ISA Transactions 60 (2016) 164–177

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research Article

Asynchronous update based networked predictive control system using a novel proactive compensation strategy

Yingyao Duan, Xin Zuo*, Jianwei Liu

Department of Automation, China University of Petroleum, Changping, Beijing, China

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form
22 August 2015
Accepted 22 August 2015
Available online 12 November 2015

Keywords:
Networked control systems (NCSs)
Networked predictive control
Random time delay
Data dropout
Stability

ABSTRACT

Networked predictive control system (NPCS) has been proposed to address random delays and data dropouts in networked control systems (NCSs). A remaining challenge of this approach is that the controller has uncertain information about the actual control inputs, which leads to the predicted control input errors. The main contribution of this paper is to develop an explicit mechanism running in the distributed network nodes asynchronously, which enables the controller node to keep informed of the states of the actuator node without a priori knowledge about the network. Based on this mechanism, a novel proactive compensation strategy is proposed to develop asynchronous update based networked predictive control system (AUBNPCS). The stability criterion of AUBNPCS is derived analytically. A simulation experiment based on Truetime demonstrates the effectiveness of the scheme.

1. Introduction

Networked control systems (NCSs) are feedback control systems, wherein the control loops are closed via network [1]. The goal of inserting the communication network is to connect the components distributed at different locations, such as actuators, sensors and controllers. This feature makes it easy for the control engineers to design large-scale systems. Compared with the traditional control systems (CCSs), NCSs have shown many appealing advantages such as low cost, reduced complexity in system integration, simple installation and maintenance, high flexibility and enhanced reliability. Important applications of NCSs include sensor networks, industrial control networks, coordinated control of the multi-agent systems, MEMS (Micro Electromechanical Systems) and gene regulation networks. The research topics on NCSs cover modeling, state estimation, controller design, stability analysis and fault detection problems [2–6]. For more details, we can refer to the survey papers [7–9], monographs [10,11] and the references therein.

Despite the benefits, the insertion of networks makes the analysis and synthesis of NCSs complex, and the imperfections of network such as random delays and data dropouts degrade the control system performance. These two issues have been investigated and many important results and approaches have been established in recent years.

The methodologies for dealing with random delays can be classified into two frameworks [9]. The first is the robustness framework, where the controller design is robust over random delays. A typical approach is to regard the NCS as a time delay system. The main steps are to construct an appropriate Lyapunov–Krasovskii function and derive conditions of system stability for controller or filter design. Some recent works in this regard include [12] and [13]. Another approach is the fuzzy-model-based approach, and the typical work can be seen in [14]. Similarly, this line of thinking is also applicable to the data dropout problems. In this context, most approaches are off-line, and the controllers are designed despite any situation of data dropouts. A typical approach is to derive the sufficient conditions offline to ensure the existence of a stabilizing controller for a given upper bound of consecutive packet losses, and some typical works in this respect are included in [15] and [16]. Another approach is to introduce some statistics of the random packet losses. For example, in [17] the packet loss is assumed to obey Bernoulli random binary distribution.

The basic idea of these approaches is the same as that of the approaches applied in CCSs, and the information about the delays and data losses is not used. They passively accept the presence of delays and data dropouts, and the methods of compensating for them actively are not considered. As a result, the implementation of NCSs becomes simpler, but the results are relatively conservative because of ignoring the features of NCSs. The controller and actuator nodes do not need buffers to store previous control signals and measurements, and they also do not need to judge if a packet is delayed or lost.

---

* Corresponding author. Tel.: +86 10 89731185, +86 18911629716.
E-mail address: zuox@cup.edu.cn (X. Zuo).

http://dx.doi.org/10.1016/j.isatra.2015.08.013
0019-0578/

In fact, we can identify three main attributes of NCSs compared with CCSs as listed below. They lead to another framework with adaptation to delays and data losses, which we will address afterwards.

1. The most important characteristic of NCSs is the packet-based transmission, based on which a data packet is capable of packaging large amount of data. However, this characteristic means that the perfect data transmission in CCSs is absent in NCSs, which results in the greatest challenges in NCSs, that is, the network-induced constraints including random delays, packet dropouts, packet disorder, etc.
2. Another difference between NCSs and CCSs is the time-stamp technique. The communication together with time-stamp in NCSs offers an advantage over that of CCSs, i.e., the transmission time is measurable for the receiving nodes. Therefore, the feedback channel delay and forward channel delay (round trip delay as well) can be known by the controller node and the actuator node, respectively.
3. In the architecture of NCSs, the distributed nodes are usually implemented with the intelligent devices, and thus they become smart nodes with the ability of data storage and information processing. Particularly, a smart actuator is equipped with the logic processor and data buffer if the network access can be realized. As a result, it is provided with the intelligence of checking and comparing the time-stamps attached to the received packets.

These features lead to some approaches belonging to the adaptation framework. In the early works, NCSs are modeled as nondeterministic switched systems or stochastic systems, where the control inputs are implemented online depending on the real situation of delays and data dropouts, even if the controller gains are computed offline. Typical works in this respect include [18–20].

In recent years, networked predictive control scheme, as a new approach in adaptation framework, is becoming more and more popular in NCSs. The natural property of predictive control is that it can predict the future system dynamics in a finite horizon. Therefore, we can obtain a number of future control commands besides the current one. If some consecutive packets are delayed or lost after a successful transmission, the smart actuator can select the corresponding ones from the last successfully received packet through appropriate buffering and selection logics. Thus, the idea requires the actuator to be equipped with a buffer including more than one storage unit and a processing unit possessing the selection and comparison functions, which are available according to the third feature of NCSs.

It is obvious that the predictive control scheme takes the specialties of NCSs into a full account, which can reduce conservatism in the analysis and design of the NCSs. The studies have shown that by implementing the control inputs in such a way, the performances are better than that of the approaches where the latest received control input is hold in the presence of delays or packet losses. The recent representative works can be found in [21–26]. Along with this line, we propose asynchronous update based networked predictive control systems (AUBNPCS) using a novel proactive compensation strategy.

We organize this paper as follows. In Section 2, the considered problems and some recent works are reviewed. AUBNPCS based on a proactive compensation strategy is proposed in Section 3. Section 4 presents the stability analysis of the closed-loop system. A simulation experiment is given in Section 5. Finally, the conclusion is demonstrated in Section 6.

2. Problem formulation

In this paper, a linear multiple inputs multiple outputs (MIMO) plant is considered. The model of the plant is expressed in the following discrete state space form.

$$\begin{cases} x_{k+1} = Ax_k + Bu_k \\ y_k = Cx_k \end{cases}, \tag{1}$$

where $x_k \in R^n$, $u_k \in R^m$ and $y_k \in R^p$ are state, input and output vectors of the system, respectively. $A \in R^{n\times n}$, $B \in R^{n\times m}$ and $C \in R^{p\times n}$ are the system matrices. It is well known that the stability of the system is an inherent characteristic, which is independent of the external reference inputs of the system, so we assume that the reference inputs are zero to simplify the controller design and stability analysis in Sections 3 and 4. In addition, the following assumptions are made.

Assumption 1. The pair (A, B) is controllable, and the pair (A, C) is observable.

Assumption 2. All the nodes in the system are smart nodes, whose drive modes are settable. The data packets are time-stamped.

Assumption 3. The transmission delays in the system are bounded. Denote the delays from sensor to actuator and from controller to actuator as τ_{sc} and τ_{ca}, respectively. The upper bounds of them are N_{ca} and N_{sc} times of the sampling period T, respectively. N_{ca} and N_{sc} are positive integers.

Assumption 4. The number of the consecutive data dropouts is also bounded. We assume that the numbers of the consecutive packet dropouts in the forward and feedback channels are not greater than N_{dca} and N_{dsc}, respectively, both of which are positive integers.

Remark 1. From the physical point of view, it is natural to assume that only a finite number of consecutive data dropouts can be tolerated to avoid the system being open-loop. Therefore, we assume the numbers of the consecutive data dropouts in both forward and feedback channels are less than a finite number. Similarly, the delays can also be assumed to be bounded. Here we treat the consecutive data dropouts as equivalent delay and define the maximum of the total equivalent delay as N, which consists of both delays and data dropouts, and thus $N = N_{sc} + N_{ca} + N_{dsc} + N_{dca}$. The delays and data dropout are random, which means that they are arbitrarily variables within the corresponding bounds and they do not have a specific probability distribution. Therefore, we cannot treat NCSs as stochastic systems, and thus we will not apply the stochastic control theory in this paper.

First, we refer to NPCS proposed by Liu et al. in [21]. Based on the system description in (1), the state observer is designed as

$$\hat{x}_{k+1|k} = \hat{A}\hat{x}_{k|k-1} + \hat{B}u_k + H(y_k - \hat{C}\hat{x}_{k|k-1}), \tag{2}$$

where $\hat{x}_{k+1|k} \in R^n$ is one-step-ahead state estimation at instant k. $\hat{A} \in R^{n\times n}$, $\hat{B} \in R^{n\times m}$ and $\hat{C} \in R^{p\times n}$ are the estimated system matrices. The matrix $H \in R^{n\times p}$ is the observer gain.

According to the system dynamics described in (1), the observer is extended to be a state estimator, which constructs the future states from the instant $k+2$ to the instant $k+N$ as follows.

$$\begin{aligned} \hat{x}_{k+2|k} &= \hat{A}\hat{x}_{k+1|k} + \hat{B}u_{k+1}, \\ &\vdots \\ \hat{x}_{k+N|k} &= \hat{A}\hat{x}_{k+N-1|k} + \hat{B}u_{k+N-1}. \end{aligned} \tag{3}$$