Information Sciences 364–365 (2016) 1–15

Contents lists available at ScienceDirect

Information Sciences

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

Initialization of the HMM-based delay model in networked control systems

Yuan Ge[a,b,*], Xiaoxin Zhang[a], Qigong Chen[a], Ming Jiang[a]

[a] School of Electrical Engineering, Anhui Polytechnic University, Wuhu 241000, Anhui, PR China
[b] Department of Electrical Engineering, Tsinghua University, Beijing 100084, PR China

ARTICLE INFO

Article history:
Received 16 December 2014
Revised 4 March 2016
Accepted 15 May 2016
Available online 19 May 2016

Keywords:
Networked control systems
Random delays
Hidden Markov models
Parameter initialization

ABSTRACT

When hidden Markov models (HMMs, including discrete HMM and semi-continuous HMM) are used to model and predict the random delays in networked control systems, there are five parameters needed to be estimated. They are the number of different network states, the initial distribution of the network states, the state transition matrix of the hidden Markov chain formed by the network states, the number of different delay observations in the discrete HMM (DHMM) or the number of the Gaussian densities in the semi-continuous HMM (SCHMM), and the delay observation matrix in the DHMM or the combination of the mixture Gaussian distributions in the SCHMM. How to initialize these parameters is very crucial to the precision of the modeling and prediction of random delays. In this paper, the entropy and cluster based initialization methods are proposed to obtain the optimal initialization of these parameters. The effectiveness of the proposed methods is demonstrated by some simulation examples.

1. Introduction

The feedback control systems, in which the components (such as sensors, controllers and actuators) are spatially distributed and connected via digital communication networks, are called networked control systems (NCSs). Compared with traditional point-to-point systems, the introduction of networks into control systems brings about many advantages including lower cost, reduced weight and power, easier installation and maintenance, and higher reliability and flexibility. So, NCSs have been finding applications in many areas such as vehicle industry, teleoperation system, intelligent manufacture, remote surgery, and power system.

However, due to the inherent network-limited bandwidth, the insertion of communication networks into feedback control loops has inevitably given rise to some new challenging problems, such as random delay, packet dropout, and packets disordering. These problems all might be the potential causes for the performance degradation or even the instability of NCSs. During the past decades, many studies of these problems have been carried out by both the control and the communication communities, see [10,21,39,43,46,47] and references therein. In general, packet dropout means that the delay of the packet transmission over networks is infinite. Packets disordering occurs when the delays of the packets transmission over networks are different, which results in that the packet sent earlier arrives at the destination node later, or vice versa. It

---

[*] Corresponding author at: School of Electrical Engineering, Anhui Polytechnic University, No. 8, Beijing Road, Wuhu, Anhui, PR China. Tel.: +86 18205538515.

E-mail address: ygetoby@mail.ustc.edu.cn (Y. Ge).

http://dx.doi.org/10.1016/j.ins.2016.05.013

can be seen that packet dropout and packets disordering are mainly caused by the randomness of delays. So, random delay is the main problem and challenge in NCSs.

There are mainly two kinds of random delays in NCSs. One is the sensor-to-controller delay (SC delay) in the backward network channel, and the other is the controller-to-actuator delay (CA delay) in the forward network channel. Random delays are the major causes for the performance deterioration and potential instability of NCSs. In order to compensate the random delays, it is often necessary to establish the mathematical model of the random delays before compensation.

During the early stage of the NCSs research, it was difficult to obtain the distribution characteristics of the random delay, so the random delay was simply modeled as a constant. Based on the constant delay model, the NCS was transformed into a deterministic system, which made it feasible for many existing deterministic control methods to be applied to NCSs. This model was often realized by setting first-in-first-out buffers at the controller node to store the sensor measurements and at the actuator node to store the controller outputs. The sizes of these two buffers were determined by the upper bounds of SC and CA delays, respectively. Thus, both SC and CA delays were modeled as two constant values, and the NCS turned into a deterministic system [28,29]. Under the constant delay model, some conventional deterministic control methodologies were used to retrieve the stability of the NCSs with random delays [18,31]. The constant delay model provides a simple and effective measure to deal with random delays. Especially for the NCS closed over a switched Ethernet, the random delay is relatively short and changes little, so it can be intuitively regarded as a constant. Nevertheless, the constant delay model tends to take the upper bound of the random delays as the constant value. Consequently, the random delay is artificially enlarged and then the system performance becomes degraded, or, even worse, the system stability margin decreases so much that the system becomes unstable, which has been proved in [12].

In real NCSs, delays are usually random since they are affected by many stochastic factors (e.g., network load, nodes competition, network congestion). In this situation, the constant delay model and the corresponding deterministic control methodologies could hardly meet the requirement of the system performance. Thus, the stochastic delay model was introduced and developed for modeling the random delays in NCSs. When the random delays are independent of each other, each delay is treated as a mutually independent stochastic variable and its distribution is described by a stochastic function. With this model, stochastic (optimal) control approaches were used to investigate the NCSs [13,30,42]. The stochastic delay can also be transformed into the uncertainty (or disturbance) of NCSs, and then a robust controller was designed to guarantee the robust stability and robust performance of NCSs [17,19,45]. Based on the stochastic delay model, some predictive control strategies were also adopted to guarantee the stability of the NCSs with random delays [23,24,38]. As for nonlinear and uncertain NCSs with random delays, the systems were modeled as Takagi–Sugeno fuzzy systems and then were stabilized through designing robust controllers [16,36]. When there are a large number of actuators and sensors but in any time interval only a part of them can be activated, control with sensors/actuators assigned by Markov chains was investigated in [9,27] where results were given in terms of the delay bounds and the transition probabilities of the Markov chains. Nevertheless, stochastic delays are not always mutually independent. Sometimes, there are some probabilistic dependencies (such as Markov chain) among delays. For the past few years, a lot of effort has been put on the research about Markov chain-based modeling and compensating methods for stochastic delays in NCSs. These methods can be divided into two categories: one considering only SC delays [11] (or CA delays [22]) and the other considering both SC delays and CA delays [33,35,41,48]. In [33,41], the SC delay and the CA delay were lumped together as a single delay, and then were modeled as a single Markov chain. In [35,48], the SC delay and the CA delay were modeled as two different Markov chains. Under the Markov chain-based delay model, the NCS is often modeled as a Markovian jump linear system (MJLS), and then many control methodologies (e.g., robust control, predictive control, fuzzy control) can be used to stabilize the NCS with random delays.

Recently, hidden Markov models (HMMs) have been introduced from other research areas (such as fault diagnosis in [20,40,44]) to NCSs (such as characterization of channel behavior in [2]). Especially, in [3,6,7,14,15,26,32], HMMs were successfully used to model random delays of NCSs. This modeling method is based on the fact that the randomness of delays is mainly due to some stochastic network factors, such as network load, nodes competition, and network congestion. These factors can be combined into an abstract and hidden variable named network state. Along with each packet transmission over the network, the network state will jump from one mode to another following a Markov chain. The network state determines the distribution of random delays. This kind of relationship between the network state and the random delays is referred as an HMM. Different from the Markov chain-based delay model in which the current delay is governed by the previous delay, the current delay in the HMM-based delay model is only governed by the current network state. Seen from this point, the HMM-based delay model reveals the essential generation mechanism of random delays.

It is worthy to notice that both the Markov chain-based delay models in [11,22,33,35,41,48] and the HMM-based delay models in [3,6,7,14,15,26,32] consider the random delay as a discrete stochastic variable. In the Markov chain-based delay models, the random delay jumps within a discrete Markovian state space. In the HMM-based delay models, the random delay is mapped to a discrete observation space through scalar quantization [3,6,7]. That is to say, the HMM used for delay modeling is strictly discrete HMM (DHMM). But actually, the random delay can take any value from its acceptable interval, which means that the random delay itself is not strictly discrete. So, the scalar quantization used in the DHMM will inevitably reduce the accuracy of the HMM-based delay model, and further affect the accuracy of prediction and compensation of random delays. In order to solve this problem, the semi-continuous HMM (SCHMM) was proposed in [5] to model the random delays in NCSs. This model is based on the fact that the random delays under any network state usually follow a Gaussian mixture distribution [32]. In this model, the random delays can be directly used to establish the delay model