho=k+1-\phi_M}^{k} \zeta_\rho^T P_4 \zeta_\rho - \sum_{\rho=k+1-\phi_k}^{k-1} \zeta_\rho^T P_4 \zeta_\rho \\
=\ & (\sigma_M + 1) \zeta_k^T P_3 \zeta_k - \zeta_{k-\sigma_k}^T P_3 \zeta_{k-\sigma_k} \\
&+ (\phi_M + 1) \zeta_k^T P_4 \zeta_k - \zeta_{k-\phi_k}^T P_4 \zeta_{k-\phi_k}. \qquad (15)
\end{aligned}
$$

$$
\begin{aligned}
&E\{\Delta V_4(\zeta_k, \sigma_k, \phi_k)\} \\
&= E\{\sigma_M^2 \xi_k^T Y_1 \xi_k\} - \sum_{\rho=k-\sigma_M}^{k-1} \sigma_M \xi_\rho^T Y_1 \xi_\rho \\
&\quad + E\{\phi_M^2 \xi_k^T Y_2 \xi_k\} - \sum_{\rho=k-\phi_M}^{k-1} \phi_M \xi_\rho^T Y_2 \xi_\rho \\
&= E\{\sigma_M^2 ((\bar{A} + \bar{B}KE_1 - E)\zeta_k + \bar{\alpha} E_2 L\bar{C} \zeta_{k-\sigma_k} \\
&\quad + (\alpha_k - \bar{\alpha}) E_2 L\bar{C} \zeta_{k-\sigma_k} + \bar{\beta} \tilde{B} K E_1 \zeta_{k-\phi_k} \\
&\quad + (\beta_k - \bar{\beta}) \tilde{B} K E_1 \zeta_{k-\phi_k})^T Y_1 ((\bar{A} + \bar{B}KE_1 - E)\zeta_k \\
&\quad + \bar{\alpha} E_2 L\bar{C} \zeta_{k-\sigma_k} + (\alpha_k - \bar{\alpha}) E_2 L\bar{C} \zeta_{k-\sigma_k} \\
&\quad + \bar{\beta} \tilde{B} K E_1 \zeta_{k-\phi_k} + (\beta_k - \bar{\beta}) \tilde{B} K E_1 \zeta_{k-\phi_k})\} \\
&\quad - \sum_{\rho=k-\sigma_M}^{k-1} \sigma_M \xi_\rho^T Y_1 \xi_\rho + E\{\phi_M^2 ((\bar{A} + \bar{B}KE_1 - E)\zeta_k \\
&\quad + \bar{\alpha} E_2 L\bar{C} \zeta_{k-\sigma_k} + (\alpha_k - \bar{\alpha}) E_2 L\bar{C} \zeta_{k-\sigma_k} \\
&\quad + \bar{\beta} \tilde{B} K E_1 \zeta_{k-\phi_k} + (\beta_k - \bar{\beta}) \tilde{B} K E_1 \zeta_{k-\phi_k})^T Y_2 \\
&\quad \times ((\bar{A} + \bar{B}KE_1 - E)\zeta_k + \bar{\alpha} E_2 L\bar{C} \zeta_{k-\sigma_k} \\
&\quad + (\alpha_k - \bar{\alpha}) E_2 L\bar{C} \zeta_{k-\sigma_k} + \bar{\beta} \tilde{B} K E_1 \zeta_{k-\phi_k} \\
&\quad + (\beta_k - \bar{\beta}) \tilde{B} K E_1 \zeta_{k-\phi_k})\} - \sum_{\rho=k-\phi_M}^{k-1} \phi_M \xi_\rho^T Y_2 \xi_\rho \\
&= \sigma_M^2 (\zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_1 (\bar{A} + \bar{B}KE_1 - E)\zeta_k \\
&\quad + \zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_1 (\bar{\alpha} E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_1 (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_1 (\bar{A} + \bar{B}KE_1 - E)\zeta_k \\
&\quad + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_1 (\bar{\alpha} E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \alpha_1^2 \zeta_{k-\sigma_k}^T (E_2 L\bar{C})^T Y_1 (E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_1 (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_1 (\bar{A} + \bar{B}KE_1) \zeta_k \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_1 (\bar{\alpha} E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_1 (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\phi_k}^T \beta_1^2 (\tilde{B} K E_1)^T Y_1 \tilde{B} K E_1 \zeta_{k-\phi_k}) \\
&\quad - \sum_{\rho=k-\sigma_M}^{k-1} \sigma_M \xi_\rho^T Y_1 \xi_\rho + \phi_M^2 (\zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_2 \\
&\quad \times (\bar{A} + \bar{B}KE_1 - E)\zeta_k + \zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_2 \\
&\quad \times (\bar{\alpha} E_2 L\bar{C}) \zeta_{k-\sigma_k} + \zeta_k^T (\bar{A} + \bar{B}KE_1 - E)^T Y_2 \\
&\quad \times (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_2 (\bar{A} \\
&\quad + \bar{B}KE_1 - E)\zeta_k + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_2 (\bar{\alpha} E_2 L\bar{C}) \\
&\quad \times \zeta_{k-\sigma_k} + \alpha_1^2 \zeta_{k-\sigma_k}^T (E_2 L\bar{C})^T Y_2 (E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\sigma_k}^T (\bar{\alpha} E_2 L\bar{C})^T Y_2 (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_2 (\bar{A} + \bar{B}KE_1) \zeta_k \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_2 (\bar{\alpha} E_2 L\bar{C}) \zeta_{k-\sigma_k} \\
&\quad + \zeta_{k-\phi_k}^T (\bar{\beta} \tilde{B} K E_1)^T Y_2 (\bar{\beta} \tilde{B} K E_1) \zeta_{k-\phi_k} \\
&\quad + \zeta_{k-\phi_k}^T \beta_1^2 (\tilde{B} K E_1)^T Y_2 \tilde{B} K E_1 \zeta_{k-\phi_k}) \\
&\quad - \sum_{\rho=k-\phi_M}^{k-1} \phi_M \xi_\rho^T Y_2 \xi_\rho. \qquad (16)
\end{aligned}
$$

Since

$$
-\sum_{\rho=k-\sigma_M}^{k-1} \sigma_M \xi_\rho^T Y_1 \xi_\rho - \sum_{\rho=k-\phi_M}^{k-1} \phi_M \xi_\rho^T Y_2 \xi_\rho
$$

$$
\begin{aligned}
&\leq -\sum_{\rho=k-a}^{k-1} a\xi_\rho^T Y_1 \xi_\rho - \sum_{\rho=k-\sigma_M}^{k-a-1} (\sigma_M - a)\xi_\rho^T Y_1 \xi_\rho \\
&\quad - \sum_{\rho=k-m}^{k-1} m\xi_\rho^T Y_2 \xi_\rho - \sum_{\rho=k-\phi_M}^{k-m-1} (\phi_M - m)\xi_\rho^T Y_2 \xi_\rho,
\end{aligned}
$$

by Lemma1, one can obtain:

$$
\begin{aligned}
&- \sum_{\rho=k-a}^{k-1} a\xi_\rho^T Y_1 \xi_\rho - \sum_{\rho=k-\sigma_M}^{k-a-1} (\sigma_M - a)\xi_\rho^T Y_1 \xi_\rho \\
&- \sum_{\rho=k-m}^{k-1} m\xi_\rho^T Y_2 \xi_\rho - \sum_{\rho=k-\phi_M}^{k-m-1} (\phi_M - m)\xi_\rho^T Y_2 \xi_\rho \\
\leq &- [\zeta_k - \zeta_{k-a}]^T Y_1 [\zeta_k - \zeta_{k-a}] \\
&- [\zeta_{k-a} - \zeta_{k-\tau_M}]^T Y_1 [\zeta_{k-a} - \zeta_{k-\tau_M}] \\
&- [\zeta_k - \zeta_{k-m}]^T Y_2 [\zeta_k - \zeta_{k-m}] \\
&- [\zeta_{k-m} - \zeta_{k-\phi_M}]^T Y_2 [\zeta_{k-m} - \zeta_{k-\phi_M}].
\end{aligned} \tag{17}
$$

From (13)-(17), one can get:

$$
\begin{aligned}
E&\{\Delta V_k\} \\
&\leq \chi_k^T \Upsilon \chi_k \\
&\leq -\lambda_{\min}(-\Upsilon)\chi_k^T \chi_k \\
&\leq -\varepsilon \|\chi_k\|^2 \\
&\leq -\varepsilon \|\zeta_k\|^2,
\end{aligned} \tag{18}
$$

where

$$
\begin{aligned}
\chi_k &= \begin{bmatrix} \zeta_k^T & \zeta_{k-a}^T & \zeta_{k-m}^T & \zeta_{k-\sigma_M}^T & \zeta_{k-\phi_M}^T \end{bmatrix}^T, \\
\varepsilon &= \inf\{-\lambda_{\min}(-\Upsilon)\} > 0.
\end{aligned}
$$

From (17), for any positive integer $N \geq 1$:

$$
\begin{aligned}
E&\left\{\sum_{k=0}^{\infty} \| \zeta_k\|^2\right\} \\
&\leq 1/\varepsilon E\{V_0\} - 1/\varepsilon E\{V_{N+1}\} \\
&\leq 1/\varepsilon E\{V_0\} \\
&= 1/\varepsilon \zeta_k^T \Gamma_{\sigma_0\phi_0} \zeta_k.
\end{aligned}
$$

It can be seen from Definition 1 that the closed-loop system (8) is stochastically stable, which completes the proof. □

The sufficient conditions in Theorem 1 need to be further processed to obtain the controller gain matrix K and the observer gain matrix L, thus Theorem 2 is obtained as follows:

Theorem 2: For given scalars $0 \leq \bar{\alpha} \leq 1$, $0 \leq \bar{\beta} \leq 1$, if there exist matrices K, L and positive definite matrices $S_{am}, S_{bn}, M_{bn} > 0, P_1 > 0, P_2 > 0, P_3 > 0, P_4 > 0, Y_1 > 0, Y_2 > 0, Z_1 > 0, Z_2 > 0$ such that

$$
\begin{bmatrix}
\mu\nu\Psi_{11} & * & * & * \\
\mu\nu\Psi_{21} & \mu\nu\Psi_{22} & * & * \\
\mu\nu\Psi_{31} & 0 & \mu\nu\Psi_{33} & * \\
\Psi_{\Omega_k^a \Xi_k^m} & 0 & 0 & \Lambda_{\Omega_k^a \Xi_k^m}
\end{bmatrix} < 0, \tag{19}
$$

$$
\begin{bmatrix}
\nu\Psi_{11} & * & * & * \\
\nu\Psi_{21} & \nu\Psi_{22} & * & * \\
\nu\Psi_{31} & 0 & \nu\Psi_{33} & * \\
\Psi_{\Omega_{uk}^a \Xi_k^m} & 0 & 0 & \Lambda_{\Omega_{uk}^a \Xi_k^m}
\end{bmatrix} < 0, \quad \forall b \in \Omega_{uk}^a \tag{20}
$$

$$
\begin{bmatrix}
\mu\Psi_{11} & * & * & * \\
\mu\Psi_{21} & \mu\Psi_{22} & * & * \\
\mu\Psi_{31} & 0 & \mu\Psi_{33} & * \\
\Psi_{\Omega_k^a \Xi_{uk}^m} & 0 & 0 & \Lambda_{\Omega_k^a \Xi_{uk}^m}
\end{bmatrix} < 0, \quad \forall n \in \Xi_{uk}^m \tag{21}
$$

$$
\begin{bmatrix}
\Psi_{11} & * & * & * \\
\Psi_{21} & \Psi_{22} & * & * \\
\Psi_{31} & 0 & \Psi_{33} & * \\
\Psi_{\Omega_{uk}^a \Xi_{uk}^m} & 0 & 0 & \Lambda_{\Omega_{uk}^a \Xi_{uk}^m}
\end{bmatrix} < 0, \quad \forall b \in \Omega_{uk}^a, \forall n \in \Xi_{uk}^m, \tag{22}
$$

$$
S_{bn} M_{bn} = E, \quad Y_\rho Z_\rho = E, \ \rho \in \{1, 2\} \tag{23}
$$

where

$$
\Psi_{11} = \begin{bmatrix}
\bar{\Psi}_{11} & * & * & * & * \\
Y_1 & -P_3 - 2Y_1 & * & * & * \\
Z_2 & 0 & -P_4 - 2Y_2 & * & * \\
0 & Y_1 & 0 & -P_1 - Y_1 & * \\
0 & 0 & Y_2 & 0 & -P_2 - Y_2
\end{bmatrix},
$$

$$
\Psi_{21} = \sigma_M \begin{bmatrix}
\bar{A} + \bar{B}KE_1 - E & \bar{\alpha}E_2 L\bar{C} & \bar{\beta}\tilde{B}KE_1 & 0 & 0 \\
0 & \alpha_1 E_2 L\tilde{C} & 0 & 0 & 0 \\
0 & 0 & \beta_1 \tilde{B}KE_1 & 0 & 0
\end{bmatrix},
$$

$$
\Psi_{22} = \mathrm{Diag}\{-Z_1, -Z_1, -Z_1\},
$$

$$
\Phi_{31} = \phi_M \begin{bmatrix}
\bar{A} + \bar{B}KE_1 - E & \bar{\alpha}E_2 L\bar{C} & \bar{\beta}\tilde{B}KE_1 & 0 & 0 \\
0 & \alpha_1 E_2 L\tilde{C} & 0 & 0 & 0 \\
0 & 0 & \beta_1 \tilde{B}KE_1 & 0 & 0
\end{bmatrix},
$$

$$
\begin{aligned}
\Psi_{33} &= \mathrm{Diag}\{-Z_2 \ \ -Z_2 \ \ -Z_2\}, \\
\bar{\Psi}_{11} &= P_1 + P_2 + (\sigma_M + 1)P_3 + (\phi_M + 1)P_4 - Y_1 \\
&\quad - Y_2 - S_{am}, \\
\Lambda_{\Omega_k^a \Xi_k^m} &= \mathrm{Diag}\{\tilde{\Lambda}_{\Omega_k^a \Xi_k^m} \tilde{\Lambda}_{\Omega_k^a \Xi_k^m} \ \ \tilde{\Lambda}_{\Omega_k^a \Xi_k^m}\}, \\
\tilde{\Lambda}_{\Omega_k^a \Xi_k^m} &= \mathrm{Diag}\{-M_{\Omega_{k_1^a} \Xi_{k_1^m}} \dots - M_{\Omega_{k_p^a} \Xi_{k_q^m}}\}, \\
\Psi_{\Omega_k^a \Xi_k^m}^T &= \begin{bmatrix} \tilde{\Psi}_{\Omega_k^a \Xi_k^m}^T & \bar{\Psi}_{\Omega_k^a \Xi_k^m}^T & \widehat{\Psi}_{\Omega_k^a \Xi_k^m}^T \end{bmatrix}, \\
\tilde{\Psi}_{\Omega_k^a \Xi_k^m}^T &= \begin{bmatrix} \sqrt{\mu_{a\Omega_{k_1^a}} \nu_{m\Xi_{k_1^m}}} \bar{\eta}_1^T & \cdots & \sqrt{\mu_{a\Omega_{k_p^a}} \nu_{m\Xi_{k_q^m}}} \bar{\eta}_1^T \end{bmatrix}, \\
\bar{\Psi}_{\Omega_k^a \Xi_k^m}^T &= \begin{bmatrix} \sqrt{\mu_{a\Omega_{k_1^a}} \nu_{m\Xi_{k_1^m}}} \bar{\eta}_2^T & \cdots & \sqrt{\mu_{a\Omega_{k_p^a}} \nu_{m\Xi_{k_q^m}}} \bar{\eta}_2^T \end{bmatrix}, \\
\widehat{\Psi}_{\Omega_k^a \Xi_k^m}^T &= \begin{bmatrix} \sqrt{\mu_{a\Omega_{k_1^a}} \nu_{m\Xi_{k_1^m}}} \bar{\eta}_3^T & \cdots & \sqrt{\mu_{a\Omega_{k_p^a}} \nu_{m\Xi_{k_q^m}}} \bar{\eta}_3^T \end{bmatrix}, \\
\Lambda_{\Omega_{uk}^a \Xi_k^m} &= \mathrm{Diag}\{\tilde{\Lambda}_{\Omega_{uk}^a \Xi_k^m} \ \tilde{\Lambda}_{\Omega_{uk}^a \Xi_k^m} \ \tilde{\Lambda}_{\Omega_{uk}^a \Xi_k^m}\}, \\
\tilde{\Lambda}_{\Omega_{uk}^a \Xi_k^m} &= \mathrm{Diag}\{-M_{b\Xi_{k_1^m}} \dots - M_{b\Xi_{k_q^m}}\}, \\
\Psi_{\Omega_{uk}^a \Xi_k^m}^T &= \begin{bmatrix} \tilde{\Psi}_{\Omega_{uk}^a \Xi_k^m}^T & \bar{\Psi}_{\Pi_{uk}^a \Xi_k^m}^T & \widehat{\Psi}_{\Omega_{uk}^a \Xi_k^m}^T \end{bmatrix}, \\
\tilde{\Psi}_{\Omega_{uk}^a \Xi_k^m}^T &= \begin{bmatrix} \sqrt{\nu_{m\Xi_{k_1^m}}} \bar{\eta}_1^T & \cdots & \sqrt{\nu_{m\Xi_{k_q^m}}} \bar{\eta}_1^T \end{bmatrix}, \\
\bar{\Psi}_{\Omega_{uk}^a \Xi_k^m}^T &= \begin{bmatrix} \sqrt{\nu_{m\Xi_{k_1^m}}} \bar{\eta}_2^T & \cdots & \sqrt{\nu_{m\Xi_{k_q^m}}} \bar{\eta}_2^T \end{bmatrix},
\end{aligned}
$$

$$\widehat{\Psi}^{T}_{\Omega^a_{uk}\Xi^m_k} = \left[\sqrt{\nu_{m\Xi_{k_1^m}}}\bar{\eta}_3^T \ \cdots \ \sqrt{\nu_{m\Xi_{k_q^m}}}\bar{\eta}_3^T\right],$$
$$\Lambda_{\Omega^a_k\Xi^m_{uk}} = \mathrm{Diag}\{\tilde{\Lambda}_{\Omega^a_k\Xi^m_{uk}}\,\tilde{\Lambda}_{\Omega^a_k\Xi^m_{uk}}\ \tilde{\Lambda}_{\Omega^a_k\Xi^m_{uk}}\},$$
$$\tilde{\Lambda}_{\Omega^a_k\Xi^m_{uk}} = \mathrm{Diag}\{-M_{\Omega_{k_1^a}n}\ldots - M_{\Omega_{k_p^a}n}\},$$
$$\Psi^T_{\Omega^a_k\Xi^m_{uk}} = \left[\tilde{\Psi}^T_{\Omega^a_k\Xi^m_{uk}} \ \ \bar{\Psi}^T_{\Omega^a_k\Xi^m_{uk}} \ \ \widehat{\Psi}^{T}_{\Omega^a_k\Xi^m_{uk}}\right],$$
$$\tilde{\Psi}^T_{\Omega^a_k\Xi^m_{uk}} = \left[\sqrt{\mu_{a\Omega_{k_1^a}}}\bar{\eta}_1^T \ \cdots \ \sqrt{\mu_{a\Omega_{k_p^a}}}\bar{\eta}_1^T\right],$$
$$\bar{\Psi}^T_{\Omega^a_k\Xi^m_{uk}} = \left[\sqrt{\mu_{a\Omega_{k_1^a}}}\bar{\eta}_2^T \ \cdots \ \sqrt{\mu_{a\Omega_{k_p^a}}}\bar{\eta}_2^T\right],$$
$$\widehat{\Psi}^{T}_{\Omega^a_k\Xi^m_{uk}} = \left[\sqrt{\mu_{a\Omega_{k_1^a}}}\bar{\eta}_3^T \ \cdots \ \sqrt{\mu_{a\Omega_{k_p^a}}}\bar{\eta}_3^T\right],$$
$$\Lambda_{\Omega^a_{uk}\Xi^m_{uk}} = \mathrm{Diag}\{\tilde{\Lambda}_{\Omega^a_{uk}\Xi^m_{uk}}\,\tilde{\Lambda}_{\Omega^a_{uk}\Xi^m_{uk}}\,\tilde{\Lambda}_{\Omega^a_{uk}\Xi^m_{uk}}\},$$
$$\tilde{\Lambda}_{\Omega^a_{uk}\Xi^m_{uk}} = \mathrm{Diag}\{-M_{bn}\ldots - M_{bn}\},$$
$$\Psi^T_{\Omega^a_{uk}\Xi^m_{uk}} = \left[\tilde{\Psi}^T_{\Omega^a_{uk}\Xi^m_{uk}} \ \ \bar{\Psi}^T_{\Omega^a_{uk}\Xi^m_{uk}} \ \ \widehat{\Psi}^{T}_{\Omega^a_{uk}\Xi^m_{uk}}\right],$$
$$\tilde{\Psi}^T_{\Omega^a_{uk}\Xi^m_{uk}} = \left[\bar{\eta}_1^T \ \cdots \ \bar{\eta}_1^T\right],$$
$$\bar{\Psi}^T_{\Omega^a_{uk}\Xi^m_{uk}} = \left[\bar{\eta}_2^T \ \cdots \ \bar{\eta}_2^T\right],$$
$$\widehat{\Psi}^{T}_{\Omega^a_{uk}\Xi^m_{uk}} = \left[\bar{\eta}_3^T \ \cdots \ \bar{\eta}_3^T\right],$$
$$\bar{\eta}_1 = \left[\eta_1 \ 0 \ 0\right],$$
$$\bar{\eta}_2 = \left[0 \ \eta_2 \ 0\right],$$
$$\bar{\eta}_3 = \left[0 \ 0 \ \eta_3\right],$$
$$\eta_1 = \left[\bar{A} + \bar{B}KE_1 \ \ \bar{\alpha}E_2L\bar{C} \ \ \bar{\beta}\tilde{B}KE_1 \ \ 0 \ \ 0\right],$$
$$\eta_2 = \left[0 \ \ \bar{\alpha}E_2L\bar{C} \ \ 0 \ \ 0 \ \ 0\right],$$
$$\eta_3 = \left[0 \ \ 0 \ \ \bar{\beta}\tilde{B}KE_1 \ \ 0 \ \ 0\right],$$
$$\mu = \sum_{b\in\Omega^a_k}\mu_{ab},$$
$$\bar{\mu} = \sum_{b\in\Omega^a_{uk}}\mu_{ab},$$
$$\nu = \sum_{n\in\Xi^m_k}\nu_{mn},$$
$$\bar{\nu} = \sum_{n\in\Xi^m_{uk}}\nu_{mn},$$

holds for all $a, b \in \Omega$, $m, n \in \Xi$, the closed-loop system (8) is stochastically stable. ■

Proof: Letting $Y_\rho^{-1} = Z_\rho$, $\rho \in \{1, 2\}$, by the Schur complement, Υ in (11) can be written as:

$$\Upsilon = \begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \begin{bmatrix}\eta_1 \\ 0 \\ 0\end{bmatrix}^T \bar{S}_{bn}$$
$$\left[\eta_1 \ 0 \ 0\right] + \begin{bmatrix}0 \\ \eta_2 \\ 0\end{bmatrix}^T \bar{S}_{bn}\left[0 \ \eta_2 \ 0\right]$$
$$+ \begin{bmatrix}0 \\ 0 \\ \eta_3\end{bmatrix}^T \bar{S}_{bn}\left[0 \ 0 \ \eta_3\right]$$
$$= (\mu\nu + \bar{\mu}\nu + \mu\bar{\nu} + \bar{\mu}\bar{\nu})(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix}$$
$$+ \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1 + \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3)$$
$$= \mu\nu(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1$$
$$+ \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3)$$
$$+ \bar{\mu}(\nu(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1$$
$$+ \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3))$$
$$+ \bar{\nu}(\mu(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1$$
$$+ \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3))$$
$$+ \bar{\mu}\bar{\nu}(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1$$
$$+ \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3).$$

Appling Schur complement again, one can obtain:

$$\mu\nu(\begin{bmatrix}\Psi_{11} & * & * \\ \Psi_{21} & \Psi_{22} & * \\ \Psi_{31} & 0 & \Psi_{33}\end{bmatrix} + \bar{\eta}_1^T\bar{S}_{bn}\bar{\eta}_1$$
$$+ \bar{\eta}_2^T\bar{S}_{bn}\bar{\eta}_2 + \bar{\eta}_3^T\bar{S}_{bn}\bar{\eta}_3) < 0 \qquad (24)$$

is equivalent to

$$\begin{bmatrix}\mu\nu\Psi_{11} & * & * & * \\ \mu\nu\Psi_{21} & \mu\nu\Psi_{22} & * & * \\ \mu\nu\Psi_{31} & 0 & \mu\nu\Psi_{33} & * \\ \Psi_{\Omega^a_k\Xi^m_k} & 0 & 0 & \bar{\Lambda}_{\Omega^a_k\Xi^m_k}\end{bmatrix} < 0 \qquad (25)$$

where $\bar{\Lambda}_{\Omega^a_k\Xi^m_k} = \mathrm{Diag}\{-S^{-1}{}_{\Omega_{k_1^a}\Xi_{k_1^m}}, \ldots, -S^{-1}{}_{\Omega_{k_p^a}\Xi_{k_q^m}}\}$.

Letting $S_{bn}^{-1} = M_{bn}$, $b \in \Omega$, $n \in \Xi$, one can obtain (19). Therefore, if (19) holds, then (25) holds. Since $\mu_{ab} \geq 0$, $\nu_{mn} \geq 0$, if (19)-(23) hold, then (11) holds, that is, the closed-loop system (8) is stochastically stable. □

Remark 2: In dealing with the unknown time-delay transition probabilities, another method is to separate the unknown probabilities from the correlation matrices and estimate the unknown probabilities with the known ones by the related lemma [15], for example, $\sum_{b\in\Omega^a_{uk}}\sum_{n\in\Xi^m_k}\mu_{ab}\nu_{mn}S_{bn} \leq (1 - \sum_{\rho\in\Omega^a_k}\mu_{a\rho})\sum_{n\in\Xi^m_k}\nu_{mn}\sum_{b\in\Omega^a_{uk}}\sum_{n\in\Xi^m_k}S_{bn}$. This method will cause certain conservativeness. In this paper, the unknown probabilities are separated from the known ones, and the obtained result is less conservative, as shown in Example 2.

Remark 3: This paper deals with time-delay by constructing a proper Lyapnov-Krasovskii functional. Another method is to convert the time-delay into the parameter matrix of the closed-loop system by the state augmentation technique [13]. However, as the time-delay mode increases, the dimension of the closed-loop system will become high, which increases the controller solution time. The method in this paper reduces the dimension of the matrix for the closed-loop system.

The conditions in Theorem 2 are a set of LMIs with non-convex constraints which can be solved by several existing iterative algorithms. The cone complementarity linearization (CCL) method [22] is used to transform the conditions in Theorem 2 into the following nonlinear minimization problem with LMI constraints.

$$\text{Min tr}\left\{\sum_{b=0}^{\sigma_M}\sum_{n=0}^{\phi_M} S_{bn}M_{bn} + \sum_{\rho=1}^{2} Y_\rho Z_\rho\right\}, \text{ s.t. (19)-(22), (26)}$$

and (27):

$$\begin{bmatrix} S_{bn} & * \\ E & M_{bn} \end{bmatrix} \geq 0, \quad b \in \Omega,\ n \in \Xi \tag{26}$$

$$\begin{bmatrix} Y_\rho & * \\ E & Z_\rho \end{bmatrix} \geq 0, \quad \rho \in \{1, 2\}. \tag{27}$$

The procedure for solving the controller and observer gain matrix is presented in Algorithm 1.

Remark 4: The method proposed in this paper can also be applied to the $\mathcal{H}_\infty$ control and guaranteed performance control where the relationship among the system performance, packet loss probability and the information amount of time-delay transition probability can be further researched.

IV. NUMERICAL EXAMPLE

In this section, two examples are presented to illustrated the effectiveness of the proposed method.

Example 1: Consider the controlled plant with the following parameters [18]:

$$A = \begin{bmatrix} 0.52 & -0.69 \\ 0 & 0.19 \end{bmatrix}, \quad B = \begin{bmatrix} 0.3 \\ 0.2 \end{bmatrix},$$

$$C = \begin{bmatrix} 1.5 & 0.7 \\ 0.2 & 0.4 \end{bmatrix}.$$

Assume S-C time-delay $\sigma_k \in \Omega = \{0, 1\}$, and C-A time-delay $\phi_k \in \Xi = \{0, 1\}$, the transition probability matrices of which are as follows:

$$\Pi = \begin{bmatrix} 0.8 & 0.2 \\ ? & ? \end{bmatrix}, \quad \Theta = \begin{bmatrix} ? & ? \\ 0.7 & 0.3 \end{bmatrix}.$$

The packet loss probability $1-E\{\alpha_k\} = 1-\bar{\alpha} = 1-E\{\beta_k\} = 1 - \bar{\beta} = 0.2$. According to Algorithm 1, a set of feasible solutions for the controller and observer gain matrices are obtained as follows:

$$K = \begin{bmatrix} 0.0927 & -0.0083 \end{bmatrix}, \quad L = \begin{bmatrix} 3.7145 & -0.8976 \\ 5.1640 & -1.8151 \end{bmatrix}.$$

By the method in [15], a set of feasible solutions can also be gotten as follows:

$$K = \begin{bmatrix} 0.0268 & -0.0720 \end{bmatrix}, \quad L = \begin{bmatrix} 4.0541 & -1.4713 \\ 2.1661 & -0.362 \end{bmatrix}.$$

The initial state of the system is $x_0^T = \begin{bmatrix} 1 & -0.5 \end{bmatrix}$. Figure 2 and Figure 3 illustrate the response of system state x_1 and x_2 using the proposed method and the method in [15]. It is observed that the proposed method outperforms the method in [15].

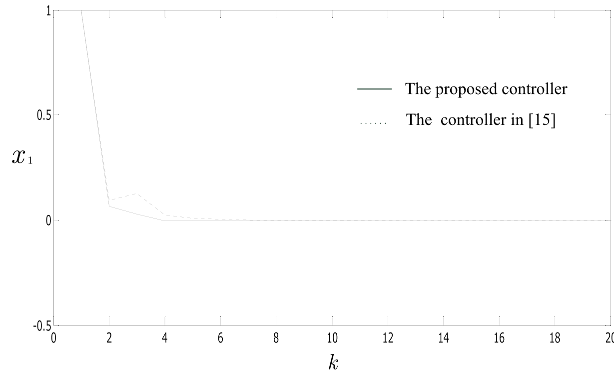

FIGURE 2. System state x_1.

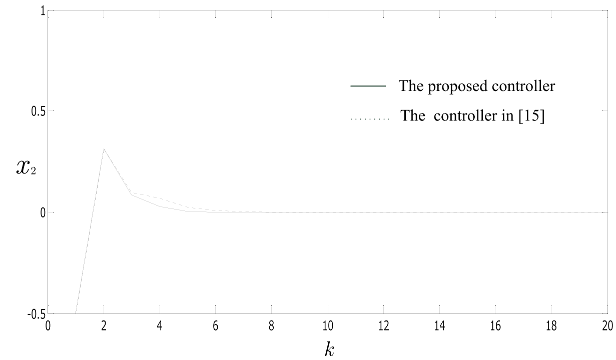

FIGURE 3. System state x_2.

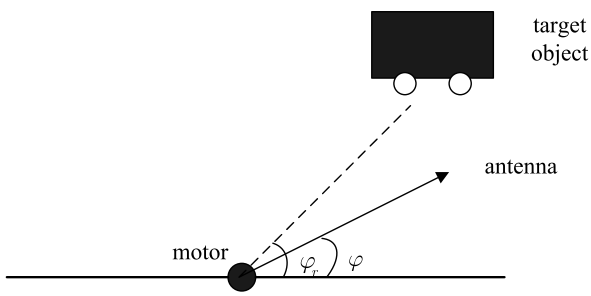

FIGURE 4. Angle position tracking system.

Example 2: Considering the angular position tracking system [23] shown in Figure 4, where φ_r is the angular position of the moving object, and φ is the angular position of the antenna. The function of this system is that the antenna can rotate with the movement of the target object by applying a voltage to the motor and satisfy $\varphi \cong \varphi_r$.

The state space model parameters of the angular position tracking system are as follows:

$$A = \begin{bmatrix} 1 & 0.0995 \\ 0 & 0.99 \end{bmatrix}, \quad B = \begin{bmatrix} 0.0039 \\ 0.0783 \end{bmatrix},$$

$$C = \begin{bmatrix} 1.4 & 0.8 \\ -0.2 & 0.4 \end{bmatrix}.$$

Obviously this system is unstable. Assume S-C time-delay $\sigma_k \in \Omega = \{0, 1\}$, and C-A time-delay $\phi_k \in \Xi = \{0, 1\}$, the transition probability matrix of σ_k and ϕ_k is as follows,

Algorithm 1 Procedure for Solving the Controller and Observer Gain Matrix

1: Set the maximum number of iterations
2: Find a set of feasible solution satisfying (19)-(22), (26) and (27), and let $k = 0$
3: Solve the following optimization problem for variables:
4: $\text{Min tr}\left\{\sum_{b=0}^{\sigma_M}\sum_{n=0}^{\phi_M}(S_{bn}^k M_{bn} + S_{bn}M_{bn}^k) + \sum_{\rho=1}^{2}(Y_\rho^k Z_\rho + Y_\rho Z_\rho^k)\right\}$, s.t. (19)-(22), (26) and (27)
5: Set ($S_{bn}^{k+1} = S_{bn}$, $M_{bn}^{k+1} = S_{bn}$, $Y_1^{k+1} = Y_1$, $Z_1^{k+1} = Z_1$, $Y_2^{k+1} = Y_2$, $Z_2^{k+1} = Z_2$, $K^{k+1} = K$, $L^{k+1} = L$)
6: **while** number of iterations <Maximum number of iterations **do**
7:     **if** (11) is satisfied **then**
8:         break
9:     **else**
10:         $k = k + 1$, go to step 4.
11:     **end if**
12: **end while**

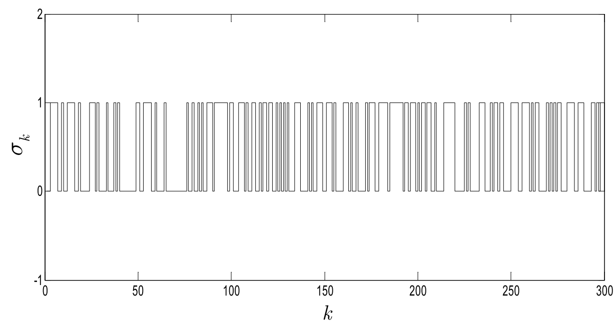

FIGURE 5. The S-C time-delay σ_k.

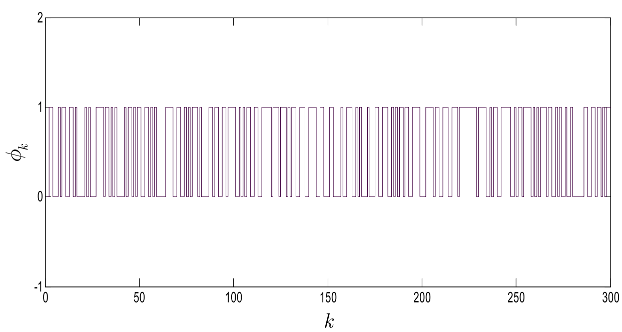

FIGURE 6. The C-A time-delay σ_k.

respectively:

$$\Pi = \begin{bmatrix} 0.7 & 0.3 \\ ? & ? \end{bmatrix}, \quad \Theta = \begin{bmatrix} ? & ? \\ 0.9 & 0.1 \end{bmatrix}$$

The S-C packet loss probability and the C-A packet loss probability $1-E\{\alpha_k\} = 1-\bar{\alpha} = 0.1$ and $1-E\{\beta_k\} = 1-\bar{\beta} = 0.2$, respectively. According to Algorithm 1, the controller and observer gain matrices are obtained as follows:

$$K = \begin{bmatrix} -0.3648 & -0.5975 \end{bmatrix}, \quad L = \begin{bmatrix} -0.0721 & -0.2065 \\ -0.0642 & -0.1445 \end{bmatrix}.$$

Assume that the initial state of the system $x_0 = \begin{bmatrix} 2 & -1 \end{bmatrix}^T$, $\hat{x}_0 = \begin{bmatrix} 1.8 & -1.2 \end{bmatrix}^T$. The time-delay σ_k and ϕ_k is shown in Figure 5 and Figure 6, respectively. The closed-loop system

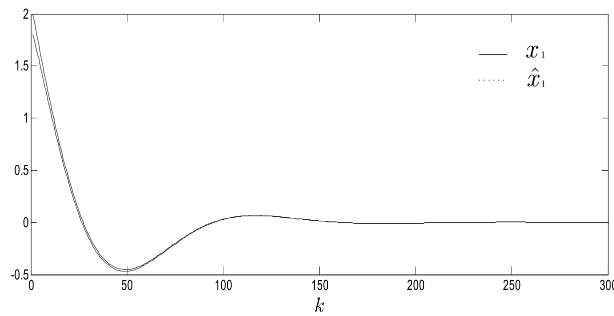

FIGURE 7. System state x_1 and estimated values $\hat{x}_1$.

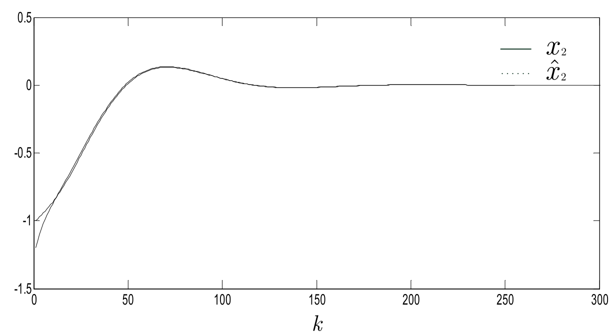

FIGURE 8. System state x_2 and estimated values $\hat{x}_2$.

state response curve under the controller designed in this paper is shown in Figure 7 and Figure 8.

Due to the introduced conservativeness, one cannot use the method in [15] to obtain a set of feasible solutions for K and L. Therefore, the method proposed in this paper is less conservative than the method in [15].

V. CONCLUSION

In this paper, the observer-based stabilization problem is studied for NCS with time-delay and packet loss in both S-C side and C-A side. Under the condition that the S-C and C-A time-delay transition probability are partially unknown, the sufficient conditions for the stability of the closed-loop system are obtained. The method of solving the controller and observer gain matrix of the NCS is also proposed.

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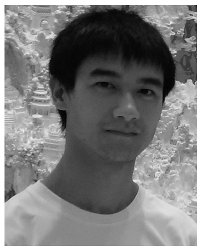

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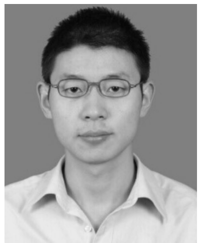

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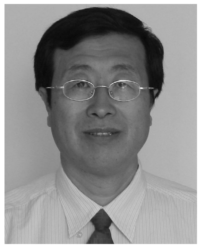

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