国外电子信息精品著作（影印版）

无线网络基础控制

Wireless Networking Based Control

Sudip K. Mazumder

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内 容 简 介

本书从理论和实践的角度，深入探讨了无线网络控制技术的核心概念以及无线网络信息交换处理等问题，并提出了一系列严谨的解决方法。本书适合相关专业高年级本科生以及研究生使用。

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《国外电子信息精品著作》序

20 世纪 90 年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近 30 本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是 2005 年后出版的，力求" 层次高、内容新、参考性强"。在内容和形式上都体现

了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王越

中国科学院院士

中国工程院院士

2006 年 12 月

Preface

Wireless networking is gaining significant momentum in several areas of application due to advantages encompassing mobility, reconfigurability, easy commissioning, and spatio-temporal sensing. While initial focus of wireless networking has been on communication and sensing alone, a new field now has emerged that uses the same communication channel for enabling network control. This leads to several interesting issues and possibilities that are not typically encountered in traditional wire-based network control. This book will emphasize on and outline some of those issues from the standpoints of both theory and applications with focus on the core theme of control using wireless network and control of the information exchanged over the wireless network. Broadly, the topics covered in this book encompass the following:

- Robust stabilization of wireless network control systems in the presence of delays, packet drop out, fading
- State estimation over wireless network under random measurement delay
- Distributed optimization algorithm for addressing feedback delay and network-throughput tradeoff in wireless control-communication network
- Cyber-physical control over wireless sensor and actuator networks
- Estimation of a dynamical system over a wireless fading channel using Kalman filter
- Control over wireless multi-hop networks based on time-delay and finite spectrum assignment
- Position localization in wireless sensor networks
- Cross-layer optimized-based protocols for control over wireless sensor networks
- Rendezvous problem and consensus protocols for application in control of distributed mobile wireless networks
- Redeployment control of mobile sensors for enhancing wireless network quality and channel capacity
- Design of IEEE 802.15.4-based performance-metrics-optimizing distributed and adaptive algorithms and protocols for wireless control and monitoring applications
- Coordinated control over low-frequency-radio-based ad-hoc underwater wireless communication network

It is my sincere hope that, by providing an overview on important, interesting, and relevant issues related to wireless network-based control, this book, which represents the work of motivated researchers, will provide a great service to the community and create greater interest in this rapidly growing field.

Chicago, Illinois, USA Sudip K. Mazumder

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Contents

Chapter 1
Implementation Considerations For Wireless Networked Control Systems

Payam Naghshtabrizi and João P. Hespanha

Abstract We show that delay impulsive systems are a natural framework to model wired and wireless NCSs with variable sampling intervals and delays as well as packet dropouts. Then, we employ discontinuous Lyapunov functionals to characterize admissible sampling intervals and delays such that exponential stability of NCS is guaranteed. These results allow us to determine requirements needed to establish exponential stability, which is the most basic Quality of Performance (QoP) required by the application layer. Then we focus on the question of whether or not the Quality of Service (QoS) provided by the wireless network suffices to fulfill the required QoP. To answer this question, we employ results from real-time scheduling and provide a set of conditions under which the desired QoP can be achieved.

Keywords Network control system · Quality of service · Quality of performance · Lyapunov functional · Delay · Scheduling · Control · Sampling · System

1.1 Introduction

Network Control Systems (NCSs) are spatially distributed systems in which the communication between sensors, actuators, and controllers occurs through a shared band-limited digital communication network, as shown in Fig. 1.1. There are two types of NCSs in terms of medium used at the physical layer: wired and wireless. Wired NCSs have been used widely in automotive and aerospace industry [14] to reduce weight and cost, increase reliability and connectivity. Particularly drive-by-wire and fly-by-wire systems have shown a high penetration rate in these industries. In wireless NCSs, the communication relies on the wireless technology and it has been finding applications in a broad range of areas that in which it is difficult or expensive to install wire, such as mobile sensor networks [17], HVAC systems [1], automated highway, and unmanned aerial vehicles [18].

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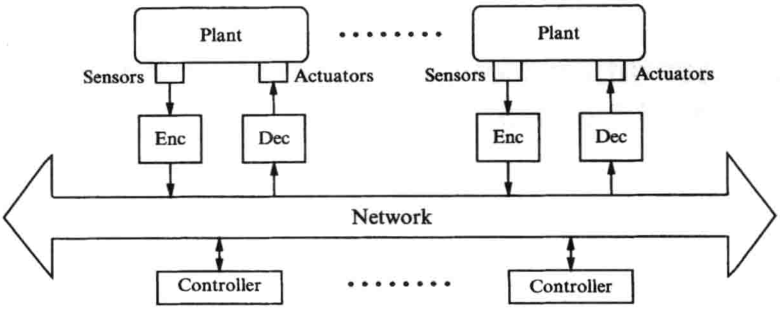

Fig. 1.1 General NCS architecture

In both the wired and wireless domains, use of a shared network – in contrast to using several dedicated independent connections – introduces new challenges to NCSs [7]. However, the reduced channel reliability and limited bandwidth that characterize the wireless domain require special care. In this paper, we mainly focus on wireless NCSs, although most of the results presented are also applicable to wired NCSs. Traditional control theory assumes the feedback data to be accurate, timely, and lossless. These assumptions do not hold for wireless NCSs and the following factors have to be considered:

Sampling and Delay. To transmit a continuous-time signal over a network, the signal must be sampled, encoded in a digital format, transmitted over the network, and finally the data must be decoded at the receiver side. This process is significantly different from the usual periodic sampling in digital control. The overall *delay* between sampling and eventual decoding at the receiverside/end can be highly variable because both the network access delays (i.e., the time it takes for a shared network to accept data) and the transmission delays (i.e., the time during which data are in transit inside the network) depend on highly variable network conditions, such as congestion and channel quality. In some NCSs, the data transmitted are time-stamped, which means that the receiver may have an estimate of the delay's duration and take appropriate corrective action.

Packet dropout. Another significant difference between NCSs and standard digital control is the possibility that data may be lost while in transit through the network. Typically, *packet dropouts* result from transmission errors in physical network links (which is far more common in wireless than in wired networks) or from buffer overflows due to congestion. Long transmission delays sometimes result in packet reordering, which essentially amounts to a packet dropout if the receiver discards "outdated" arrivals.

Systems architecture. Figure 1.1 shows the general architecture of an NCS. In this figure, the *encoder* blocks map measurements into streams of "symbols" that can be transmitted across the network. Encoders serve two purposes: they decide *when* to sample a continuous-time signal for transmission and *what* to send through the network. Conversely, the *decoder* blocks perform the task of mapping the streams of symbols received from the network into continuous actuation signals. One could

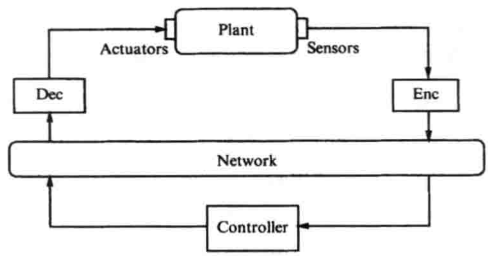

Fig. 1.2 Single-loop NCS

also include in Fig. 1.1 encoding/decoding blocks to mediate the controllers' access to the network. Throughout this paper, the encoder is simply a sampler and the decoder is a hold. However, in Sect. 1.3.1.3 we will consider more sophisticated encoder/decoder pairs.

Most of the research on NCSs considers structures simpler than the general one depicted in Fig. 1.1. For example, some controllers may be collocated (and therefore can communicate directly) with the corresponding actuators. It is also often common to consider a single feedback loop as in Fig. 1.2. Although considerably simpler than the system shown in Fig. 1.1, this architecture still captures many important characteristics of NCSs, such as bandwidth limitations, variable communication delays, and packet dropouts. In this paper, we only consider linear plants and controllers; however, some of the results can be extended to nonlinear systems [11].

In Sects. 1.2 and 1.3, we show that delay impulsive systems provide a natural framework to model (wireless) NCSs with variable sampling intervals and delays as well as packet dropouts. Then, we employ discontinuous Lyapunov functionals to derive a condition that can be used to guarantee stability of the closed-loop NCS. This condition is expressed in the form of a set of LMIs that can be solved numerically using software packages such as MATLAB. By solving these LMIs, one can characterize admissible sampling intervals and delays for which exponential stability of the NCS is guaranteed.

From a networking perspective, the NCS is implemented using the usual layered architecture consists of application layer, network layer, MAC layer and physical layer [10]. From this perspective, our goal is to determine under what conditions the network can provide stabilization, which is the most basic form of Quality of Performance (QoP). In essence, the stability conditions place requirements on the Quality of Service (QoS) that the lower layers need to provide to the application layer to obtain the desired QoP.

Section 1.4 is focused precisely on determining conditions under which the network provides a level of QoS that permits the desired application layer QoP. We review different real-time scheduling policies and identify the ones implementable on wireless NCSs. Among the discussed policies, the most desirable is Earliest Deadline First (EDF) because it has the advantage of being a dynamic algorithm that can adapt to changes in the wireless network. For EDF scheduling, we provide a set of conditions, often known as scheduling tests in real-time literature, that when satisfied, ensures the desired QoS of wireless NCS. Finally, in Sect. 1.5, we address the question of how to implement EDF scheduling policy on LAN wireless NCSs.

Notation. We denote the transpose of a matrix P by P'. We write $P > 0$ (or $P < 0$) when P is a symmetric positive (or negative) definite matrix and we write a symmetric matrix $\begin{bmatrix} A & B \\ B' & C \end{bmatrix}$ as $\begin{bmatrix} A & B \\ * & C \end{bmatrix}$. We denote the limit from below of a signal $x(t)$ by $x^-(t)$, i.e., $x^-(t) := \lim_{\tau \uparrow t} x(\tau)$. Given an interval $I \subset \mathbb{R}$, $B(I, \mathbb{R}^n)$ denotes the space of real functions from I to $\mathbb{R}^n$ with norm $\|\phi\| := \sup_{t \in I} |\phi(t)|, \phi \in B(I, \mathbb{R}^n)$, where $|.|$ denotes any one of the equivalent norms in $\mathbb{R}^n$. x_t denotes the function $x_t : [-r, 0] \to \mathbb{R}^n$ defined by $x_t(\theta) = x(t + \theta)$, and r is a fixed positive constant.

1.1.1 Related Work

To reduce network traffic in NCSs, significant work has been devoted to finding maximum allowable transmission interval τ_{MATI} that are not overly conservative (see [7] and references therein). First, we review the related work in which there is no delay in the control loop. In [21], τ_{MATI} is computed for linear and nonlinear systems with Round-Robin (static) or Try-Once-Discard (TOD) (dynamic) protocols. Nesic et al. [15, 16] study the input–output stability properties of nonlinear NCSs based on a small gain theorem to find τ_{MATI} for NCSs. Fridman et al. [6], Naghshtabrizi et al. [13], Yue et al. [24] consider linear NCSs and formulate the problem of finding τ_{MATI} by solving LMIs. In the presence of variable delays in the control loop, [5, 12, 25] show that for a given lower bound $\tau_{\min}$ on the delay in the control loop, stability can be guaranteed for a less conservative τ_{MATI} than in the absence of the lower bound.

Ye et al. [23] introduced prioritized Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for mixed wireless traffic, in which some of the network capacity is devoted to real-time control and monitoring. They introduced and validated several new algorithms for dynamically scheduling the traffic of wireless NCSs. We use a similar MAC protocol for the wireless network (more precisely wireless LAN networks). Liu and Goldsmith [10] presented a cross layer codesign of network and distributed controllers and addressed the tradeoff between communication and controller performance. The designed controller is robust and adaptive to the communication faults, such as random delays and packet losses, while the network should be designed with the goal of optimizing the end-to-end control performance. Tabbara et al. [19] defined the notion of persistently exciting scheduling protocols and showed that it is a natural property to demand, especially for the design of wireless NCSs. Xia et al. [22] developed a cross layer adaptive feedback scheduling scheme to codesign control and wireless communications. The authors identified that the Deadline Miss Ratio (DMR) is an important factor to determine the sampling intervals. Consequently, the authors proposed a sampling algorithm that is the minimum of a function of DMR and maximum sampling period.

1.2 Delay Impulsive Systems: A Model For NCSs With Variable Sampling And Delay, SISO Case

Consider the system depicted in Fig. 1.3. The LTI process has a state space model of the form $\dot{x}(t) = Ax(t) + Bu(t)$, where x, u are the state and input of the process. At the sampling time s_k, $k \in \mathbb{N}$ the process state, $x(s_k)$ is sent to update the process input to be used as soon as it arrives and it should be kept constant until the next control command update. We denote the k*-th input update time* by t_k, which is the time instant at which the k-th sample arrives at the destination. In particular, denoting by τ_k the total delay that the k-th sample experiences in the loop, then $t_k := s_k + \tau_k$. The resulting closed-loop system can be written as

$$\dot{x}(t) = Ax(t) + Bx(s_k), \qquad t \in [s_k + \tau_k, s_{k+1} + \tau_{k+1}),\ k \in \mathbb{N}. \tag{1.1}$$

We write the resulting closed-loop system (1.1) as an impulsive system of the form

$$\dot{\xi}(t) = F\xi(t), \quad t \neq t_k,\ \forall k \in \mathbb{N} \tag{1.2a}$$

$$\xi(t_k) = \begin{bmatrix} x^-(t_k) \\ x(s_k) \end{bmatrix}, \quad t = t_k,\ \forall k \in \mathbb{N}, \tag{1.2b}$$

where

$$F := \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix}, \quad \xi(t) := \begin{bmatrix} x(t) \\ z(t) \end{bmatrix}.$$

The overall state of the system ξ is composed of the process state, x, and the *hold state*, z where $z(t) := x(s_k),\ t \in [t_k, t_{k+1})$.

1.2.1 NCSs Modeled By Impulsive Systems

Equations (1.2) or (1.1) can be used to model NCSs in which a linear plant $\dot{x}_p(t) = A_p x_p(t) + B_p u_p(t)$ where $x_p \in \mathbb{R}^n$, $u_p \in \mathbb{R}^m$ are the state and the input of the plant, respectively, is in feedback with a static feedback gain K. At time s_k, $k \in \mathbb{N}$ the plant's state, $x(s_k)$, is sent to the controller and the control command $Kx(s_k)$ is sent back to the plant to be used as soon as it arrives and it should be kept constant

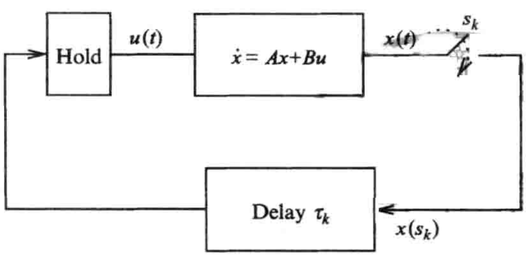

Fig. 1.3 An abstract system with delay τ_k, where $u(t) = x(s_k)$ for $t \in [s_k + \tau_k, s_{k+1} + \tau_{k+1})$

until the next control command update. In particular, denoting by τ_k the total delay that the k-th sample experiences in the loop, then $t_k := s_k + \tau_k$. Then the closed-loop system can be written as (1.2) with $x := x_p,\ A := A_p,\ B := B_p K$.

Remark 1. Note that we only index the samples that reach the destination, which enables us to capture sample drops [24]. Consequently, even if the sampling intervals are constant, because of the sample drops the closed-loop should still be seen as a system with variable sampling intervals.

1.2.2 Exponential Stability Of SISO NCSs

In this section, we provide conditions in terms of LMIs to guarantee exponential stability of the linear delay impulsive system in (1.2) which models the NCS described in Sect. 1.2.1. The system (1.2) is said to be (globally uniformly) exponentially stable over a given set $\mathscr{S}$ of sampling-delay sequences, if there exist $c, \lambda > 0$ such that for every $(\{s_k\}, \{\tau_k\}) \in \mathscr{S}$ and every initial condition x_{t_0} the solution to (1.2) satisfies $|x(t)| \leq c\|x_{t_0}\|e^{-\lambda(t-t_0)},\ \forall t \geq t_0$.

In this paper, we are mostly interested in class $\mathscr{S}$ of admissible sampling-delay sequences characterized by three parameters: The maximum interval of time τ_{MATI} between a signal is sampled and the *following* sample arrives at the destination; the minimum delay $\tau_{\min}$; and the maximum delay $\tau_{\max}$. Specifically, to be consistent with the results in [12, 25], and [5], we characterize the admissible set $\mathscr{S}$ of sampling-delay sequences $(\{s_k\}, \{\tau_k\})$ such that

$$s_{k+1} + \tau_{k+1} - s_k \leq \tau_{\text{MATI}}, \qquad \tau_{\min} \leq \tau_k \leq \tau_{\max}. \tag{1.3}$$

Although we adopt the above characterization, (1.3) is not in a convenient form to provide the sampling rule. Another characterization is the admissible set $\bar{\mathscr{S}}$ of sampling-delay sequences $(\{s_k\}, \{\tau_k\})$ such that

$$s_{k+1} - s_k \leq \gamma_{\max}, \qquad \tau_{\min} \leq \tau_k \leq \tau_{\max}, \tag{1.4}$$

which provides an explicit bound on the sampling intervals. Note that if any sampling-delay sequence belongs to $\bar{\mathscr{S}}$, it necessarily belongs to $\mathscr{S}$ provided that $\gamma_{\max} := \tau_{\text{MATI}} - \tau_{\max}$.

The following theorem was proved in [11] based on the Lyapunov functional

$$\begin{aligned} V :=\, & x'Px + \int_{t-\rho_1}^{t} (\rho_{1\max} - t + s)\dot{x}'(s)R_1\dot{x}(s)\mathrm{d}s \\ & + \int_{t-\rho_2}^{t} (\rho_{2\max} - t + s)\dot{x}'(s)R_2\dot{x}(s)\mathrm{d}s + \int_{t-\tau_{\min}}^{t} (\tau_{\min} - t + s)\dot{x}'(s)R_3\dot{x}(s)\mathrm{d}s \\ & + \int_{t-\rho_1}^{t-\tau_{\min}} (\rho_{1\max} - t + s)\dot{x}'(s)R_4\dot{x}(s)\mathrm{d}s + (\rho_{1\max} - \tau_{\min}) \int_{t-\tau_{\min}}^{t} \dot{x}'(s)R_4\dot{x}(s)\mathrm{d}s \\ & + \int_{t-\tau_{\min}}^{t} x'(s)Zx(s)\mathrm{d}s + (\rho_{1\max} - \rho_1)(x-w)'X(x-w), \end{aligned} \tag{1.5}$$