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Research article

H_∞ control for uncertain linear system over networks with Bernoulli data dropout and actuator saturation

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ABSTRACT

This paper investigates the H_∞ control problems for uncertain linear system over networks with random communication data dropout and actuator saturation. The random data dropout process is modeled by a Bernoulli distributed white sequence with a known conditional probability distribution and the actuator saturation is confined in a convex hull by introducing a group of auxiliary matrices. By constructing a quadratic Lyapunov function, effective conditions for the state feedback-based H_∞ controller and the observer-based H_∞ controller are proposed in the form of non-convex matrix inequalities to take the random data dropout and actuator saturation into consideration simultaneously, and the problem of non-convex feasibility is solved by applying cone complementarity linearization (CCL) procedure. Finally, two simulation examples are given to demonstrate the effectiveness of the proposed new design techniques.

1. Introduction

Networked control systems (NCSs) have attracted a great deal of attention in both the control and communication areas due to the great advantages of low cost, enhanced flexibility, reduced wiring, simple installation and maintains, and so on [1,2]. As such, network-based control strategies have been successfully adopted in a wide variety of areas such as industrial automation, unmanned vehicles, remote surgery, mobile sensor networks vehicles, etc [3]. However, as a result of network intervention, many inevitable challenging issues such as data dropout, network-induced delay and signal quantization have followed [4–9]. In these issues, intermittent data dropout is considered to be one of the most important and special issues which may cause the performance deterioration or even instability of NCSs and it has aroused great interest in research in the past few years [10–15]. This paper focuses on the impact of data dropout on the controller design of the linear NCSs.

It is well known that the phenomenon of random data dropout could be viewed as a Bernoulli probability distribution which took values of zero and one with certain probability among the communication channels [16–18]. In addition to this method, there were also some research findings in which a Markovian jumping parameter was used to model a discrete-time linear system with data dropout in NCSs [19–21]. Other literature such as [22,23] modeled the data dropout process by means of replacing the data dropout by zeros and then establishing an incompleteness matrix in the measurement. Based on these theories, many nice results about NCSs with data dropout have been put forward. For example, under the consideration of data dropout, the H_∞ control problems have been investigated for NCSs in Refs. [17,18,24–26]. In Refs. [27,28], some model predictive control strategies have been developed to deal with the missing measurements by sending a sequence of control input predictions in one data dropout and then selecting the appropriate one corresponding to the current network condition. In Ref. [12], exponential stability criteria were raised for the NCSs with transmitted data dropout by using a common quadratic Lyapunov function and a fuzzy Lyapunov function. In Ref. [29], a compensator was introduced to compensate the effect of data dropout in NCSs and a controller which was used to adopt the estimate state generated by the compensator was designed in order to compute control variable when the sensor data was missing in the current period.

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It should be pointed out that apart from the influence of data dropout in NCSs, some other factors which may affect system stability and performance also exist in NCSs. In actual engineering control, actuator saturation problems often occur. Actuator saturation not only can seriously reduce the performance of the closed-loop system but also may make a stable closed-loop system become unstable if subject to some large perturbation. So in order to avoid the system getting worsen and even losing the stability, actuator saturation has been considered in the process of designing a closed-loop system. In recent years, saturated actuator problems have been discussed for control systems in large quantities of literature [30–38]. For example, it has been shown in Ref. [30] that the problem of input saturation could be dealt with by introducing a group of auxiliary matrices. Considering the control systems with actuator saturation, some advanced and less conservative model predictive control methods were presented in Refs. [31,32], and these methods led to a considerable improvement in the closed-loop system performance. In Ref. [33], an active fault-tolerant control method for discrete-time linear systems with actuator saturation was introduced. In Ref. [34], a robust finite-time H_∞ control method which was subject to time-varying delay and actuator saturation simultaneously was designed for discrete-time singular Markovian jump systems.

Note that all the literature mentioned above about NCSs assume that the state of the controlled object is measurable. However, in the actual NCSs, not all state variables are measurable as a result of the limitation of environment and economic conditions. So we must reconstruct the state of the system and use the reconstructed state to replace the real state of the system to achieve our required state feedback. These situations put forward a higher demand on our controller design. Usually, an observer is used to solve the problem of state non measurable. Recently, there have been some relevant research results on this topic [25,39–44]. In Ref. [25], a state feedback-based H_∞ observer has been utilized to achieve stability criteria as well as the H_∞ performance for NCSs with data dropout. In Refs. [39,40], some control algorithm based on state observers were presented in the presence of data dropout. In Ref. [42], a sampled-data observer was applied to satisfy the output-feedback predictor-based stabilization of a networked uncertain time-delay system and the observer designed in this literature gave an estimate state and the estimate was also used in a predictor which partially compensated unknown network delays.

With the fact that few literature about networked linear systems have simultaneously taken both random data dropout and actuator saturation into consideration, while in the case of random data dropout, few research concern has been focused on the system-performance requirements such as the H_∞ disturbance-rejection-attenuation as well as the observer-based controller design issues. Therefore, this paper aims to address the above-mentioned gap. In this paper, we intend to deal with the H_∞ control problems for a class of uncertain linear systems over networks with stochastic data dropout and actuator saturation. In addition, we will concern the observer-based H_∞ output feedback control when the system state is unmeasurable where our objective is to design an observer-based H_∞ controller such that the closed-loop system is exponentially mean-square stable while the prescribed H_∞ performance is satisfied. It is worth mentioning that we employ Bernoulli random binary distribution to construct a linear function with stochastic variables to model the random data dropout process. Furthermore, we provide an advanced method which has been developed in Ref. [30] to deal with the issue of actuator saturation. With these considerations, the stability analysis and controller synthesis problems have thoroughly taken into account. Sufficient conditions for the existence of the state feedback-based H_∞ controller and the observer-based H_∞ controller are obtained, such that not only the closed-loop networked linear system is stochastically exponentially stable but also the H_∞ disturbance-rejection-attenuation performance is realized. By using the proposed cone complementarity linearization (CCL) algorithm [45], the design criteria of the controller which are characterized as non-convex matrix inequalities can be turned into a minimization problem subject to LMI constraints.

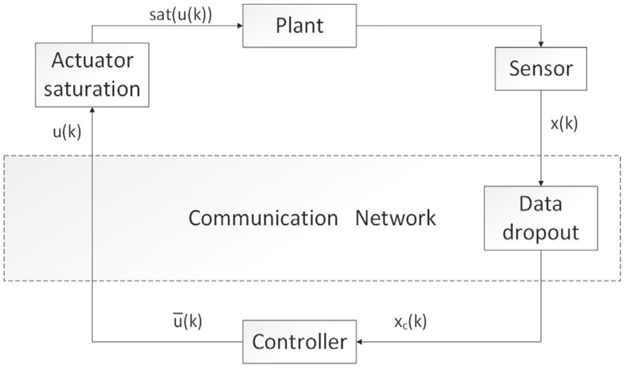

Fig. 1. Networked control system.

The remainder of this paper is organized as follows. Section 2 inspects the problem formulation of NCSs with random data dropout and actuator saturation. Section 3 presents the stability analysis and state feedback-based H_∞ controller design for the proposed NCSs. Section 4 presents the problem of observer-based H_∞ controller design. Section 5 gives two simulation examples based on our design. Conclusions are given in Section 6.

Notation. $E\{x\}$ denotes the expectation of the stochastic variable x. $R^{n\times m}$ is a set of all $n\times m$ real matrices. The superscript T indicates the transpose of matrices. $Prob\{\cdot\}$ stands for the occurrence probability of the event "·". For any vector x and matrix Q, $\|x\|_Q^2 = x^TQx$. $X > 0$ indicates that X is a symmetric positive definite while $X < 0$ means a symmetric negative definite. If A is a matrix, $\lambda_{\max}(A)$ represents the largest eigenvalue of A and $\lambda_{\min}(A)$ represents the smallest eigenvalue of A. The notation $\|\cdot\|$ stands for the Euclidean vector norm or the induced matrix 2-norm. diag$\{b_1, b_2, \ldots, b_n\}$ denotes a block-diagonal matrix. In the symmetric block matrices, "*" expresses as an ellipsis for terms induced by symmetry.

2. Problem formulation

Consider the uncertain linear NCS with data dropout and actuator saturation shown in Fig. 1. The controlled system is an uncertain linear system. The random data dropout exists in the communication channel from sensor to controller and the input saturation constraint is added to actuator. In this paper, the plant is assumed to be of the form

$$\begin{aligned} x(k+1) &= (A+\Delta A)x(k) + (B+\Delta B)\,sat(u(k)) + D\omega(k) \\ z(k) &= C_1x(k) + D_1\omega(k) \\ y(k) &= C_2x(k) \end{aligned} \tag{1}$$

where $x(k)\in\Re^n$ is the state vector, $u(k)\in\Re^m$ denotes the control input, $\omega(k)\in\Re^l$ refers to the disturbance input, $z(k)\in\Re^r$ represents the controlled output, $y(k)\in\Re^p$ is the measured output at the plant side, A, B, D, C_1, D_1 and C_2 are known real constant matrices with appropriate dimensions. The function $sat:\Re^m \Longrightarrow \Re^m$ is a vector-valued standard saturation function defined as $sat(u) = [sat(u_1), sat(u_2), \ldots, sat(u_m)]^T$, with $sat(u_i) = \text{sign}(u_i)\min\{|u_i|, 1\}$.

The parameter uncertainties ΔA, ΔB are assumed to be norm-bounded of the following form

$$[\Delta A \quad \Delta B] = ZF(k)[E_1 \quad E_2] \tag{2}$$

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