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Quantized control for NCSs with communication constraints

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ABSTRACT

This paper studies the stabilization problem for networked control systems (NCSs) affected by data quantization, time-varying transmission intervals, time-varying transmission delays and communication constraints. Time-varying transmission intervals and delays, by limiting the upper and lower bounds of which, can be described by a two-dimensional convex region. Combined with the coupling role of data quantization, communication constraints mean that only one node can occupy the network and send its quantized values in each transmission. The order in which node transmits its quantized values is determined by a given periodic network protocol. By introducing a variable called proportionality coefficient of saturation value in well-known zoom strategy to deal with the complex coupling relationship between system states and quantized variables, some sufficient conditions are derived for reaching asymptotic stability of NCSs under properly designed quantizer parameters. A simulation example is given to illustrate the effectiveness of the theoretical analysis.

1. Introduction

The introduction of the network in the control systems has brought us a lot of convenience and advantages, such as decreased the complexity, increased the flexibility, improved the convenience of installation and maintenance, and reduced wiring and cost. However, networking the control systems also brings new challenges which can be divided into six categories in general: (i) data quantization; (ii) data packet loss; (iii) time-varying transmission intervals; (iv) time-varying transmission delays; (v) communication constraints, which impose that not all of the sensor and actuator signals can be transmitted simultaneously; (vi) network-induced external disturbance. Combined with the performance constraints of the controlled object itself, such as actuator saturation, control algorithms should be pursued to handle with these communication imperfections and constraints simultaneously [1,2].

In recent years, much effort has been dedicated to the stability analysis of NCSs just affected by one or two of these phenomena [3–19]. For NCSs with (i)–(iii), a binary variable modeling stochastic sampling process and logarithmic quantization is introduced to describe the networked communication process in [20]. A randomly switched Takagi–Sugeno fuzzy system with multiple input-delay subsystems is proposed to model the nonlinear NCSs with (i), (ii) and (v) in [21]. The problem of achieving parameterized input to state stability with respect to (i), (ii) and (vi) for NCSs is studied in [22]. Delta operator approach is adopted in [23] to deal with the stabilization problem of NCSs with (i), (ii) and actuator saturation. Ne š i ć and Liberzon [24] formulate a unified controller design framework for NCSs with types (i), (iii) and (v). Cloosterman et al. [25] proposes a discrete-time model for NCSs that incorporates imperfections (ii)–(iv). Focusing on NCSs that are subject to (iii)–(v), Donkers et al. [26] presents a new modeling framework to derive the stability results. Under the influence of (iv)–(vi), the ultimate boundedness of the estimation error is guaranteed in [27]. Literature [28–31] research types (i), (ii) and (iv). All the above papers study the stability and stabilization issues of NCSs including three imperfections. For four imperfections, a novel NCSs model is described in [32], which includes multi-rate sampled-data, quantized signal, time-varying delay and packet dropout. In this paper, we will focus on the stability of NCSs with data quantization, time-varying transmission intervals, time-varying transmission delays and communication constraints, i.e., types (i), (iii), (iv) and (v).

Donkers et al. [26] proposes skillfully a convex overapproximation method to analyze the stability of NCSs with imperfections (iii)–(v), but which is invalid to handle with data quantization simultaneously. To achieve the stability analysis of NCSs with (i)–(v), Loon et al. [33] promotes this convex overapproximation method, which ensures the stability under both uniform quantizer and logarithmic quantizer. Comparing the asymptotic stability under

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logarithmic quantizer with infinite quantization level and practical stability under uniform quantizer in [33], we will, by modifying the overapproximation procedure, pursue the asymptotic stability conditions by using a uniform quantizer with finite quantization level.

As we know, time variability of quantizer parameters is the necessary condition ensuring asymptotic stability, under which the quantization errors can tend to zero. Zoom strategy proposed in [34] is a efficacious method to adjust the time-varying quantizer parameters. With the advantages of finite quantization level and adjustable variables, zoom strategy has been adopted by many articles to deal with the issues of quantization and data packet loss [19,22], or disturbance [22], or saturation [23]. But it has not been used to study the issues of (i), (iii), (iv) and (v) so far, which is one of the innovations of this paper. Due to the complex coupling relationship between system states and quantized variables, we introduce a variable called proportionality coefficient of saturation value to improve the zoom strategy, which ensures the unsaturation of the quantized variables, and guarantees that the system states load in the time-varying invariant regions at the same time.

Above all, our contributions are three aspects with respect to earlier literature. First, a modified procedure is proposed to approximate the switched uncertain quantized system which is transferred from NCSs discussed here. Under this procedure, the decreasing rate of the related parameters is promoted, which allows that the overapproximation achieves tightness at a faster rate. Second, zoom strategy is adopted here to discuss the asymptotic stability of NCSs affected by imperfections (i), (iii), (iv) and (v), which has not been studied before. Third, a variable called proportionality coefficient of saturation value is introduced to improve the zoom strategy. Under which, the complex coupling relationship between system states and quantized variables can be dealt effectively, and thus the unsaturation of the quantized variables and the asymptotic stability of the closed-loop system can be guaranteed by adjusting the quantizer parameters suitably.

The outline of this paper is as follows. In Section 2, we introduce the detailed model, network and problem descriptions. A method is given to write the NCSs model as a switched uncertain quantized system in Section 3. Next, we propose an improved procedure to overapproximate the NCSs according to a polytopic system in Section 4. In Section 5, we obtain the conditions to ensure the stability of the NCSs based on LMIs, and the detailed proof of which is given in Section 6. A numerical benchmark example is adopted to illustrate the effectiveness of the main results in Section 7 and conclusions are given in Section 8. The supplementary proofs of some lemmas and theorems are shown in Appendix.

The notations used in this paper are very regular. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. $\mathbb{R}^+$ and $\mathbb{N}$ denote the set of positive real numbers and positive integers, respectively. We denote by $\|\cdot\|$ the standard Euclidean norm in $\mathbb{R}^n$ and the corresponding induced matrix norm in $\mathbb{R}^{n\times n}$. $\lambda_{max}(P)$ and $\lambda_{min}(P)$ denote the maximum eigenvalue and minimum eigenvalue of matrix P, respectively. The signal diag $(A_1,\dots,A_n)$ is used to denote a block-diagonal matrix with the diagonal elements $A_1,\dots,A_n$. $A^T\in\mathbb{R}^{m\times n}$ denotes the transposed of matrix $A\in\mathbb{R}^{n\times m}$. For brevity, the symmetric matrix $\begin{bmatrix} A & B\\ B^T & C\end{bmatrix}$ is sometimes written as $\begin{bmatrix} A & B\\ * & C\end{bmatrix}$. The limits as s approaches t from above and below are denoted by $\lim_{s\downarrow t}$ and $\lim_{s\uparrow t}$, respectively. We use co$\{A\}$ to denote the convex hull of a set A. The signals $\lceil\cdot\rceil$ and $\lfloor\cdot\rfloor$ indicate the integer function upward and downward, respectively.

2. Model, network and problem descriptions

2.1. Model description

The NCSs considered here are shown in Fig. 1, in which the plant is described by the following linear time-invariant (LTI) continuous-time equation:

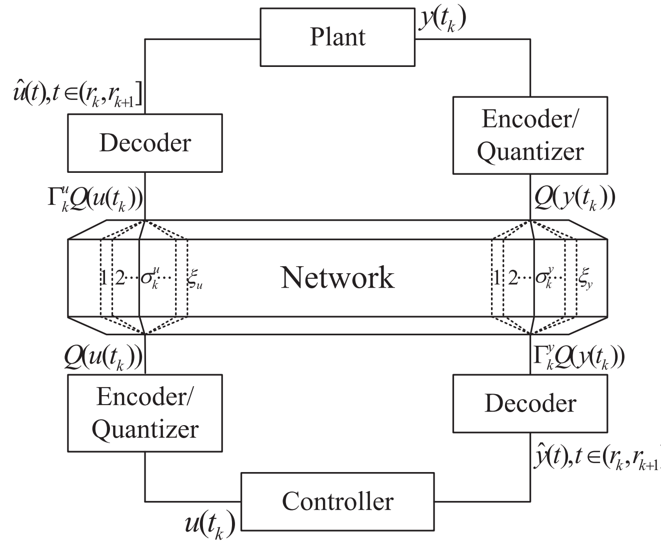

Fig. 1. System configuration.

$$\begin{cases} \dot{x}^p(t) = A_p x^p(t) + B_p\hat{u}(t)\\ y(t) = C_p x^p(t), \end{cases} \tag{1}$$

where $x^p\in\mathbb{R}^{n_p}$ denotes the plant state, $\hat{u}\in\mathbb{R}^{n_u}$ is as the most recently received control variable, $y\in\mathbb{R}^{n_y}$ denotes the output of the plant, $t\in\mathbb{R}^+$ denotes the time, and A_p, B_p, C_p are the given constant matrices with approximate dimensions.

Due to the controller is typically implemented in a digital, and thus the discrete-time form, we design it as the following LTI discrete-time system:

$$\begin{cases} x^c_{k+1} = A_c x^c_k + B_c\hat{y}_k\\ u(t_k) = C_c x^c_k + D_c\hat{y}(t_k), \end{cases} \tag{2}$$

where $x^c\in\mathbb{R}^{n_c}$ denotes the controller state, $\hat{y}\in\mathbb{R}^{n_y}$ is as the most recently received output of the plant, $u\in\mathbb{R}^{n_u}$ represents the controller output, and A_c, B_c, C_c, D_c are constant matrices.

2.2. Network description

(i) Data quantization. The quantizer adopted here is the same as the one in [34], i.e.,

$$q_\mu(x(k)) = \mu(k)\ q\left(\frac{x(k)}{\mu(k)}\right), \tag{3}$$

where $\mu(k)\in\mathbb{R}^+$. Assume that the following conditions on $q_\mu(\cdot)$ are satisfied:

I. If $\|x(k)\|\le M\mu(k)$, then $\|q_\mu(x(k)) - x(k)\|\le\triangle\mu(k)$,

II. If $\|x(k)\| > M\mu(k)$, then $\|q_\mu(x(k))\| > M\mu(k) - \triangle\mu(k)$, where M is the saturation value and $\triangle$ the sensitivity.

(ii) Time-varying transmission intervals and delays. For all $k\in\mathbb{N}$, we assume that transmission interval h_k and transmission delay τ_k are all time-varying, and belong to the set Θ defined by

$$\Theta := \left\{(h,\tau)\in\mathbb{R}^2 | h\in[\underline{h},\bar{h}],\ \tau\in[\underline{\tau}, \min\{h,\bar{\tau}\}),\ \bar{h}\ge\underline{h}>0,\ \bar{\tau}\ge\underline{\tau}\ge 0\right\}.$$

(iii) Communication constraints. At each transmission instant t_k, $k\in\mathbb{N}$, the plant outputs $y(t_k)$ and controller outputs $u(t_k)$ are sampled and quantized, and parts of the quantized value $q_\mu(y(t_k))$ and $q_\mu(u(t_k))$ are transmitted through the network. Assuming that the quantized values arrive at time instant r_k which is called the arrival instant. The signal transmission situation illustrated above

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