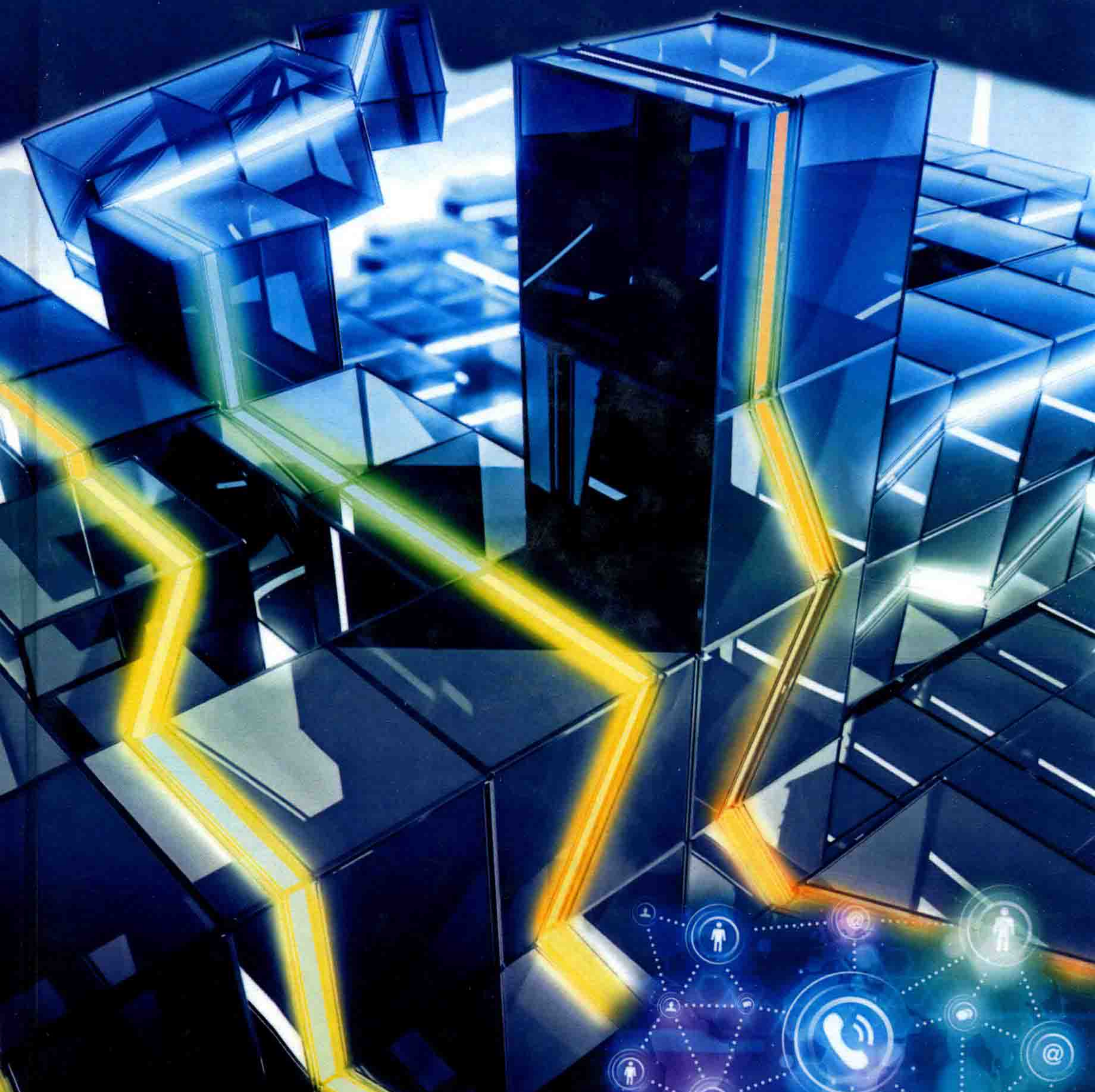
Networked Filtering and Fusion in Wireless Sensor Networks



Magdi S. Mahmoud
Yuanqing Xia

CRC Press
Taylor & Francis Group

Networke and Fusion in Wireless Sensor Networks

Magdi S. Mahmoud
Yuanqing Xia

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20140728

International Standard Book Number-13: 978-1-4822-5096-1 (Hardback)

Library of Congress Cataloging-in-Publication Data

Mahmoud, Magdi S.
Networked filtering and fusion in wireless sensor networks / authors, Magdi S. Mahmoud, Yuanqing Xia.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4822-5096-1 (hardback)
1. Multisensor data fusion. 2. Information filtering systems. I. Xia, Yuanqing. II. Title.

TK7872.D48M34 2014
004.6--dc23 2014027990

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Networked Filtering and Fusion in Wireless Sensor Networks

To My Loving Wife **Salwa**,
To the **"M"** *Family: Medhat, Monda, Mohamed, Menna and Malak, Mostafa, Mohamed and Ahmed Gouda*

MsM

To My Honest and Diligent Wife **Wang Fangyu**,
To My lovely Daughter Xia Jingshu

YX

Notations and Symbols

$\Re$	$=$	*set of real numbers*
$\Re^n$	$=$	*set of all n-dimensional real vectors*
$\Re^{n \times m}$	$=$	*set of* $n \times m$*–dimensional real matrices*
x^t or A^t	$=$	*transpose of vector x or matrix A*
A^{-1}	$=$	*inverse of matrix A*
I	$=$	*identity matrix of arbitrary order*
e_j	$=$	*jth column of matrix I*
$\lambda(A)$	$=$	*eigenvalue of matrix A*
$\varrho(A)$	$=$	*spectral radius of matrix A*
$\lambda_j(A)$	$=$	j*th eigenvalue of matrix A*
$\lambda_m(A)$	$=$	*minimum eigenvalue of matrix A* *where* $\lambda(A)$ *are real*
$\lambda_M(A)$	$=$	*maximum eigenvalue of matrix A* *where* $\lambda(A)$ *are real*
$A^\dagger$	$=$	*Moore–Penrose-inverse of matrix A*
$P > 0$	$=$	*matrix P is real symmetric* *and positive-definite*
$P \geq 0$	$=$	*matrix P is real symmetric* *and positive semi-definite*
$P < 0$	$=$	*matrix P is real symmetric* *and negative-definite*
$P \leq 0$	$=$	*matrix P is real symmetric* *and negative semi-definite*
$A(i,j), A_{ij}$	$=$	ij*-th element of matrix A*
$\mathbf{det}(A)$	$=$	*determinant of matrix A*
$\mathbf{trace}(A)$	$=$	*trace of matrix A*

$\mathbf{rank}(A)$	=	*rank of matrix A*
$\lvert a \rvert$	=	*absolute value of scalar a*
$\lvert\lvert x \rvert\rvert$	=	*Euclidean norm of vector x*
$\lvert\lvert A \rvert\rvert$	=	*induced Euclidean norm of matrix A*
$\lvert\lvert x \rvert\rvert_p$	=	*ℓ_p norm of vector x*
$\lvert\lvert A \rvert\rvert_p$	=	*induced ℓ_p norm of matrix A*

List of Acronyms

ACK	*positive acknowledgment*
CF	*consensus filters*
CIM	*centralized integration method*
CTS	*clear to send*
DBF	*diffusion-based filtering*
DC	*distributed control*
DCF	*distributed coordination function*
DF	*distributed filtering*
$DIFS$	*distributed interframe space*
DIP	*distributed information processing*
$DMPC$	*distributed model predictive control*
DPF	*distributed particle filtering*
EKF	*extended Kalman filter*
EMA	*expected maximization algorithm*
IUB	*industrial utility boiler*
LKF	*Lyapunov–Krasovskii functional*
LMI	*linear matrix inequality*
$MSDF$	*multi-sensor data fusion*
μKF	*micro-Kalman filters*
PE	*performance evaluation*
PKF	*partitioned Kalman filter*
RTS	*request to send*
$SIFS$	*short interframe space*
SNS	*sensor networked systems*
STF	*self-tuning filtering*
WSN	*wireless sensor networks*

Acknowledgments

We are indebted to the people who made the writing of this book possible. Professor Mahmoud thanks KFUPM management for the continuous encouragement and facilitating all sources of help. Particular appreciation goes to the deanship of scientific research (DSR) for providing a superb competitive environment of research activities through internal funding grants. It is a great pleasure to acknowledge the financial funding afforded by DSR through project no. IN131039 and for providing overall support of research activities at KFUPM. Professor Mahmoud owes a measure of gratitude to the National Natural Science Foundation of China (61225015) for fully sponsoring the technical visit to BIT, China during January–March, 2014.

During the past five years, we had the privilege of teaching various senior and graduate courses. The course notes, updated and organized, were instrumental in generating different chapters of this book, and valuable comments and/or suggestions by graduate students were greatly helpful, particularly those who attended the courses SE 537, SE 652 and SE 658 offered at the Systems Engineering Department over the period 2007–2011.

Most of all, however, we would like to express our deepest gratitude to all the members of our families for their enthusiastic support, without which this volume would not have been finished.

We would appreciate any comments, questions, criticisms, or corrections that readers may kindly provide to Professor Mahmoud at
msmahmoud@kfupm.edu.sa or magdisadekmahmoud@gmail.com.

Magdi S. Mahmoud
Dhahran, Saudi Arabia

Yuanqing Xia
Beijing, China

Acknowledgments

We are indebted to the people who made the writing of this book possible. Professor Mahmoud thanks the KFUPM administration for the continuous encouragement and facilitating all academic help. Particular appreciation goes to the Deanship of Scientific Research (DSR) for providing a superb supportive environment of research activities through internal research projects. It is a great pleasure to acknowledge the financial funding afforded by DSR through project no. IN141039 and the prevailing overall support in research activities at KFUPM. Professor Mahmoud owes a measure of gratitude to the National Natural Science Foundation of China (61225015) for kindly sponsoring the technical visit to BIT, China during January–March, 2014.

During the past five years, we had the privilege of teaching various senior and graduate courses. The course notes, updated and organized, were instrumental in generating different chapters of the book. Invaluable comments and/or suggestions by graduate students were greatly helpful, particularly those who attended the classes of SCE 517, SCE 612, and SCE 614 offered at the Systems Engineering Department during the period 2007–2011.

Most of all, however, we would like to express our deepest gratitude to all the members of our families for their unlimited support, without which this volume would not have been finished.

We would appreciate any comments, questions, criticisms, or corrections that readers may kindly provide to Professor Mahmoud at
[illegible]

Magdi S. Mahmoud
Dhahran, Saudi Arabia

Yuanqing Xia
Beijing, China

Authors

MagdiSadek Mahmoud earned a BSc (Honors) in communication engineering, a MSc in electronic engineering and PhD in systems engineering, all from Cairo University in 1968, 1972 and 1974, respectively. He has been a professor of engineering since 1984. He is now a distinguished university professor at King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia. He has been on the faculty at different universities world-wide including Egypt (CU, AUC), Kuwait (KU), UAE (UAEU), UK (UMIST), USA (Pitt, Case Western), Singapore (Nanyang Technological) and Australia (Adelaide). He has lectured in Venezuela (Caracas), Germany (Hanover), UK (Kent), USA (University of Texas at San Antonio), Canada (Montreal, Alberta) and China (BIT, Yanshan). He is the principal author of 34 books, inclusive book chapters and the author/co-author of more than 510 peer-reviewed papers. Dr. Mahmoud is the recipient of two national, one regional, and four university prizes for outstanding research in engineering and applied mathematics. He is a fellow of the IEE, a senior member of the IEEE, the CEI (UK), and a registered consultant engineer of information engineering and systems (Egypt). He is currently actively engaged in teaching and research in the development of modern methodologies of distributed control and filtering, networked control systems, triggering mechanisms in dynamical systems, fault-tolerant systems and information technology.

Yuanqing Xia graduated from the Department of Mathematics, Chuzhou University, Chuzhou, China, in 1991. He earned his MS degree in fundamental mathematics from Anhui University, China, in 1998 and his PhD degree in control theory and control engineering from Beijing University of Aeronautics and Astronautics, Beijing, China, in 2001. From 1991–1995, he was a teacher with Tongcheng Middle-School, Anhui, China. From January 2002 to November 2003, he was a postdoctoral research associate at the Institute of Systems Science, Academy of Mathematics and System Sciences, Chinese Academy of Sciences, Beijing, China, where he worked on navigation, guidance and control. From November 2003 to February 2004, he joined the National University of Singapore as a research fellow, where he worked on variable structure control. From February 2004 to February 2006, he was with the University of Glamorgan, Pontypridd, UK, as a research fellow, where he worked on networked control systems. From February 2007 to June 2008, he was a guest professor with Innsbruck Medical University, Innsbruck, Austria, where he worked on biomedical signal processing. Since July 2004, he has been with the Department of Automatic Control, Beijing Institute of Technology, Beijing, first as an associate professor, and then, since 2008, as a professor. His current research interests are in the fields of networked control systems, robust control, sliding mode control, active disturbance rejection control and biomedical signal processing.

Preface

In recent years, wireless sensor networks (WSN) have produced a large amount of data that need to be processed, delivered, and assessed according to the application objectives. The way these data are manipulated by the sensor nodes is a fundamental issue. Information fusion arises as a response to process data gathered by sensor nodes and benefits from their processing capability. By exploiting the synergy among the available data, information fusion techniques can reduce the amount of data traffic, filter noisy measurements, and make predictions and inferences about a monitored entity. The book introduces the subject of multi-sensor fusion as the method of choice for implementing distributed systems.

This book is about the current state-of-the-art of information fusion, presenting the known methods, algorithms, architectures, and models of information fusion, and discussing their applicability in the context of wireless sensor networks. Particular considerations are given to covering wide topics that were treated in the literature and presenting results of typical case studies. The key feature is to provide a teaching-oriented volume with research-supported elements and comprehensive references.

The book applies recently developed convex optimization theory and high efficient algorithms in estimation fusion, which opens a very attractive research subject on distributed estimation and fusion for sensor networks. Supplying powerful and advanced mathematical treatment of the fundamental problems, it will help to greatly broaden prospective applications of such developments in practice.

The ultimate vision of this work is that information-based control designers will be able to model parts of dynamic systems (much as control engineers model electrical and mechanical systems), and use those models to develop distributed fusion control algorithms based on a theory of feedback control. It is intended to present a cohesive overview of the key results of theory and applications of information fusion–related problems in networked systems in a unified framework.

Throughout this book, the following terminologies, conventions and notations have been adopted. All of them are quite standard in the scientific media and only vary in form or character. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations. In symmetric block matrices or complex matrix expressions, we use the symbol $\bullet$ to represent a term that is induced by symmetry.

Many modern large-scale systems are automatically managed through networks of computers that are tied to sensors and actuators, leading to networked control systems. The inter-relationships among communication, computation, and control in such systems are clearly a subject of great interest. Therefore, networked fusion and filtering are attracting increasing attention in view of their wide industrial implications. The idea for writing the book arose and developed through the consecutive visits of the first author to the second author at the BIT, China. In writing this volume, we took the approach of referring within the text to papers and/or books which we believe taught us some concepts, ideas, and methods. We further complemented this by adding remarks and notes within and at the end of each chapter to shed some light on other related results.

Contents