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$\mathcal{H}_\infty$ Control of Networked Control System With Data Packet Dropout via Observer-Based Controller

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ABSTRACT The $\mathcal{H}_\infty$ control problem for networked control system with data packet dropout in both S-C link and C-A link via observer-based controller is researched in this paper. Firstly, the networked control system with data packet dropout in both S-C link and C-A link is modeled as a discrete Markov jump linear system. Secondly, the sufficient and necessary conditions on the stochastic stability of the closed-loop system is established, the solution method of the controller and observer gain matrix are also given on condition that the transition probability matrix is completely known and partly unknown, respectively. The minimal disturbance suppression performance index is also obtained. Finally, two simulation examples illustrate the validity of the proposed method.

INDEX TERMS Markov jump system, data packet dropout, observer, stochastic stability, closed-loop system.

I. INTRODUCTION

The data packet dropout and time-delay are known to be two main causes to performance deteriorations or even instability of networked control system (NCS) [1]–[5]. The control problem of NCS with data packet dropout and time-delay has attracted considerable research interests in the past decades [6]–[9]. This paper is concerned with the impact of data packet dropout on the controller design of NCS.

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In the existing literatures, the method of dealing with the data packet dropout phenomenon can be divided into three types. The first type of method is to treat the data packet dropout as an event, and the NCS is modeled as an asynchronous dynamical system (see, e.g., [10]–[12]). The $\mathcal{H}_\infty$ filtering for NCS with time-delay longer than one sampling period and data packet dropout was researched. The sufficient conditions on the exponential stability of the closed-loop system were established by use of the theory of asynchronous dynamical systems [10]. The stability of iterative learning control problem with data packet dropout was researched.

By use of the super vector formulation, an iterative learning control system with data packet dropout was modeled as an asynchronous dynamical system with constraints on event rate in the iteration domain [11]. A controller design method was proposed for a class of NCS with uncertain time-varying delay and data packet dropout. When the data packet dropout occurred, the predicted state was used to replace the current object state. Combined with the state predictor, the NCS with long time-delay and data packet dropout was modeled as an asynchronous dynamic system with event rate constraints [12].

The second type of method is to model the phenomenon of data packet dropout as a binary switching sequence taking values of zero or one which is specified by a Bernoulli probability distribution (see, e.g., [13]–[17]). For a class of NCS with random data packet dropout, a novel robust model predictive control method with active compensation mechanism was proposed. The probability distribution of data packet dropout was described as the Bernoulli distributed white sequences. The sufficient existing conditions on the controller were derived [13]. The problem of fault detection for a kind of fuzzy NCS with quantization and data packet dropout was researched. The probability of data packet dropout was governed by an individual random Bernoulli distribution. The residual system was stochastically stable with a given $\mathcal{H}_\infty$ performance under the designed fault filter [14]. The problem of robust integral sliding mode control for NCS with multiple data packet dropout was researched. The data packet dropout occurred in both the link from sensor to controller (S-C) and the link from controller to actuator (C-A) which was modeled by independent Bernoulli distributed sequences. An integral sliding mode controller was designed such that the reachability of the specified sliding mode domain was achieved [15]. The problem of iterative learning control was investigated for stochastic linear systems with data packet dropout modeled by a Bernoulli random variable. Under stochastic noises and random data packet dropout, the input sequences were proved to converge to the desired input in an almost sure sense [16]. The data packet dropout in S-C link and C-A link was described by two random variables obeying the Bernoulli distribution, respectively. The sufficient conditions on the existence of the controller were established by constructing the appropriate Lyapunov-Krasovskii functional [17].

In real communication network, the data packet dropout at the current time instant is related to the data packet dropout at the previous time instant. However, the first and second methods cannot describe this relationship. The third type of method is to model the data packet dropout as a finite Markov chain which can be used to describe the dependency between the data packet dropout at the current time instant and the data packet dropout at the previous time instant (see, e.g., [18]–[20]). For the NCS with time-delay and the data packet dropout in S-C link, the closed-loop system was modeled as a Markov jump linear system (MJLS) with two running modes. The design method of the state feedback controller was also obtained without the consideration of time-delay and the data packet dropout in C-A link [18]. The data packet dropout was model as a finite state Markov chain. Lyapunov-Krasovskii based approaches were applied to establish sufficient conditions on stochastic stability of closed-loop sampled-data bilateral teleportation system [19]. The robust model predictive tracking control problem for NCS with Markov data packet dropout was researched. By introducing a data packet dropout compensation strategy, the effects of data packet dropout on the system performance was considered [20].

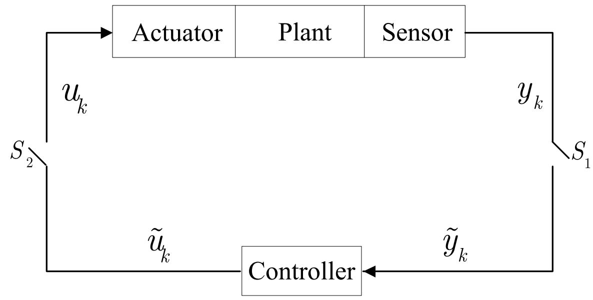

FIGURE 1. Structure of NCS with random data packet dropout.

Most existing literatures only considered Markov data packet dropout in S-C Link or C-A link. The $\mathcal{H}_\infty$ control problem for NCS in the presence of data packet dropout in both S-C link and C-A link via observer-based controller needs to be further researched which motivates the current investigation. The main contributions of this paper can be presented as follows:

1) An observer is constructed for NCS with data packet dropout in S-C link and C-A link. Through the analysis of the system's operating mode changing with the data packet dropout, the closed-loop system model is obtained.
2) The sufficient and necessary conditions on the stochastic stability for the closed-loop systems are established and the controller design method is derived on condition that the transition probability matrix is completely known and partly unknown, respectively.

The rest content of the paper is organized as follows. In Section II, the closed-loop system model is obtained through the analysis of the system's operating mode change with the data packet dropout. In section III, stability analysis and controller design methods are given. In Section IV, two simulation examples are given to illustrate the effectiveness of the proposed controller. The conclusions are addressed in Section V.

II. PROBLEM FORMULATION

The structure of the NCS with random data packet dropout considered in this paper is shown in Figure 1, where the controlled plant is a linear system and the state equation of which is as follows:

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

where x_k is the system state, u_k is the control input, ω_k is the external disturbance, y_k is the output; A, B, B_ω, C, D_ω are known real constant matrices with appropriate dimensions.

The stochastic variable $\alpha_k(\beta_k)$ takes value from $\{0, 1\}$. When $\alpha_k(\beta_k) = 1$, it means that the switch $S_1(S_2)$ closes, and the data packet is transmitted successfully. When $\alpha_k(\beta_k) = 0$, it means that the switch $S_1(S_2)$ opens, and a data packet dropout occurs.

Construct the following observer at the controller side

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

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

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

Due to the data packet dropout in S-C link, the system output obtained at the controller node at time instant k is as follows:

$$\tilde{y}_k = \alpha_k y_k \tag{4}$$

Because of the data packet dropout in C-A link, the control input acting on the controlled plant at time instant k is as follows:

$$u_k = \beta_k\tilde{u}_k \tag{5}$$

Define the following state estimation error and augmentation vector:

$$e_k = x_k - \hat{x}_k, \quad \zeta_k = \begin{bmatrix} x_k^T & e_k^T \end{bmatrix}^T \tag{6}$$

The state equation of the closed-loop system can be obtained from equations (1)-(6):

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{\alpha_k,\beta_k}\zeta_k + \tilde{B}_{\alpha_k,\beta_k}\omega_k \\ y_k = \tilde{C}_{\alpha_k,\beta_k}\zeta_k + D_\omega\omega_k \end{cases} \tag{7}$$

where

$$\tilde{A}_{\alpha_k,\beta_k} = \begin{bmatrix} A + \beta_k BK & -\beta_k BK \\ (1-\beta_k)BK & A + (1-\beta_k)BK - \alpha_k LC \end{bmatrix},$$

$$\tilde{B}_{\alpha_k,\beta_k} = \begin{bmatrix} B_\omega \\ B_\omega - \alpha_k LD_\omega \end{bmatrix}, \quad \tilde{C}_{\alpha_k,\beta_k} = \begin{bmatrix} I & 0 \end{bmatrix}.$$

The closed-loop system (7) consists of the following 4 subsystems:

1) When $\alpha_k = \beta_k = 0$, that is data packet dropout occur in both S-C link and C-A link, the model of system (7) is expressed as

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{0,0}\zeta_k + \tilde{B}_{0,0}\omega_k \\ y_k = \tilde{C}_{0,0}\zeta_k + D_\omega\omega_k \end{cases} \tag{8}$$

where

$$\tilde{A}_{0,0} = \bar{A} + M_1KN_1, \quad \bar{A} = \begin{bmatrix} A & 0 \\ 0 & A \end{bmatrix}, \ M_1 = \begin{bmatrix} 0 \\ B \end{bmatrix},$$

$$N_1 = \begin{bmatrix} -I & I \end{bmatrix}, \quad \tilde{B}_{0,0}^T = \begin{bmatrix} B_\omega^T & B_\omega^T \end{bmatrix},$$

$$\tilde{C}_{0,0} = \begin{bmatrix} I & 0 \end{bmatrix}.$$

2) When $\alpha_k = 0$, $\beta_k = 1$, that is data packet dropout occur in S-C link, the model of system (7) is described as

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{0,1}\zeta_k + \tilde{B}_{0,1}\omega_k \\ y_k = \tilde{C}_{0,1}\zeta_k + D_\omega\omega_k \end{cases} \tag{9}$$

where

$$\tilde{A}_{0,1} = \bar{A} + M_2KN_2, \quad M_2 = \begin{bmatrix} B \\ 0 \end{bmatrix}, \ N_2 = \begin{bmatrix} I & -I \end{bmatrix},$$

$$B_{0,1}^T = \begin{bmatrix} B_\omega^T & B_\omega^T \end{bmatrix}, \quad \tilde{C}_{0,1} = \begin{bmatrix} I & 0 \end{bmatrix}.$$

3) When $\alpha_k = 1$, $\beta_k = 0$, that is data packet dropout occur in C-A link, the model of system (7) is written as

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{1,0}\zeta_k + \tilde{B}_{1,0}\omega_k \\ y_k = \tilde{C}_{1,0}\zeta_k + D_\omega\omega_k \end{cases} \tag{10}$$

where

$$\tilde{A}_{1,0} = \bar{A} + M_3KN_3 + E_3LF_3, \quad M_3 = \begin{bmatrix} 0 \\ B \end{bmatrix},$$

$$N_3 = \begin{bmatrix} -I & I \end{bmatrix}, \quad E_3 = \begin{bmatrix} 0 \\ I \end{bmatrix},$$

$$F_3 = \begin{bmatrix} 0 & -C \end{bmatrix},$$

$$\tilde{B}_{1,0} = \tilde{B}_{0,0} - E_3LD_\omega, \quad \tilde{C}_{1,0} = \begin{bmatrix} I & 0 \end{bmatrix}.$$

4) When $\alpha_k = 1$, $\beta_k = 1$, that is data packet dropout occur neither in S-C link nor in C-A link, the model of system (7) is as follows

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{1,1}\zeta_k + \tilde{B}_{1,1}\omega_k \\ y_k = \tilde{C}_{1,1}\zeta_k + D_\omega\omega_k \end{cases} \tag{11}$$

where

$$\tilde{A}_{1,1} = \bar{A} + M_4KN_4 + E_4LF_4, \quad M_4 = \begin{bmatrix} B \\ 0 \end{bmatrix},$$

$$N_4 = \begin{bmatrix} -I & I \end{bmatrix}, \quad E_4 = \begin{bmatrix} 0 \\ I \end{bmatrix}, \ F_4 = \begin{bmatrix} 0 & -C \end{bmatrix},$$

$$\tilde{B}_{1,1} = \tilde{B}_{0,0} - E_4LD_\omega, \quad \tilde{C}_{1,1} = \begin{bmatrix} I & 0 \end{bmatrix}.$$

As data packet dropout occurs, the closed-loop system (7) jumps among the 4 subsystems (8)-(11). Because the data packet dropout at the current time instant is related to the data packet dropout at the previous time instant, it is reasonable to model the closed-loop system (7) as a MJLS consisting 4 subsystems:

$$\begin{cases} \zeta_{k+1} = \tilde{A}_{r_k}\zeta_k + \tilde{B}_{r_k}\omega_k \\ y_k = \tilde{C}_{r_k}\zeta_k + D_\omega\omega_k \end{cases} \tag{12}$$

where $\{r_k, k \in Z\}$ is a discrete Markov chain which takes values in the set $\mathcal{M} = \{1, 2, 3, 4\}$, and $\tilde{A}_1 \triangleq \tilde{A}_{0,0}$, $\tilde{A}_2 \triangleq \tilde{A}_{0,1}$, $\tilde{A}_3 \triangleq \tilde{A}_{1,0}$, $\tilde{A}_4 \triangleq \tilde{A}_{1,1}$, $\tilde{B}_1 \triangleq \tilde{B}_{0,0}$, $\tilde{B}_2 \triangleq \tilde{B}_{0,1}$, $\tilde{B}_3 \triangleq \tilde{B}_{1,0}$, $\tilde{B}_4 \triangleq \tilde{B}_{1,1}$, $\tilde{C}_1 \triangleq \tilde{C}_{0,0}$, $\tilde{C}_2 \triangleq \tilde{C}_{0,1}$, $\tilde{C}_3 \triangleq \tilde{C}_{1,0}$, $\tilde{C}_4 \triangleq \tilde{C}_{1,1}$. The transition probability matrix of r_k is $\Pi = [\pi_{pq}]$, where π_{pq} is defined as $\pi_{pq} = \Pr\{r_{k+1} = q | r_k = p\}$, $\pi_{pq} \geq 0$, $\sum_{q=1}^{4} \pi_{pq} = 1, p, q \in \mathcal{M}$.

It is necessary to introduce the notion of stochastic stability for the closed-loop system (12) before the main results are presented.

Definition 1 [21]: When $\omega_k = 0$, the closed-loop system (12) is said to be stochastically stable if for arbitrary initial mode $r_0 \in \mathcal{M}$ and initial state ζ_0, there exists a positive-definite matrix $W > 0$ such that $E\left\{\sum_{k=0}^{\infty} \| \zeta_k \|^2 | r_0, \zeta_0\right\} < \zeta_0^T W \zeta_0$ holds.

Remark 1: Different from the traditional point to point control system, the control input of the observer $\tilde{u}_k$ in (2) is different from the control input of the controlled plant u_k in (1), which brings difficulties in the controller design.

The objective of this paper is to design the observer (2) and the observer-based controller (3) for the controlled plant (1), such that, the closed-loop system (12) is stochastically stable in the presence of the random data packet dropout in both S-C link and C-A link and a certain $\mathcal{H}_\infty$ performance is also achieved. Specifically, the closed-loop system (12) satisfies the following two requirements under the observer-based controller (3):

1) The closed-loop system (12) is stochastically stable.
2) Under the zero-initial condition, for all $\omega_k \neq 0$, the output y_k satisfies:

$$E\left\{\sum_{k=0}^{\infty} \| y_k \|^2\right\} < \gamma^2 E\left\{\sum_{k=0}^{\infty} \| \omega_k \|^2\right\} \tag{13}$$

where γ is the disturbance suppression performance index.

III. MAIN RESULTS

In this section, the sufficient and necessary conditions on the stochastic stability for the closed-loop systems (12) will be established and the controller design method will be derived on condition that the transition probability matrix Π is completely known and partly unknown, respectively.

Theorem 1: The closed-loop system (12) is stochastically stable, if and only if there exist positive-definite matrices $P_p > 0$, $P_q > 0$ and matrices K, L such that the following matrix inequality holds for all $p, q \in \mathcal{M}$. ■

$$\Theta = \tilde{A}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{A}_p - P_p < 0 \tag{14}$$

Proof: Sufficiency: Define a Lyapunov function $V_k = \zeta_k^T P_{r_k} \zeta_k$, where $P_{r_k} > 0$.
From (12) with $\omega_k = 0$, one has:

$$\begin{aligned} E\{\Delta V_k\} &= E\left\{\zeta_k^T P_{r_k} \zeta_k | r_k = p\right\} - \zeta_k^T P_{r_k} \zeta_k \\ &= \zeta_k^T (\tilde{A}_{r_k}^T \sum_{q\in\mathcal{M}} \pi_{pq} P_{r_{k+1}} \tilde{A}_{r_k} - P_{r_k}) \zeta_k. \end{aligned}$$

Hence, if (14) holds, one has

$$\begin{aligned} E\{\Delta V_k\} &\leq -\lambda_{\min}(-\Theta) \zeta_k^T \zeta_k \\ &= -\lambda_{\min}(-\Theta) \| \zeta_k \|^2. \end{aligned}$$

For any positive integer $N \geq 0$, the following holds:

$$\begin{aligned} E\left\{\sum_{k=0}^{N} \| \zeta_k \|^2\right\} &\leq \frac{1}{\lambda_{\min}(-\Theta)} (E\{V_0\} - E\{V_{N+1}\}) \\ &\leq \frac{1}{\lambda_{\min}(-\Theta)} E\{V_0\} \\ &= \frac{1}{\lambda_{\min}(-\Theta)} \zeta_k^T P_{r_0} \zeta_k. \end{aligned}$$

By Definition 1, the closed-loop systems (12) is stochastically stable.

Necessity: Assuming that the closed-loop system (12) is stochastically stable, one has

$$E\left\{\sum_{k=0}^{\infty} \| \zeta_k \|^2 | r_0, \zeta_0\right\} < \zeta_0^T W \zeta_0. \tag{15}$$

Consider the following function for $\zeta_k \neq 0$:

$$\zeta_k^T \tilde{P}_{r_k} \zeta_k \triangleq E\left\{\sum_{t=k}^{T} \zeta_t^T Z_{r_t} \zeta_k | r_k, \zeta_k\right\}, \tag{16}$$

where $Z_{r_t} > 0$. From (15), it can be inferred that $\zeta_k^T \tilde{P}_{r_k} \zeta_k$ is bounded, and one has:

$$\begin{aligned} \zeta_k^T P_{r_k} \zeta_k &\triangleq \lim_{T\to\infty} \zeta_k^T \tilde{P}_{r_k} \zeta_k \\ &= \lim_{T\to\infty} E\left\{\sum_{t=k}^{T} \zeta_t^T Z_{r_t} \zeta_k | r_k, \zeta_k\right\} \end{aligned}$$

Since (17) holds for any ζ_k, one has $P_{r_k} \triangleq \lim_{T\to\infty} \tilde{P}_{r_k}$. Because $Z_{r_t} > 0$, it can be obtained that $P_{r_k} > 0$ from (17). Moreover, one has:

$$\begin{aligned} & E\left\{\zeta_k^T \tilde{P}_{r_k} \zeta_k - \zeta_{k+1}^T \tilde{P}_{r_{k+1}} \zeta_{k+1} | r_k, \zeta_k\right\} \\ &\quad = \zeta_k^T (\tilde{P}_p - \tilde{A}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} \tilde{P}_q \tilde{A}_p) \zeta_k \\ &\quad = \zeta_k^T Z_p \zeta_k \\ &\quad > 0. \end{aligned}$$

Letting $T \to \infty$, one has $\Theta < 0$, and this completes the proof. □

Sufficient and necessary conditions on the existence of the observer-based controller are given in Theorem 1. Sufficient conditions such that not only the closed-loop system (12) is stochastically stable but also a certain $\mathcal{H}_\infty$ performance is also achieved are exhibited in Theorem 2.

Theorem 2: If there exist positive-definite matrices $P_p > 0$, $Y_p > 0$ and matrices K, L such that

$$\begin{bmatrix} -Y_p & * & * & * \\ 0 & -\gamma^2 I & * & * \\ C_p & D_\omega & -I & * \\ \tilde{A}_p & \tilde{B}_p & 0 & -\tilde{P}_q \end{bmatrix} < 0 \tag{17}$$

$$Y_p P_p = I \tag{18}$$

where

$$\tilde{A}_p^T = \left[\ \sqrt{\pi_{p1}}A_p, \quad \cdots, \quad \sqrt{\pi_{p4}}A_p\ \right],$$
$$\tilde{A}_p^T = \left[\ \sqrt{\pi_{p1}}B_p, \quad \cdots, \quad \sqrt{\pi_{p4}}B_p\ \right],$$
$$\tilde{P}_q = \mathrm{Diag}\left\{ P_1, \quad \cdots, \quad P_4 \right\},$$

hold for all $p, q \in \mathcal{M}$, the closed-loop system (12) is stochastically stable and $\mathcal{H}_\infty$ performance (13) is also achieved. ■

Proof: For any $\omega_k \neq 0$, it follows from (12) that

$$\begin{aligned}
E\{\Delta V_k\} &+ y_k^T y_k - \gamma^2 \omega_k \\
&= x_k^T(\tilde{A}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{A}_p + \tilde{C}_p^T \tilde{C}_p - P_p) x_k \\
&\quad + x_k^T(\tilde{A}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{B}_p + \tilde{C}_p^T D_\omega)\omega_k \\
&\quad + \omega_k^T(\tilde{B}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{A}_p + D_\omega^T \tilde{C}_p) x_k \\
&\quad + \omega_k^T(\tilde{B}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} \tilde{B}_p + D_\omega^T D_\omega - \gamma^2 I)\omega_k \\
&= \zeta_k^T \Omega_p \zeta_k
\end{aligned} \tag{19}$$

where

$$\Omega_p = \begin{bmatrix} \Omega_{11} & * \\ \Omega_{21} & \Omega_{22} \end{bmatrix},$$
$$\Omega_{11} = \tilde{A}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{A}_p + \tilde{C}_p^T \tilde{C}_p - P_p,$$
$$\Omega_{21} = \tilde{B}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} P_q \tilde{A}_p + D_\omega^T \tilde{C}_p,$$
$$\Omega_{22} = \tilde{B}_p^T \sum_{q\in\mathcal{M}} \pi_{pq} \tilde{B}_p + D_\omega^T D_\omega - \gamma^2 I.$$

Letting $Y_p = P_p^{-1}, p \in \mathcal{M}$, and by applying the Schur complement, $\Omega_{r_k} < 0$ is equivalent to (17). Hence, it can be concluded from (17) and (19) that

$$E\{\Delta V_k\} + y_k^T y_k - \gamma^2 \omega_k < 0. \tag{20}$$

Summing up (20) form 0 to ∞ with respect to k yields

$$E\left\{\sum_{k=0}^{\infty} \| y_k \|^2\right\} < \gamma^2 E\left\{\sum_{k=0}^{\infty} \| \omega_k \|^2\right\} - E\{V_0\} - E\{V_\infty\}.$$

Since the closed-loop system (12) is stochastically stable with the zero-initial condition, (13) can be readily obtained, which completes the proof. □

The conditions presented in Theorem 2 are a set of LMIs with some matrices inverse constraints which can be solved by the cone complementary linearization (CCL) algorithm. The problem of solving the controller gain matrix K and the observer gain matrix L can be transformed into the following nonlinear minimization problem:

$$\mathrm{Min\ tr}\Big(\sum_{p=1}^{4} P_p Y_p\Big) \quad \text{s.t. (17) and (21).}$$

$$\begin{bmatrix} P_p & I \\ I & Y_p \end{bmatrix} > 0, \quad p \in \mathcal{M}. \tag{21}$$

The procedure for solving K, the observer gain matrix L and the minimal disturbance suppression performance index $\gamma_{\min}$ is given in Algorithm 1 where τ is a proper positive scalar.

The controller and observer gain matrix K and L are derived in Theorem 2 on condition that all probabilities in Π are all available. However, it is usually difficult to obtain the all transition probabilities. It is necessary to design the controller without the information of all transition probabilities. Thus, the transition probabilities of the jumping process of r_k are considered to be partly unavailable in Theorem 3, i.e., some elements in matrix Π are unknown. For example, the transition probabilities matrix Π may be as follows

$$\Pi = \begin{bmatrix} ? & \pi_{12} & \pi_{13} & ? \\ \pi_{21} & \pi_{22} & ? & ? \\ ? & ? & ? & \pi_{34} \\ \pi_{41} & \pi_{42} & \pi_{43} & \pi_{44} \end{bmatrix}$$

where "?" represents the unknown elements. For notational clarity, the set $\mathcal{M}$ can be denoted as $\mathcal{M} = \mathcal{M}_k^p + \mathcal{M}_{uk}^p$ with $\mathcal{M}_k^p = \{q : \pi_{pq} \text{ is known}\}$, $\mathcal{M}_{uk}^p = \{q : \pi_{pq} \text{ is unknown}\}$. Moreover, if $\mathcal{M}_k^p \neq \emptyset$, it can be further described as $\mathcal{M}_k^p = \{k_1^p, k_2^p \cdots k_d^p\}$, $1 \leq d \leq 4$, where k_d^p represents the column subscript of the d th known element in the p th row of the matrix Π. $\mathcal{M}_{uk}^p$ is described as $\mathcal{M}_{uk}^p = \{\bar{k}_1^p, \bar{k}_2^p \cdots \bar{k}_{4-d}^p\}$, where $\bar{k}_{4-d}^p$ represents column subscript of the $(4-d)$ th unknown element in the p th row of the matrix Π.

Theorem 3: The closed-loop system (12) is stochastically stable and $\mathcal{H}_\infty$ performance (13) is also achieved, if there exist positive-definite matrices $P_p > 0$, $Y_p > 0$ and matrices K, L such that

$$\begin{bmatrix} -\tilde{\pi} Y_p & * & * & * \\ 0 & -\tilde{\pi}\gamma^2 I & * & * \\ \tilde{\pi} C_p & \tilde{\pi} D_\omega & -\tilde{\pi} I & * \\ \widehat{A}_p & \widehat{B}_p & 0 & -\widehat{P}_q \end{bmatrix} < 0 \tag{22}$$

$$\begin{bmatrix} -Y_p & * & * & * \\ 0 & -\gamma^2 I & * & * \\ C_p & D_\omega & -I & * \\ A_p & B_p & 0 & -P_q \end{bmatrix} < 0, \quad q \in \mathcal{M}_{uk}^p \tag{23}$$

$$Y_p P_p = I \tag{24}$$

where

$$\widehat{A}_p^T = \left[\ \sqrt{\pi_{p1}}A_p, \quad \cdots, \quad \sqrt{\pi_{pd}}A_p\ \right],$$
$$\widehat{B}_p^T = \left[\ \sqrt{\pi_{p1}}B_p, \quad \cdots, \quad \sqrt{\pi_{pd}}B_p\ \right],$$
$$\widehat{P}_q = \mathrm{Diag}\left\{ P_1, \quad \cdots, \quad P_d \right\},$$
$$\tilde{\pi} = \sum_{q\in\mathcal{M}_k^p} \pi_{pq},$$

hold for all $p, q \in \mathcal{M}$. ■

Algorithm 1 Procedure for Solving K, L and $\gamma_{\min}$

1: Set the maximal number of iterations $R_{\max}$ and the disturbance suppression performance index $\gamma = \gamma_0$
2: Find a set of feasible solution (P_p^0, Y_p^0, K^0, L^0) satisfying (17) and (21), and let $k = 0$
3: Solve the following optimization problem for variables:
$$\text{Min tr}\left(\sum_{p=1}^{4}(P_p^k Y_p + Y_p^k P_p)\right) \text{ s.t. (17) and (21)}$$
4: Set $P_p^k = P_p$, $Y_p^k = Y_p$, $K^k = K$, $L^k = L$
5: **while** number of iterations $< R_{\max}$ **do**
6:   **if** (17), (18) is satisfied **then**
7:     $\gamma = \gamma - \tau$, $k = k + 1$, go to step 3
8:   **else**
9:     $k = k + 1$, go to step 3
10:   **end if**
11: **end while**
12: **if** $\gamma < \gamma_0$ **then**
13:   $\gamma_{\min} = \gamma + \tau$
14: **else**
15:   this optimization problem has no solution within the given number of iterations$R_{\max}$
16: **end if**

Proof: It is noticed that $\sum_{q\in\mathcal{M}} \pi_{pq} = 1$, by the Schur complement, $\Omega_{r_k} < 0$ is equivalent to

$$\begin{aligned}
&\begin{bmatrix} -Y_p & * & * \\ 0 & -\gamma^2 I & * \\ C_p & D_\omega & -I \end{bmatrix} + \begin{bmatrix} A_p & B_p & 0 \end{bmatrix}^T \\
&\quad \times \sum_{q\in\mathcal{M}} \pi_{pq} P_{r_{k+1}} \begin{bmatrix} A_p & B_p & 0 \end{bmatrix} \\
&= \sum_{q\in\mathcal{M}_k^p} \pi_{pq} \begin{bmatrix} -Y_p & * & * \\ 0 & -\gamma^2 I & * \\ C_p & D_\omega & -I \end{bmatrix} + \begin{bmatrix} A_p & B_p & 0 \end{bmatrix}^T \\
&\quad \times \sum_{q\in\mathcal{M}_k^p} \pi_{pq} P_{r_{k+1}} \begin{bmatrix} A_p & B_p & 0 \end{bmatrix} \\
&\quad + \sum_{q\in\mathcal{M}_{uk}^p} \pi_{pq} \begin{bmatrix} -Y_p & * & * \\ 0 & -\gamma^2 I & * \\ C_p & D_\omega & -I \end{bmatrix} + \begin{bmatrix} A_p & B_p & 0 \end{bmatrix}^T \\
&\quad \times \sum_{q\in\mathcal{M}_{uk}^p} \pi_{pq} P_{r_{k+1}} \begin{bmatrix} A_p & B_p & 0 \end{bmatrix} \\
&= \begin{bmatrix} -\tilde{\pi} Y_p & * & * \\ 0 & -\tilde{\pi}\gamma^2 I & * \\ \tilde{\pi} C_p & \tilde{\pi} D_\omega & -\tilde{\pi} I \end{bmatrix} + \begin{bmatrix} A_p & B_p & 0 \end{bmatrix}^T \\
&\quad \times \sum_{q\in\mathcal{M}_k^p} \pi_{pq} P_{r_{k+1}} \begin{bmatrix} A_p & B_p & 0 \end{bmatrix} \\
&\quad + \sum_{q\in\mathcal{M}_{uk}^p} \pi_{pq} \Bigg(\begin{bmatrix} -Y_p & * & * \\ 0 & -\gamma^2 I & * \\ C_p & D_\omega & -I \end{bmatrix} + \begin{bmatrix} A_p & B_p & 0 \end{bmatrix}^T \\
&\quad \times P_{r_{k+1}} \begin{bmatrix} A_p & B_p & 0 \end{bmatrix} \Bigg) \\
&< 0.
\end{aligned}$$

Appling Schur complement again, it can be concluded that $\Omega_{r_k} < 0$ if (22)-(24) holds. This ends the proof. □

Remark 2: Similar to Algorithm 1, (22)-(24) in Theorem 3 can also be solved by the CCL algorithm. The detail algorithm is thus omitted.

Remark 3: Regarding the unknown probabilities, the method adopted in this paper is to separate the known probabilities from the unknown ones, and then discard the unknown ones. Another method is to separate the probabilities from the correlation matrices ([21], [22]), for example, $\sum_{q\in\mathcal{M}} \pi_{pq} P_q \leq \sum_{q\in\mathcal{M}} \pi_{pq} \sum_{q\in\mathcal{M}} P_q$ which greatly increases the conservativeness of the results.

Remark 4: For the method of separating the known probabilities from the unknown ones, as the number of unknown probabilities increases, the number of matrix inequalities to be satisfied will increase. In Theorem 3, if all transition probabilities are known, the number of matrix inequalities to be satisfied is four; When all transition probabilities are unknown, the number of matrix inequalities to be satisfied is sixteen.

IV. NUMERICAL EXAMPLES

In this section, two examples are provided to demonstrate the effectiveness of the proposed method.

Example 1: Consider the angular positioning system in Figure 2, which consists of a rotating antenna at the origin of the plane driven by a motor, where φ is the angular position of the antenna, and φ_r is the angular position of the moving object [23]. The function of the system is to rotate the antenna to point the direction of the moving object by adjusting the input voltage of the motor.

The state variables of the system are chosen as $[\varphi \quad \dot{\varphi}]^T$, then the parameter of the angular positioning system are as

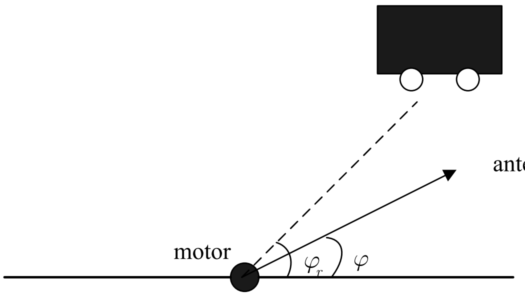

FIGURE 2. The angular positioning system.

follows:

$$A = \begin{bmatrix} 1 & 0.0995 \\ 0 & 0.99 \end{bmatrix}, \quad B = \begin{bmatrix} 0.0039 \\ 0.0783 \end{bmatrix}, B_\omega = \begin{bmatrix} 0.005 \\ 0.003 \end{bmatrix},$$
$$C = \begin{bmatrix} 1.4 & 0.8 \\ -0.2 & 0.4 \end{bmatrix}, \quad D_\omega = \begin{bmatrix} 0.007 \\ 0.009 \end{bmatrix}.$$

The relevant parameters of the resulting closed-loop system (12) can be calculated as follows:

$$\begin{aligned} M_1^T &= M_3^T = \begin{bmatrix} 0 & 0 & 0.0039 & 0.0783 \end{bmatrix}, \\ M_2^T &= M_4^T = \begin{bmatrix} 0.0039 & 0.0783 & 0 & 0 \end{bmatrix}, \\ N_1 &= N_3 = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}, \\ N_2 &= N_4 = \begin{bmatrix} -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}, \\ E_3^T &= E_4^T = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \\ F_3^T &= F_4^T = \begin{bmatrix} 0 & 0 & -1.5 & 0.7 \\ 0 & 0 & -0.2 & 0.4 \end{bmatrix}. \end{aligned}$$

The close-loop system mode $r_k \in \{1, 2, 3, 4\}$, the transition probability matrix of which is as follows:

$$\Pi = \begin{bmatrix} 0.3 & 0.4 & 0.1 & 0.2 \\ 0.1 & 0.5 & 0.3 & 0.1 \\ 0.5 & 0.1 & 0.2 & 0.2 \\ 0.4 & 0.3 & 0.2 & 0.1 \end{bmatrix}.$$

By use of Theorem 2, the controller gain matrix K, the observer L and the minimal disturbance suppression performance index $\gamma_{\min}$ are obtained as follows:

$$K = \begin{bmatrix} -4.0078 & -5.2012 \end{bmatrix},$$
$$L = \begin{bmatrix} 0.5670 & 0.4922 \\ 0.4005 & 1.6271 \end{bmatrix}, \quad \gamma_{\min} = 0.1703.$$

The initial states are assumed to be $x_0^T = \begin{bmatrix} 2 & -1 \end{bmatrix}$, $\hat{x}_0^T = \begin{bmatrix} 2.1 & -1.1 \end{bmatrix}$ and the disturbance input is $\omega_k = 1/k$. Figure 3 - Figure 5 show the system mode and the states curve of the closed-loop system.

Example 2: Consider the controlled the plant of which the parameters are given as follows:

$$A = \begin{bmatrix} 0.52 & -0.69 \\ 0 & 0.19 \end{bmatrix}, \quad B_u = \begin{bmatrix} 0.3 \\ 0.2 \end{bmatrix}, B_\omega = \begin{bmatrix} 0.01 \\ 0.23 \end{bmatrix},$$

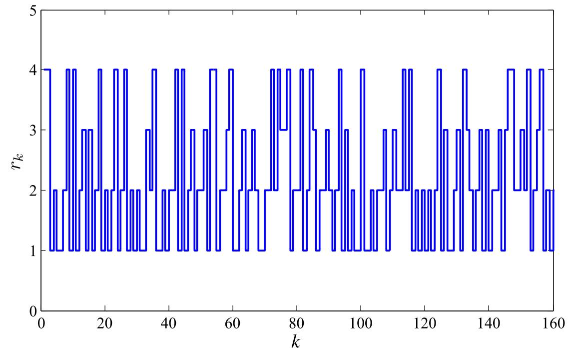

FIGURE 3. The mode of the angular positioning system σ_k.

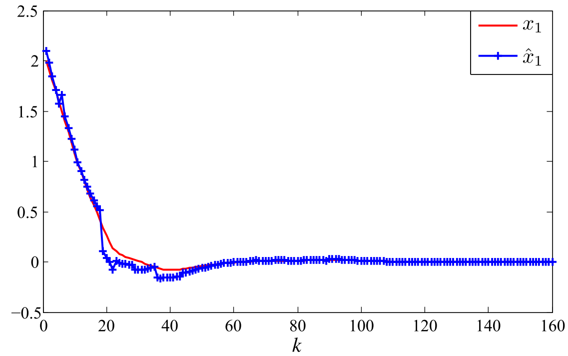

FIGURE 4. x_1 and its estimated value $\hat{x}_1$ of the angular positioning system.

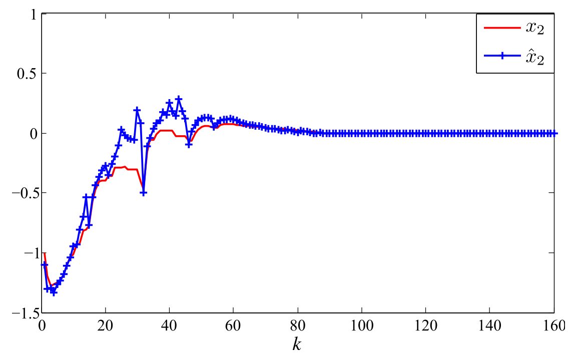

FIGURE 5. x_2 and its estimated value $\hat{x}_2$ of the angular positioning system.

$$C = \begin{bmatrix} 1.5 & 0.7 \\ 0.2 & 0.4 \end{bmatrix}, \quad D_\omega = \begin{bmatrix} 0.03 \\ 0.05 \end{bmatrix}.$$

The transition probability matrix of close-loop system mode r_k is as follows:

$$\Lambda = \begin{bmatrix} 0.3 & ? & ? & 0.2 \\ 0.1 & ? & 0.5 & ? \\ 0.5 & 0.1 & ? & ? \\ 0.4 & 0.3 & 0.2 & 0.1 \end{bmatrix}.$$

By use of Theorem 3, the controller gain matrix K, the observer L and the minimal disturbance suppression performance index $\gamma_{\min}$ are obtained as follows:

$$K = \begin{bmatrix} -0.1866 & -0.5995 \end{bmatrix},$$
$$L = \begin{bmatrix} 0.694 & -2.6930 \\ -0.0559 & 0.2138 \end{bmatrix}, \quad \gamma_{\min} = 0.0837.$$

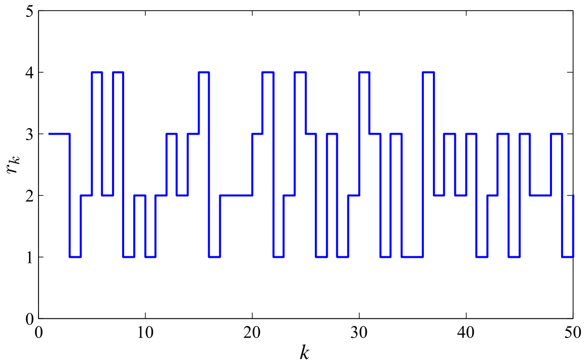

FIGURE 6. The system mode σ_k.

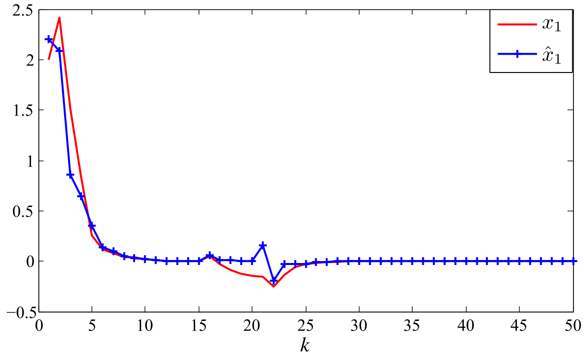

FIGURE 7. The state x_1 and its estimated value $\hat{x}_1$.

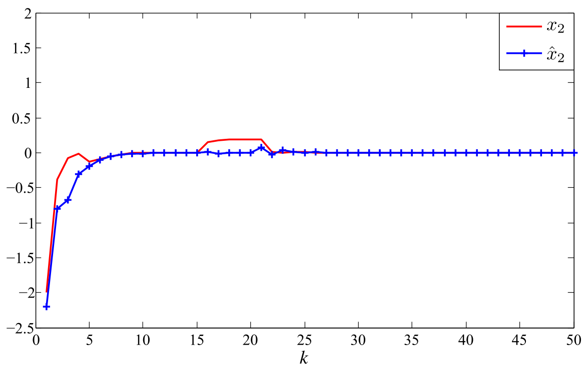

FIGURE 8. The state x_2 and its estimated value $\hat{x}_2$.

The initial values of the system are assumed to be $x_0^T = \begin{bmatrix} 2 & -2 \end{bmatrix}$, $\hat{x}_0^T = \begin{bmatrix} 2.2 & -2.2 \end{bmatrix}$ and the disturbance input is

$$\omega_k = \begin{cases} 1, & k \in \begin{bmatrix} 15 & 20 \end{bmatrix} \\ 0, & \text{otherwise} \end{cases}$$

Figure 6 - Figure 8 show the system mode and the states curve of the closed-loop system.

By the method in [21] and [22], the controller gain matrix K, the observer L and the minimal disturbance suppression performance index $\gamma_{\min}$ are obtained as follows:

$$K = \begin{bmatrix} -1.3822 & 1.3110 \end{bmatrix},$$
$$L = \begin{bmatrix} 0.1759 & -0.9068 \\ -0.0152 & 0.8021 \end{bmatrix},$$

$\gamma_{\min} = 0.0775.$

Obviously, the minimal disturbance suppression performance index $\gamma_{\min}$ obtained by the proposed method is smaller than that in [21] and [22].

V. CONCLUSION

An observer-based $\mathcal{H}_\infty$ control problem for networked control system with random data packet dropout has been investigated. Both the data packet dropout in S-C link and the data packet dropout in C-A link are taken into consideration. The sufficient conditions on the existence of the observer-based controller have been derived such that the closed-loop system is stochastically stable and achieves certain $\mathcal{H}_\infty$ disturbance rejection level. Simulation results have demonstrated the feasibility of the proposed method.

REFERENCES

[1] C. Peng and J. Zhang, "Event-triggered output-feedback H_∞ control for networked control systems with time-varying sampling," *IET Control Theory Appl.*, vol. 9, no. 9, pp. 1384–1391, 2015.
[2] X.-M. Zhang and Q.-L. Han, "Event-triggered dynamic output feedback control for networked control systems," *IET Control Theory Appl.*, vol. 8, no. 4, pp. 226–234, Mar. 2014.
[3] F. Yang and Q.-L. Han, "H_∞ control for networked systems with multiple packet dropouts," *Inf. Sci.*, vol. 252, pp. 106–117, Dec. 2013.
[4] H. Chen, J. Gao, T. Shi, and R. Lu, "H_∞ control for networked control systems with time delay, data packet dropout and disorder," *Neurocomputing*, vol. 179, pp. 211–218, Feb. 2016.
[5] F. Yang, W. Wang, Y. Niu, and Y. Li, "Observer-based H_∞ control for networked systems with consecutive packet delays and losses," *Int. J. Control, Automat. Syst.*, vol. 8, no. 4, pp. 769–775, 2010.
[6] L. Qiu, S. Li, B. Xu, and G. Xu, "H_∞ control of networked control systems based on Markov jump unified model," *Int. J. Robust Nonlinear Control*, vol. 25, no. 15, pp. 2770–2786, Oct. 2015.
[7] E. Tian and D. Yue, "A new state feedback H_∞ control of networked control systems with time-varying network conditions," *J. Franklin Inst.*, vol. 349, no. 3, pp. 891–914, 2012.
[8] W.-A. Zhang and L. Yu, "Modelling and control of networked control systems with both network-induced delay and packet-dropout," *Automatica*, vol. 44, no. 12, pp. 3206–3210, Dec. 2008.
[9] J. Zhang, Y. Lin, and P. Shi, "Output tracking control of networked control systems via delay compensation controllers," *Automatica*, vol. 57, pp. 85–92, Jul. 2015.
[10] Y. Cai, N. Pan, and X. Xu, "H_∞ filtering for networked control systems with long time-delay and data packet dropout," *Control Decis.*, vol. 25, no. 12, pp. 1826–1830, 2010.
[11] X.-H. Bu and Z.-S. Hou, "Stability of iterative learning control with data dropouts via asynchronous dynamical system," *Int. J. Autom. Comput.*, vol. 8, no. 1, pp. 29–36, Feb. 2011.
[12] C. Xie, "Modeling and control for networked control systems with packet dropout," *Sci. Technol. Eng.*, vol. 14, no. 18, pp. 76–80, 2014.
[13] H.-B. Cai, P. Li, C.-L. Su, and J.-T. Cao, "Robust model predictive control with randomly occurred networked packet loss in industrial cyber physical systems," *J. Central South Univ.*, vol. 26, no. 7, pp. 1921–1933, Jul. 2019.
[14] S. Wang, Y. Jiang, Y. Li, and D. Liu, "Fault detection and control codesign for discrete-time delayed fuzzy networked control systems subject to quantization and multiple packet dropouts," *Fuzzy Sets Syst.*, vol. 306, pp. 1–25, Jan. 2017.
[15] C. Mnasri, D. Chorfi, and M. Gasmi, "Robust integral sliding mode control of uncertain networked control systems with multiple data packet losses," *Int. J. Control, Autom. Syst.*, vol. 16, no. 5, pp. 2093–2102, Oct. 2018.
[16] D. Shen, C. Zhang, and Y. Xu, "Two updating schemes of iterative learning control for networked control systems with random data dropouts," *Inf. Sci.*, vol. 381, pp. 352–370, Mar. 2017.
[17] Y. Wang, P. He, H. Li, X. Sun, W. Wei, Z. Wei, and Y. Li, "Stabilization for networked control system with time-delay and packet loss in both S-C side and C-A side," *IEEE Access*, vol. 8, pp. 2513–2523, 2020.
[18] Y.-F. Wang, Y.-W. Jing, and B.-Q. Yu, "State feedback for networked control systems with time-delay and data packet dropout," in *Proc. Chin. Control Decis. Conf. (CCDC)*, May 2011, pp. 306–309.

[19] A. A. Ghavifekr, A. R. Ghiasi, M. A. Badamchizadeh, F. Hashemzadeh, and P. Fiorini, ''Stability analysis of the linear discrete teleoperation systems with stochastic sampling and data dropout,'' *Eur. J. Control*, vol. 41, pp. 63–71, May 2018.
[20] J. Yu, C. Kuang, and X. Tang, ''Model predictive tracking control for networked control systems subject to Markovian packet dropout,'' in *Proc. 36th Chin. Control Conf. (CCC)*, Jul. 2017, pp. 301–305.
[21] S. Yu, J. Li, and Y. Tang, ''Dynamic output feedback control for nonlinear networked control systems with random packet dropout and random delay,'' *Math. Problems Eng.*, vol. 2013, Nov. 2013, Art. no. 820280.
[22] G. Wang, Q. Zhang, and V. Sreeram, ''Partially mode-dependent filtering for discrete-time Markovian jump systems with partly unknown transition probabilities,'' *Signal Process.*, vol. 90, no. 2, pp. 548–556, Feb. 2010.
[23] A. Liu, L. Yu, and W.-A. Zhang, ''One-step receding horizon control for networked control systems with random delay and packet disordering,'' *ISA Trans.*, vol. 50, no. 1, pp. 44–52, Jan. 2011.

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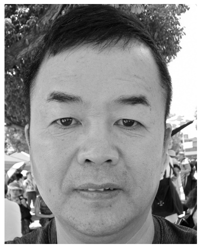

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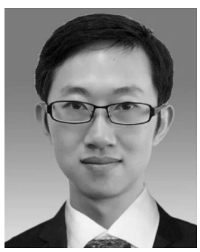

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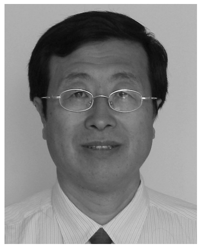

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