Asynchronous Control for Networked Systems

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Editors

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Springer

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ISBN 978-3-319-21298-2 ISBN 978-3-319-21299-9 (eBook)
DOI 10.1007/978-3-319-21299-9

Library of Congress Control Number: 2015945570

Mathematics Subject Classification (2010): 93

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Preface

The term ‘networked control system’ (NCS) encompasses a relatively large number of situations and problems. The feature that distinguishes a NCS from a classical control system is the presence of a communication network affecting or inside the loop. New challenges arise as a consequence. In this sense, asynchronous control and, particularly, event-based control, have received an important impulse in the last decade due to its benefits when applied to NCSs, specially on energy-aware devices. Instead of taking periodic actions as in classical control approaches, asynchronous control bases its decisions on the state of the system and, in general, reduces the amount of communication.

The book presents novel results on asynchronous control of NCSs in a concise and clear style that are supported by simulation or experimental examples and it also provides examples of application. The manuscript is written with material collected from articles written by the authors, technical reports, and lectures given to graduate students, in which the ideas have been originally presented together with the formal proofs. Emphasis is laid on the presentation of the main results and the illustration of these results by examples.

The book is mainly aimed at graduate students, Ph.D. students, and researchers in control and communication, as well as practitioners, both from the control engineering community, although it can be followed by a wide range of readers, as only basic knowledge of control theory and sampled data systems is required.

The first chapter gives an introduction to asynchronous control and NCSs, including the main research trends and introducing concepts that have been used through the book. Then, the volume has been structured in two parts. The first part accounts for centralized control schemes, whereas the second block is focused on distributed estimation and control. A summary of each chapter is given next.

Part I Asynchronous Control for Single-Loop Schemes. Centralized Solutions

Chapter 2 focuses on the study of the limit cycles that appear in a control scheme based on a PI controller with an event-based send-on-delta sampling. The processes investigated are integrator processes plus time delay and first- and second-order processes plus time delay, which are of interest because of their frequent use as models in many industrial processes. An algorithm to calculate the limit cycles properties is presented, and then the results obtained in simulations are compared with experiments performed on real plants, such as a distributed solar collector field at the Solar Platform of Almería (PSA, Spain).

Chapter 3 considers a scenario in which the sensor and controller are connected by a bidirectional network. Whenever a fresh measurement is received from the plant, the following sampling instant is decided on the controller following a self-trigger strategy. To do so, the controller includes a model of the plant to generate predictions of the evolution of the states. In order to compute the sampling times, a set of quadratic optimization problems must be solved online.

Chapter 4 presents the analysis and the design of remote controllers for packet-based NCS, following the paradigm of anticipative controllers. The remote controller uses a model of the plant and a basis controller to compute a sequence of future control actions to compensate the effect of delays and packet dropouts. Event-based transmission rules are proposed to save network bandwidth. Different extensions such as disturbance estimators, output measurement, and LTI anticipative controllers are discussed. Finally, the design is evaluated over experimental plants characterized by response-times closed to the network delays.

Chapter 5 is concerned with the design of mixed H_2/H_∞ controllers for networked control systems through the Lyapunov–Krasovskii approach. The main contribution of the method does not lie in the use of novel Lyapunov–Krasovskii functionals or bounding techniques, but in the optimization method that can be used for different functionals and a variety of different constraints on the delay. Furthermore, the chapter investigates an asynchronous sampling approach based on events that allow a reduction of the bandwidth usage and the energy consumption. The relation between the boundedness of the stability region and the threshold that triggers the events is studied. The robustness and performance of the proposed technique is showed by numerical simulations.

Chapter 6 presents a practical algorithm to design networked control systems able to cope with high data dropout rates. The algorithm is intended for application in packet-based networks protocols (Ethernet-like) where data packets typically content large data fields. The key concept is using such packets to transmit not only the current control signal, but predictions on a finite horizon without significantly increasing traffic load. Thus, predictive control is used together with buffered actuators and a state estimator to compensate for eventual packet dropouts. Additionally, some ideas are proposed to decrease traffic load, limiting packet size and media access frequency. Simulation results on the control of a three-tank system are given to illustrate the effectiveness of the method.

Part II Asynchronous Control and Estimation for Large-Scale Plants. Distributed Solutions

Chapter 7 discusses different control strategies of distributed event-based control for linear interconnected systems. From the analytical point of view, two aspects are considered to compare the different existing approaches: Convergence to the equilibria and inter-event times. Later on the chapter, two extensions are presented. The first extension is based on the fact that the frequency of actuation may be high in distributed control schemes if the neighborhood of the subsystem is large, even if each agent is not transmitting so often. To deal with this problem, an error function is defined for the control input and a second set of trigger functions is proposed to deal with this problem, updating the control law when a condition is violated. The second improvement relies on the existence of smart actuators, so that continuous-time signals can be applied instead of constant piecewise signals (ZOH). A model-based control design is proposed in which each agent has knowledge of the dynamics of its neighborhood.

Chapter 8 presents a generalized framework for distributed estimation in sensor networks. A distributed event-based estimation technique based on the stabilizing properties of the predesigned observers is proposed and analyzed, showing the reduction of both energy expenditure and network traffic load due to unnecessary transmissions. The observers's structure is based on both, local Luenberger observers and consensus strategies, which take into account the information that is received from neighboring nodes. Using the same structure, actuation capabilities in the nodes are included, yielding to a control scheme based on state estimation.

Chapter 9 contributed the field of distributed estimation and control with a novel method that allows to design both the controllers and the observers at one common step. The objective is to synthesize stabilizing suboptimal controllers, in the sense that the upper bound of a given cost function is minimized. The reduction of the bandwidth usage is attained exploiting an event-based communication policy between agents. The results have been applied to an experimental plant consisting of a four coupled tank system. The efficiency of the proposed method, in terms of reduction of the traffic and tuning capabilities, is shown.

Chapter 10 extends the results of Chap. 7 for non-reliable networks. Even though event-based control has been shown adequate to reduce the communication to face the problem of reduced bandwidth, network delays and packet losses cannot be avoided. Hence, the consequences of a non-reliable channel are analyzed, and upper bounds on the delay and the number of consecutive packet losses are derived. The design of network protocols is also presented, and simulation examples are given to illustrate the theory.

Chapter 11 is an extension of Chap. 8, and focuses on the following network related issues: delays, packet dropouts and communication policy (time and event-driven). The design problem is solved via linear matrix inequalities and stability proofs are provided. The technique is of application for sensor networks and large-scale systems where centralized estimation schemes are not advisable and energy-aware implementations are of interest. Simulation examples are provided to show the performance of the proposed methodologies.

Chapter 12 deals with the formation control of networked mobile robots as an example of multi-agent systems in which the group of robots achieves a common objective (the formation) by means of distributed control laws and event-based communications. An interactive simulator to emulate this kind of setups has been developed. The distributed event-based control algorithms have also been implemented in a testbed of mobile robots, and the results are presented. A study of the energy consumption and the performance is given.

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May 2015

Acknowledgments

The authors would like to thank a number of people and institutions who have made this book possible. We would like to thank several individuals whose work, either independently or through collaboration, has shaped the contents of the book. Our particular mention is for Pablo Millán, Luis Orihuela, Carlos Vivas, and José Sánchez, who took an active role in the revision of the whole manuscript.

Most of the material included in the book is the result of research work funded by the Spanish Ministry of Economy and Competitiveness under grants DPI2007-61068, DPI2011-27818-C02-02, DPI2012-31303, and DPI2013-44135-R, the European Commission under grant *Feedback Design for Wireless Networked Systems. (FeedNetBack)* (FP7-ICT-2007-2, Contract number: INFSO-ICT-223866), the *Consejera de Innovación, Ciencia y Empresa de la Junta de Andalucía* under grant P09-AGR-4782, and the IV Regional Plan of Scientific Research and Technological Innovation (PRICIT) of the Autonomous Region of Madrid under Project S-0505/DPI/0391. We gratefully acknowledge these institutions for their support. Also our thank to the people of the Automation Engineering, Control, and Robotics (TEP-201) research group of the Universidad de Sevilla.

Finally, the authors thank their families for their support, patience, and understanding of family time lost during the writing of the book.

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Notation

The symbols are chosen according to the following conventions. Matrices are represented by capital letters, and vector and scalars by lower-case letters. The elements of a vector x or a matrix A are $x_1,\ldots,x_n$ and $a_{11},a_{12},\ldots,a_{nm}$, respectively. For a block matrix E, E_{ij} denotes the (i,j) block. Calligraphic letters are generally reserved to sets, like $\mathscr{V}$ or $\mathscr{G}$.

Matrix $A = \mathrm{diag}(a_1,\ldots,a_n)$ is a diagonal matrix with diagonal entries $a_1,\ldots,a_n$. Eigenvalues of a square matrix A are denoted by λ, where $\lambda_{max}(A)$ and $\lambda_{min}(A)$ are the maximum and minimum eigenvalues, respectively.

The absolute value is denoted by $|a|$. The notations $||x||$ and $||A||$ represent the vector or matrix norm. By default, $||\cdot||$ is the 2-norm computed as

$$||x||_2 = \left(\sum_{i=1}^{n} x_i^2\right)^{1/2}$$

$$||A||_2 = \sup_{x\neq 0} \frac{||Ax||_2}{||x||_2} = \sqrt{\lambda_{max}(A^*A)},$$

where A^* is the conjugate transpose of A. We also use the supremum and 1-norms:

$$||x||_\infty = \max_{i=1,\ldots,n} |x_i| \qquad ||A||_\infty = \max_{i=1,\ldots,n} \sum_{j=1}^{m} |a_{ij}|$$

$$||x||_1 = \sum_{i=1}^{n} |x_i| \qquad ||A||_1 = \max_{j=1,\ldots,n} \sum_{i=1}^{m} |a_{ij}|.$$

Finally, a positive definite matrix is denoted by $P > 0$ or $P \succ 0$.

The rest of the symbols can be found in the subsequence.

Indices

$(\cdot)^*$	Conjugate transpose of a matrix
$(\cdot)^{-1}$	Inverse of a matrix
$(\cdot)^T$	Transpose of a vector or matrix
$(\cdot)_0$	Initial value
$(\cdot)_b$	Broadcasted signal
$(\cdot)_c$	Referring to the controller (Signal or matrix)
$(\cdot)_m$	Referring to a model
$(\cdot)_i/(\cdot)^i$	Referring to a subsystem i
$(\cdot)_{ij}\Big/(\cdot)^{ij}$	Referring to transmission from a subsystem i to j

Scalars

n	Dimension of the state vector
m	Dimension of the input vector
r	Dimension of the output vector
k	Discrete instant
ℓ	Counter
t	Continuous time
τ	Delay
T_s	Sampling time
T_W	Waiting time
δ	Event constant threshold
t_k	Event time
ℓ_k	Event time (discrete time)
τ_{max}	Delay bound
τ_{sc}	Delay from sensor to controller
τ_{ca}	Delay from controller to actuator
n_p	Maximum number of consecutive packet losses
p	Packet losses rate
$\kappa(A)$	Condition number of A ($\kappa(A) = \|A\|\|A^{-1}\|$)
N_a	Number of agents
N_u	Length of control sequence

Vectors

x	State vector
u	Input vector

w	Disturbance vector
y	Output vector
v	Noise vector
$\hat{x}$	Observed state
e	Observer error
ε	Event-based control error
y_{sp}	Set-point
ξ	Augmented state vector
$\mathbf{r}$	Desired inter-vehicle relative position vector
$\bar{1}$	Column vector whose components are ones
$\mathcal{U}$	Augmented control vector

Matrices

A	System matrix
B	Input matrix
C	Output matrix
D	Feedforward matrix
K	Feedback gain
A_K	System matrix of a closed-loop system ($A_K = A + BK$)
M	Observer gain
N_{ij}	Consensus gains
U_k	Control sequence
$\mathbf{0}$	Null matrix of appropriate size
I_n	$n \times n$ identity matrix

Other

$\mathcal{G}$	Graph
$\mathcal{V}$	Set of vertices and set of edges
$\mathcal{E}$	Edges
$\mathcal{N}_i$	Neighborhood of the i-th node
$\mathcal{O}$	Order of complexity
V	Lyapunov function

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