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H_∞ control for networked control systems with time delay, data packet dropout and disorder ☆

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ABSTRACT

This paper considers H_∞ output feedback control for networked control systems (NCSs) with time delay, data packet dropout and disorder, occurred in both sensor-to-controller and controller-to-actuator channels. A logic data packet processor (DPP) is adopted to solve the data packet disorder and data packet dropout is seemed as a special case of the time delay. Time delay is modeled as Markov chains taking values in a finite set. Finally, the closed-loop system is modeled as a Markov jump system. An output feedback controller is designed to stabilize the closed-loop system with a pre-described H_∞ performance index. A numerical example is presented to illustrate the effectiveness of the proposed method.

1. Introduction

With the rapid development of communication technologies, the network is used as a kind of signal transmission medium and applied to the engineering applications more and more frequently. Remote control often is needed in many engineering applications, which is impossible or uneconomical by using the traditional signal transmission technologies. Networks just can be used to transmit communication signals to the remote area. As a result, controlled equipment, sensor, controller and actuator constitute a closed loop system, which is connected by networks. Such a closed loop system is often called as networked control system (NCS). Compared with the traditional control system, NCS shares so many advantages, such as lowcost, reduced weight and power requirements. So more and more attention has been drawn to the study of the NCS.

Due to the communication constraints, some new problems occur in NCS. Time delays and data packet dropouts are two main problems, which have attracted many research interests, see for more details in [1,2,3-6,7,11–21,23,28]. Many other problems, such as quantization, filtering, guaranteed cost control and optimal control problem, also have been considered in [23–30]. Time delays are usually caused by limited bit rate of the communication channel and data packet dropouts are often aroused by the unavoidable errors or losses in the process of transmission. For time delays, constant, time-varying or random-varying ones are considered in many papers. But there is obvious that the random-varying time delays are more applicable to reality. Following a similar way, for data packet dropouts, the uncertain one is more appropriate to be adopted. Before the analysis of these two problems, modeling them by mathematical description is necessary. In [1], multiple data packet dropouts are considered, and NCS is modeled as a stochastic parameter system which contains two independent Bernoulli distributed white sequences. In [2,6,7], time delays or data packet dropouts are modeled as a Markov chain, thus NCS is modeled as a Markov jump linear system.

Many significant results about time delay and data packet dropout of NCS are obtained. However, the two problems make us wonder not all the data packets transmitted in the network can follow a "first send first arrive" principle. This means that a data packet sent earlier may arrive at its destination node later than the one sent later or vice versa, i.e., the so-called "data packet disorder", see more details in [8,9,13].

H_∞ output feedback control for NCS with time delays, data packet dropouts and disorders, occurred in both sensor-to-controller and controller-to-actuator channels, is discussed in this paper. Three factors which motivate us to make this study are:

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(a) many papers have not taken into account time delays or data packet dropouts happened in both sensor-to-controller and controller-to-actuator channels simultaneously, i.e., many of them only consider either of the two channels; (b) only a few papers have referred to the data packet disorders; (c) less papers have considered the H_∞ output feedback control for NCS.

In this paper, the data packet generator (DPG) in the sensor side is used to pack the measured output y_k labeled with the time stamp k as a data packet. Then, a unique logic data packet processor (DPP) is utilized to handle the data packet disorders and a zero order holder (ZOH) is adopted for necessity in the actuator side. Meanwhile, time delays existed in both sensor-to-controller and controller-to-actuator channels are modeled as two independent Markov chains and data packet dropout is seemed as a special case of the time delay. So the closed-loop system is modeled as a Markov jump linear system. Sufficient condition for NCS's stability and solvability of the H_∞ output feedback controller's design problem are presented. A numerical example is adopted to illustrate the effectiveness of the proposed method.

Notation: All referred notations in this paper are fairly standard. Superscript T and -1 represent the transposition of vectors or matrices and matrix inverse, respectively. R^n denotes the n dimensional Euclidean space with the norm $\|x\| = (x^T x)^{1/2}$ and $E(\cdot)$ stands for the mathematical expectation operator. $l_2[0,\infty)$ describes the space of square summable infinite sequences with the norm $\|w_k\|_2 = (\sum_0^\infty \|w_k\|^2)^{1/2}$ and $\|z_k\|_E = (E(\sum_0^\infty \|z_k\|^2))^{1/2}$. In addition, $*$ is used to denote the symmetry entries of symmetry matrices. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations. The notation $P>0$ (≥ 0) means P is real symmetric positive (semi-positive) definite. I and 0 represent identity matrix and zero matrix, respectively. For avoiding confusion, 0_a and $0_{a\times a}$ denote the zero vector and the zero matrix of the proper dimensions, respectively.

2. Model description and problem formulation

NCS is a closed-loop feedback control system, which is consisted of plant, sensor, controller and actuator connected by networks. Fig. 1 shows the framework of NCS referred in this paper. The plant is described with the following form:

$$
\begin{aligned}
x_{k+1} &= Ax_k + Bu_k + D_1 w_k \\
y_k &= Cx_k + D_2 w_k \\
z_k &= Gx_k + G_1 u_k + D_3 w_k
\end{aligned} \tag{1}
$$

where $x_k \in R^n$ is the state, $u_k \in R^m$ is the control input, i.e., u_k denotes the data received by actuator from the controller, $z_k \in R^q$ is the output to be controlled, $w_k \in R^p$ is the disturbance input which belongs to $l_2[0,\infty)$. $y_k \in R^r$ is the measured output. Matrices A, B, C, D_1, D_2, D_3, G and G_1 are of appropriate dimensions.

Remark 1. In practical environment, w_k include the process noise and measurement noise. Though this paper only considers the process noise, the measurement noise is also possible to be extended to the results in this paper. As the size of measurement noise changes randomly, the measurement noise can be modeled by another stochastic variable $\tilde{w}_k$, which can be added to (1) following a similar form. For simplifying computation, this paper have not taken measurement noise into account.

Mathematical model description of the dynamic output feedback controller is given as

$$
\begin{aligned}
\hat{x}_{k+1} &= \hat{A}\hat{x}_k + \hat{B}\bar{y}_k \\
\bar{u}_k &= \hat{C}\hat{x}_k
\end{aligned} \tag{2}
$$

where $\hat{x}_k \in R^n$ is the state of the dynamic output feedback

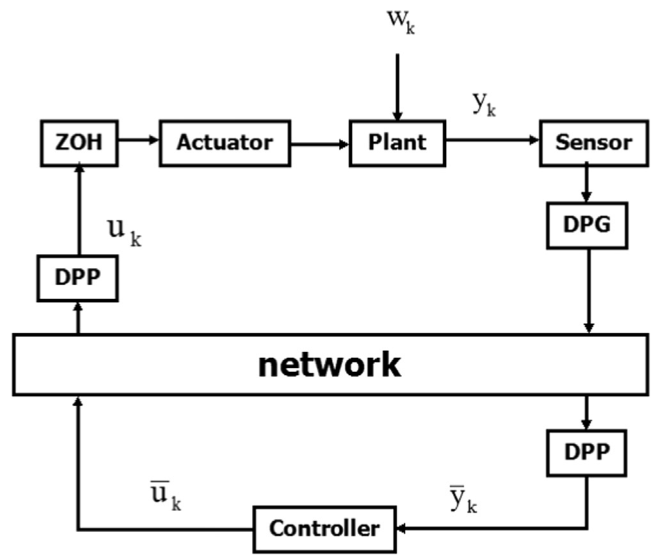

Fig. 1. The framework of NCS.

controller. $\bar{y}_k$ is the received information of the controller, i.e., $\bar{y}_k$ denotes the data received by the controller from the sensor. $\bar{u}_k$ is the output of the controller, see more details in Fig. 1. $\hat{A}$, $\hat{B}$ and $\hat{C}$ are the parameters of the controller to be computed.

2.1. Methods to tackle the data packet disorder

The whole system is a closed-loop system, where sensor-to-controller channel and controller-to-actuator channel are both connected by networks. So the three problems taken into account in this paper will occur on both the two communication channels. Before processing, a basic premise that transmission form of the data packet in NCS is single packet form is necessary to declare. On the condition of that premise, a data packet composed by the measured output y_k and the time stamp k is generated by the DPG. Then, the data packet is transmitted to the controller side after the process of the DPP, which is mainly used to tackle the problem of data packet disorder. Subsequently, the process scheme of the data packet disorder problem is presented as follows.

Algorithm 1 (*Zhao et al. [8]*).

(S1) The sensors sample the output of the plant.
(S2) DPG at the sensor side is used to label the sampled data packet with the current time instant and send it to the controller.
(S3) Logic Comparator (LC), one part of the DPP at the controller side, determines whether the newly arrived sampled data packet is up to date or not. If yes, then update the register; otherwise the register remain unchanged.
(S4) If the register at the controller side is updated, the controller then calculates the control signal and sends the control data packet to the actuator with the time stamp in its corresponding sampled data packet.
(S5) A similar comparison process as in S3 is done at the actuator side and the register is updated accordingly.
(S6) The actuator applies the control signal in the register to the plant.

2.2. Description of the time delay

After the process of DPP, the problem of data packet disorder is tackled very well. This part discusses the problem of time delay. Before the discussion, assuming sensor, controller and actuator