

Xi-Ming Sun
Kun-Zhi Liu
Xue-Fang Wang
Andrew R. Teel

Control and Optimization Based on Network Communication

 Springer

Control and Optimization Based on Network Communication

Xi-Ming Sun · Kun-Zhi Liu · Xue-Fang Wang ·
Andrew R. Teel

Control and Optimization Based on Network Communication

 Springer

Xi-Ming Sun
School of Control Science and Engineering
Dalian University of Technology
Dalian, Liaoning, China

Kun-Zhi Liu
School of Control Science and Engineering
Dalian University of Technology
Dalian, Liaoning, China

Xue-Fang Wang
School of Control Science and Engineering
Dalian University of Technology
Dalian, Liaoning, China

Andrew R. Teel
Department of Electrical and Computer
Engineering
University of California, Santa Barbara
Santa Barbara, CA, USA

ISBN 978-981-19-9533-0

ISBN 978-981-19-9534-7 (eBook)

<https://doi.org/10.1007/978-981-19-9534-7>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2023

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd. The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

With the rapid development of science and technology, networks play an important role in control systems. Typically, in a control system, the plant and the controller may communicate via a network. Such systems are called networked control systems and they have received significant attention in the literature. The introduction of a network has many advantages such as low cost, easy installation, and maintenance. However, a network also introduces some imperfections such as varying sampling, transmission delays, transmission protocols, packet losses, and so on. Besides, the network may also suffer from network attacks such as Denial of Service attacks. These imperfections may degrade the system performance and even make the closed-loop systems unstable. Therefore, it is necessary to investigate the effect of these imperfections on the stability and performance of control systems in a quantitative manner.

The content of this book consists of two parts. The first part aims at proposing modeling and analyzing approaches for network-based control systems under different problem settings. Model-based event-triggered transmission strategies are proposed to reduce the data transmissions in the network. We also consider the stability problem for networked control systems in the presence of stochastic noise and stochastic detecting instants. For all of these cases, hybrid models are established and Lyapunov functions are constructed. The second part first investigates the distributed unconstrained optimization problem which is solved over a network communication topology. The network may be destroyed by persistent attackers that result in communication failures. A distributed switching algorithm is proposed and a hybrid model is established to analyze stability. Then, the proposed method is extended to constrained aggregative games which are subject to unknown time-varying disturbances and unmodeled terms, and the communication topology is also influenced by attacks. This book provides a unifying framework to understand the complex dynamics of network-based control systems. The content is appropriate

for students, control engineers, and scientists who are interested in network-based control and optimization problems.

Dalian, China
Dalian, China
Dalian, China
Santa Barbara, USA

Xi-Ming Sun
Kun-Zhi Liu
Xue-Fang Wang
Andrew R. Teel

Acknowledgements

We would like to express our gratitude to Prof. Wei Wang in Dalian University of Technology for his support. This book benefits from the support of many organizations. We are especially grateful to the Dalian University of Technology for its great support. We also acknowledge the support of research grants, including the National Key R&D Program of China under Grant 2018YFB1700102, National Natural Science Foundation of China under Grants 08120002, 61890921, 61773086 and 61803070, and Fundamental Research Funds for the Central Universities with Grant Nos. DUT21RC(3)040. We would also like to express our gratitude to the University of California, Santa Barbara; much of the research contained in this book was completed at this beautiful university.

Contents

1	Introduction	1
1.1	Network-Based Control	1
1.2	Basic Knowledge About Hybrid Systems	3
1.2.1	Hybrid Dynamical Systems	3
1.2.2	Stochastic Hybrid Systems	5
Part I Modeling and Stability Analysis for Networked Control Systems		
2	Model-Based Event-Triggered Control for Distributed Networked Control Systems	11
2.1	Introduction	11
2.2	Model Description	12
2.3	Design of Triggering Function and Stability Analysis	17
2.4	Distributed Model-Based Dynamic Event-Triggered Control	21
2.5	Example and Simulation	27
2.6	Conclusions	30
3	Periodic Event-Triggered Control for Decentralized Linear Systems with Quantization Effects and External Disturbances	33
3.1	Introduction	33
3.2	Preliminaries	34
3.3	Model Description	34
3.4	Stability and Performance	38
3.5	Example	43
3.6	Conclusions	46
4	Event-Triggered Stabilization for Nonlinear Systems by Uniting the Local and Global Controller	47
4.1	Introduction	47
4.2	Motivation Example and Problem Description	48

4.3	Hybrid Event-Triggered Stabilization	49
4.4	Example Studies	57
4.5	Conclusions	63
5	Event-Triggered Control for Nonlinear Systems With Stochastic Dynamics, Transmission Instants and Protocols	65
5.1	Introduction	65
5.2	Model Description	66
5.3	Stability Analysis	69
5.4	Example Studies	73
	5.4.1 Linear Systems	73
	5.4.2 Nonlinear Systems	75
5.5	Conclusions	78
 Part II Distributed Optimization with Network Communication		
6	Stability Analysis of Distributed Convex Optimization Under Persistent Attacks	81
6.1	Introduction	81
6.2	Knowledge About Graph	82
6.3	Problem Formulation	82
6.4	Stability Analysis of the Algorithm Under Attacks	85
6.5	Stability Analysis	88
	6.5.1 A Construction of Hybrid System	89
	6.5.2 An Explicit Lyapunov Function Proof of Convergence	90
6.6	Example	91
6.7	Conclusions	94
7	Distributed Robust Nash Equilibrium Seeking for Aggregative Games Under Persistent Attacks	95
7.1	Introduction	95
7.2	Problem Formulation and Model Description	96
	7.2.1 Game Formulation	96
	7.2.2 Physical Model Description	97
	7.2.3 Networked Attack Descriptions	98
7.3	Distributed Algorithm Design	99
7.4	Stability of the Hybrid Algorithm	103
7.5	Proofs of the Main Theorems	105
7.6	Example	111
7.7	Conclusions and Future Work	113
 References		115

Notations

\mathbb{R}^n	n-dimensional Euclidean space
$ \cdot $	2-norm of a matrix
\mathbb{B}	unit ball
\mathbb{B}_r	ball with radius r
$\langle x, y \rangle$	inner product of two vectors
x^T	transpose of vector x
$col(x, y)$	$(x^T, y^T)^T$
\mathbb{Z}	set of integers
$\mathbb{R}_{\geq 0}$	$[0, \infty)$
$\mathbb{R}_{\leq 0}$	$(-\infty, 0]$
$\mathbb{Z}_{\geq 0}$	set of non-negative integers
$\mathbb{Z}_{\leq 0}$	set of non-positive integers
$\mathbb{R}_{> 0}$	$(0, \infty)$
$\mathbb{Z}_{> 0}$	set of positive integers
$\mathbb{R}_{\geq 0}^N$	$\{(x_1, \dots, x_N)^T \mid x_i \in \mathbb{R}_{\geq 0}\}$
$\mathbb{Z}_{\geq 0}^N$	$\{(x_1, \dots, x_N)^T \mid x_i \in \mathbb{Z}_{\geq 0}\}$
$ x _{\mathcal{W}}$	distance of a point x to a set \mathcal{W}
$\mathbf{0}_n$	n -dimensional zero matrix
I_n	n -dimensional identity matrix
$\mathbf{0}$	zero vector with appropriate dimension
$\mathbf{1}_n$	n -dimensional vector with all elements being 1
$diag\{M_1, \dots, M_N\}$	block diagonal matrix
$\lambda_{max}(P)$	maximal eigenvalue of a positive definite matrix
$\lambda_{min}(P)$	minimal eigenvalue of a positive definite matrix
$A \otimes B$	Kronecker product of matrices A and B
$\overline{\text{con}}\Omega$	closed convex hull of a set
$\overline{\Omega}$	closure of a set
$x + \Omega$	$\{y \mid y = x + z, z \in \Omega\}$
$x \cdot \Omega$	$\{y \mid y = x \cdot z, z \in \Omega\}$
$int(\Omega)$	interior of a set Ω

$S + \varepsilon\mathbb{B}$	$\{x : x _S \leq \varepsilon\}$
$S + \varepsilon\mathbb{B}^\circ$	$\{x : x _S < \varepsilon\}$
S^p	$\{(x_1, \dots, x_p) x_i \in S\}$
$sgn(x)$	$sgn(x) = 1, \text{ for } x > 0, 0, \text{ for } x = 0 \text{ and } -1 \text{ for } x < 0$
$sgn\left((x_1^T, \dots, x_n^T)^T\right)$	$(sgn(x_1), sgn(x_2), \dots, sgn(x_n))^T$
$SGN(x)$	$SGN(x) = 1, \text{ for } x > 0, [-1, 1], \text{ for } x = 0 \text{ and } -1 \text{ for } x < 0$
$SGN\left((x_1^T, \dots, x_n^T)^T\right)$	$(SGN(x_1), SGN(x_2), \dots, SGN(x_n))^T$

Chapter 1

Introduction



1.1 Network-Based Control

Networked control systems refer to control systems in which the plant and the controller communicate via a network channel. Introduction of the network brings some benefits such as low cost, easy installation and maintenance. On the other hand, the network also introduces some imperfections such as varying transmission intervals, varying transmission delays, communication constraints, quantization effects and packet losses. The network may also suffer from various kinds of attacks such as denial-of-service attacks which can block the transmission channels. Therefore, it is necessary to investigate the effects of various kinds of imperfections on stability and performance of the closed-loop systems in a quantitative manner. Besides, in networked control systems, another important problem is how to reduce the data transmissions because the network resources are limited. There are mainly two transmission strategies. One is the time-triggered transmission strategy, which triggers the data transmission periodically, and the other is the event-triggered transmission strategy, which triggers the data transmission based on a triggering condition involving the system state and error variable. The latter has the potential to reduce data transmissions because a transmission happens only when it is necessary.

In networked control systems, there are mainly two modeling approaches. One is the delay system approach, which models the sampled-data control system into an input delay system and then the Lyapunov functional approach is applied to analyze the stability and performance of the resulted closed-loop system. The delay system approach has the advantage of less conservativeness but is often restricted to linear systems. The other modeling approach is the hybrid system approach, which models the networked control system as a hybrid system. The hybrid system approach is more appropriate for nonlinear systems and is flexible enough to model various kinds of complex dynamical systems such as event-triggered control systems.