Preface

Feedback control of dynamical systems has benefited from recent development of sensing and actuation nodes with strong local computation capabilities and from the use of digital communication networks for system interconnections. With all these advancements, the detailed analysis of feedback control systems remains an important part of the complex networked control applications. System uncertainties have always been a central issue in control systems. It is critical to address uncertainty effects on the stability and performance of control systems when it is not possible to obtain continuous feedback measurements. Such is the case in Networked Control Systems (NCS) where the communication channel is of limited bandwidth and it is also shared by different subsystems.

This book presents a specific framework, the Model-Based Networked Control Systems (MB-NCS) framework, for design and analysis of NCS. This approach places special emphasis on model uncertainties. Detailed development of the basic results is provided and a number of important extensions are addressed; multiple examples are given as well. Using the model-based approach we introduce several types of architectures and control strategies that aim at improving performance in NCS. The overall performance of NCS considers the appropriate use of network resources, network bandwidth in particular, in addition to the desired response of the system being controlled. The plant model is used at the controller/actuator side to approximate the plant behavior so that the sensor is able to send data at lower rates, since the model can provide information to generate appropriate control inputs while the system is running in open-loop mode.

It is assumed that readers are familiar with the basics concerning Linear Systems. This book is intended for graduate students, researchers, and practitioners with interest in the study of control over networks, distributed systems, and control with communication constraints. These readers typically have the background or have completed a graduate-level course on Linear Systems.

In this book we take the MB-NCS framework, from its initial configuration and apply it to many complex applications. Different basic problems in control theory are studied in the context of NCS using the model-based approach. The general idea is that, in the absence of continuous feedback, the available knowledge about the system dynamics provides a useful tool for designing and implementing simple, yet robust controllers that provide good performance in the presence of multiple communication constraints. The problems and scenarios studied in this book provide examples of a large number of potential applications in which the MB-NCS framework brings an innovative advantageous perspective in the analysis and design of control systems.

This book is divided in two parts. Part I focuses on the stability aspects of MB-NCS while considering systems with different types of dynamics: linear, nonlinear, continuous-time, and discrete-time systems. Different network constraints are also considered in Chaps. 2–8 of Part I such as limited bandwidth, network delays, and signal quantization.

Part II, Chaps. 9–14, deals mainly with the performance of MB-NCS. In the following we introduce the main topics covered in each chapter of this book.

Description of Chapter Contents

Chapter 1 introduces Networked Control Systems and several approaches used for analysis of this type of control systems. Detailed literature review of prior and relevant work is addressed in this chapter. Particular approaches are emphasized in Chap. 1: model-based frameworks and event-triggered control.

Part I: Chaps. 2–9

Chapter 2 presents and explains with great detail the MB-NCS framework. The contents of this chapter are fundamental in being able to follow the material in the remaining chapters. Once the main contents of Chap. 2 have been studied there is no strict order for the rest of this book. Besides presenting the MB-NCS framework, Chap. 2 offers the first main results related to this approach which are built on one of the most basic cases we study in the book: state feedback with periodic communication. This chapter considers both continuous-time and discrete-time systems. Recent additional results are provided at the end of the chapter.

In Chap. 3 two important problems are studied: output feedback and network induced delays. Both continuous-time and discrete-time systems are considered. One of the main important lessons of this chapter is that the MB-NCS framework can be applied to many different control problems; the problems in this chapter are two of the main extensions when considering networked systems in general. In the output feedback problem, we introduce a state observer and the overall system now contains three subsystems: plant, model, and observer. A similar approach is used for the network induced delay problem; a third subsystem is introduced that helps in obtaining a current estimate of the system state based on delayed measurements.

The contents of Chap. 4 analyze the stability and the selection of update periods and other network parameters when intermittent feedback is used along with the model-based architecture previously introduced. Two intermittent feedback approaches are described in this chapter. In the first approach the networked system operates in two different modes: closed-loop and open-loop mode. The closed-loop mode of operation requires a strong assumption concerning the ability of transmission of continuous signals over the network. To relax this assumption, we describe a second intermittent feedback approach that operates using two different update rates. The faster update rate now takes the place of the closed-loop mode of operation. Stability results are provided for continuous-time and discrete-time systems and for the state and output feedback cases.

An important aspect present in many networked systems is considered in Chap. 5, namely, time-varying transmission intervals. In many implementations access to the communication channel may be random and strict periodic transmission of information may not be possible. This chapter provides different stability results first when no statistical information about the update periods is known and then when the update periods follow a prescribed statistical distribution.

Chapter 6 also presents an approach for updating the model using time-varying intervals under event-triggered control. The main difference with respect to Chap. 5 is that in event-triggered control the main purpose in using nonperiodic transmission intervals is to adapt the update instants according to the current conditions of the system. Chapter 6 provides details on how to implement event-triggered techniques in the MB-NCS framework. It also describes different strategies that provide different results and varying performance. This approach is also used for systems subject to network induced delays.

The MB-NCS framework is used in Chap. 7 to consider nonlinear systems. Continuous-time systems are considered first and the focus is on finding stability conditions under periodic transmissions. This chapter also considers discrete-time systems using models described by input–output representations; event-triggered control techniques are used in this case.

The work in Chap. 8 addresses another important constraint in NCS, namely, signal quantization. Since measurements need to be transmitted over digital communication networks, they need to be quantized in order to be represented in digital form. This chapter provides a thorough analysis of MB-NCS with quantization of measurements. Different types of quantizers are discussed and the corresponding results provide the design parameters needed in this case which are the quantization parameters and the update intervals. The joint effect of quantization and network delays is also studied and similar results are provided.

Part II: Chaps. 9–14

Two main topics with respect to the optimal performance of MB-NCS are discussed in Chap. 9. The first one is related to the implementation of event-triggered control techniques for systems that operate optimally assuming continuous feedback. The second topic is concerned with the optimal design (nonperiodic in general) of transmission instants. In the latter case we consider finite-horizon optimal control problems and use Dynamic Programming in order to find optimal decisions concerning transmission of state updates based on the current behavior of the system.

Chapter 10 provides a detailed analysis of the performance of continuous-time MB-NCS. Two different performance metrics are used to quantify the performance of model-based control systems with periodic updates. Design of optimal controllers is also addressed in this chapter, under the assumption of periodic transmission.

Reference input tracking with limited feedback and using the model-based approach is analyzed in Chap. 11. This chapter deals with continuous-time systems using periodic updates and conditions on the update period are given in order to provide a bound on the tracking error. In this chapter we also consider linear discrete-time systems described by input–output representations. Dynamic controllers are considered in this case. One of the advantages of using this type of system representation is that common types of uncertainties such as additive and multiplicative uncertainties can be considered. This implies that knowledge of the system dimension is not assumed and available models with different dimensions than the real system can be used for both controller design and for implementation in the MB-NCS framework.

In Chap. 12 the model of the system is not considered to be fixed. Parameter estimation algorithms are described in the context of networked systems and used to upgrade the model. In other words, by measuring the current response of the system it is possible to find new parameters that better approximate the real values than the initial model parameters. Systems with measurement noise in addition to parameter uncertainties are considered as well. Different types of applications are described where the algorithms for estimation of parameters described in this chapter are of great use. These applications include switched systems, fault identification, and systems with input disturbances.

Chapter 13 studies multirate systems. Several problems are discussed. The first one corresponds to the case where multiple sensors are used to measure the state of an uncertain system. These sensors represent different nodes in an NCS attempting to send their measurements to a centralized controller. The problem considered is to find transmission periods, not necessarily the same for all nodes, which guarantee stability of the networked system. The second problem considers a two-channel networked system where the connection from controller to actuator is implemented using the communication network.

Distributed systems are studied in Chap. 14. Two approaches are considered. First we consider periodic updates for discrete-time systems and discuss both the single-rate and the multirate implementations. Then we consider continuous-time systems using event-based updates. For this problem, we study both centralized and decentralized controller design and implementation.

The Appendix collects different results concerning vector and matrix norms, Jordan canonical forms, similarity transformations, and other linear algebra concepts. It also contains basic control theory definitions and other results about linear systems.

Finally, the appendix provides a summary of definitions and theorems broadly used in Lyapunov analysis.

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