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Model predictive control of non-linear systems over networks with data quantization and packet loss

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ABSTRACT

This paper studies the approach of model predictive control (MPC) for the non-linear systems under networked environment where both data quantization and packet loss may occur. The non-linear controlled plant in the networked control system (NCS) is represented by a Tagaki-Sugeno (T-S) model. The sensed data and control signal are quantized in both links and described as sector bound uncertainties by applying sector bound approach. Then, the quantized data are transmitted in the communication networks and may suffer from the effect of packet losses, which are modeled as Bernoulli process. A fuzzy predictive controller which guarantees the stability of the closed-loop system is obtained by solving a set of linear matrix inequalities (LMIs). A numerical example is given to illustrate the effectiveness of the proposed method.

1. Introduction

Networked control systems (NCSs) are a type of closed-loop systems, in which the control loops are closed through communication networks [1]. NCSs have been found applications in a broad range of fields, such as mobile sensor networks, remote surgery, automated highway systems and urban water resource management system [2–4]. The main features of NCSs are reducing connection, simple implement resource sharing, and ease of maintenance. However, since the communication bandwidth is limited, a number of undesirable phenomena may occur in NCSs, such as time delays, packet losses and data quantizations. These phenomena might be potential sources of poor control performance, even cause instability of control system.

Many scholars did lots of researches on the stability analysis and controller design of linear NCSs, and many achievements have been made, see, e.g. [5–11]. Ref. [5] investigates the stabilization problem of linear NCS with packet losses in both the sensor to controller and controller to actuator links, where bounded packet loss process and Markovian packet loss process are considered. Ref. [6] considers the case that the communication delays exist in both the system state and the mode signal. By modeling the delays as Markov chain, a Markovian jump linear system with two jumping parameters is introduced to describe the linear closed-loop systems, and a necessary and sufficient condition on the existence of stabilizing controllers is provided. By considering both the network-induced delay and time delay in the plant, a new model of linear NCS is presented in [7], and a controller is designed by applying the delay-dependent approach. Ref. [8] considers the stabilization problem for the linear continuous-time NCS with packet loss and transmission delays in both the sensor to controller and controller to actuator links. In [9], output-feedback controller design in linear NCSs with data quantization and packet dropout is studied in the sensor to controller links. Ref. [10] addresses the optimal stabilization problem for linear NCSs with time delays and packet losses in both the sensor to controller and controller to actuator links, and the stability conditions are derived in terms of linear matrix inequalities (LMI). Ref. [11] studies the stability problem of linear NCSs with random time delays and packet losses which are modeled by two independent Markov chains. Sufficient condition of the stochastic stability is obtained by Lyapunov method, and the output feedback controller is designed based on obtained stability condition. Ref. [12] provides a unifying modeling framework that incorporates quantization effects, packet dropouts, time-varying transmission intervals, time varying transmission delays and communication constraints, and studies the stability problem. Ref. [13] considers the stability analysis of NCS that are subject to time varying transmission intervals, time-varying transmission delays, packet losses and communication constraints. The transmission intervals and transmission delays are described by continuous random variables, result is

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derived in terms of linear matrix inequalities. Ref. [14] investigates the stability of NCSs which suffer from time-varying transmission delays, time-varying transmission intervals, and communication constraints, and a modeling framework based on discrete-time switched linear uncertain systems be presented. Ref. [15] presents a general framework of non-linear NCS that incorporates varying delays, varying sampling intervals and communication constraints, and a continuum of Lyapunov functions guarantee stability of the NCS that will derive bounds on the maximally allowable transmission interval and the maximally allowable delay. Refs. [16–18] studied event-triggered controllers for discrete-time linear systems. More results can be found in [19,21,20,22], and reference therein. Undoubtedly, these papers have achieved very nice results, but they did not take the model predictive control (MPC) into consideration, which is a popular technique for the control of industrial process.

Model predictive control commonly refers to a class of computer control algorithms that use an explicit process model to forecast the future response of a plant [23]. Its control sequence is obtained by solving an optimization problem that minimizes the objective function at each sampling instant. Since the MPC has the ability to handling the input and output constraints in a systematic manner, it is widely applied in industrial field. Hence, it is necessary and interesting to extend the MPC approach to the NCSs area. There have been a lot of nice results in this field, see, e.g. [24–29,25,30]. In [24], a constrained MPC algorithm to overcome packet loss in sensor to controller link of NCS is proposed, and a buffer is designed to storage control sequence computed by MPC algorithm. Based on the standpoint of robust control, [25] presents the synthesis approach of MPC for NCS with bounded packet losses, and [26] investigates the synthesis approach of MPC for NCS with both effects of data quantization and bounded packet loss. The synthesis approaches of MPC for NCS subject to data quantizations in both links is considered in [27], and the stability results which satisfy the input and state constraints are provided by applying the Lyapunov method. A finite switching horizon MPC for NCSs with less than one sampling state transmission delay is discussed in [28], the control strategy is characterized as a constrained optimization problem over the quadratic objective function at each sampling instant. Ref. [29] provides a data-driven predictive controller for NCS with random network-induced delay, which consists of control prediction generator and network-induced delay compensator. Based on a new quadratic performance criterion, [30] addresses a moving-horizon scheduling strategy to handle the communication scheduling for NCS with communication constraints, and a moving-horizon state estimator is also provided.

The above-mentioned papers only consider the linear controlled plant, few attention has been paid on the non-linear plant. Since the industrial process becomes more complex and non-linear characteristics of the controlled object becomes more prominent, it is of great practical significance to study the non-linear system under the networked environment. The related results can be found in [31–33]. By describing the non-linear plant as Tagaki–Sugeno (T–S) fuzzy model, the tracking control for non-linear NCSs is investigated in [31]. Ref. [32] also takes a T–S fuzzy model to describe the NCSs with Markov delays, and the fault detection problem is studied. In [33], the compensation problem for non-linear NCSs with delays is concerned. Both state feedback and output feedback fuzzy delay compensation controllers are designed, and a new approach is proposed to analyze the stability of closed-loop system.

Unfortunately, to the best of the authors' knowledge, much less scholars have studied the MPC approach of non-linear NCSs, especially for non-linear NCSs with both packet loss and data quantizations in double-sided links, which stimulates our research. This paper aims to design a fuzzy model predictive controller for non-linear system under networked environment with both packet losses and data quantizations. The packet losses are modeled by Bernoulli processes, the data quantizations are described as sector bound uncertainty, and the overall closed-loop system is established as T–S fuzzy model by considering both the effects of packet loss and data quantization. Then, the stability result for the obtained closed-loop system is provided by applying the Lyapunov method, and fuzzy model predictive controller is presented based on LMI technique.

Notations: $\mathfrak{R}^n$ denotes the n dimensional Euclidean space. For any vector x and matrix Q, $\|x\|_Q^2 = x^T Q x$. $X>0$ $(X<0)$ means that X is a symmetric positive definite (negative definite). The superscript T denotes the transpose of matrices. The star $*$ denotes blocks that are readily inferred by symmetry. The E means mathematical expectation.

2. The model of NCS

The structure of NCSs in this paper is shown in Fig. 1, where the plant is a discrete-time non-linear system. $x(k) \in \mathfrak{R}^n$ is the state vector; $s_1(k) \in \mathfrak{R}^n$ is the output of the quantizer g; $w(k) \in \mathfrak{R}^n$ and $v(k) \in \mathfrak{R}^m$ are input and output of the controller, respectively. $s_2(k) \in \mathfrak{R}^m$ is the output of the quantizer f; $u(k) \in \mathfrak{R}^m$ is the input vector.

Assuming, in the sensor to controller link, that a single packet of the data set $x(k)$ is sent at each k, which is subject to quantization and possibility of packet loss. In the controller to actuator link, a single packet of the data set $v(k)$ is sent at each k, which is also subject to quantization and possibility of packet loss.

2.1. T–S fuzzy model

We consider the following non-linear plant:

$$x(k+1) = h(x(k), u(k)), \quad k \ge 0 \tag{1}$$

where $h(\cdot)$ is a non-linear function. T–S fuzzy model is based on using a set of fuzzy rules to describe a global non-linear system in terms of a set of local linear models which are smoothly connected by fuzzy membership functions. Generally, we can set up the follow IF–THEN rule to describe T–S fuzzy model:

$$\text{Plant rule } i: \text{IF } \theta_1(k) \text{ is } M_1^i, \text{ and}, \ldots, \theta_n(k) \text{ is } M_n^i,$$

$$\text{Then } x(k+1) = A_i x(k) + B_i u(k) \tag{2}$$

where $\theta_1(k), \theta_2(k), \ldots, \theta_n(k)$ are the premise variables; M_l^i $(i = 1, 2, \ldots, r, l = 1, 2, \ldots, n)$ is the fuzzy set; r is the number of fuzzy rules; $A_i \in \mathfrak{R}^{n\times n}$ and $B_i \in \mathfrak{R}^{n\times m}$ are some constant matrices of compatible dimensions. By using a fuzzy inference method, which includes a singleton fuzzifier, product fuzzy inference and center-

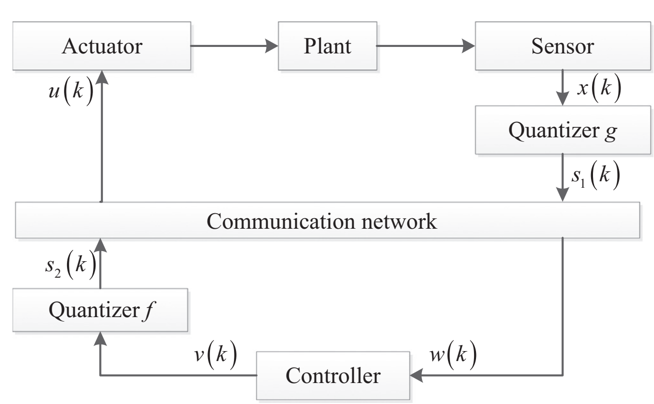

Fig. 1. Networked control system structure.