Springer Series on
SIGNALS AND COMMUNICATION TECHNOLOGY
Foundations and Applications of Sensor Management
A.O. Hero III, D. Castañón, D. Cochran, and K. Kastella (Eds.)

Human Factors and Voice Interactive Systems, Second Edition
D. Gardner-Bonneau and H. Blanchard

Wireless Communications: 2007 CNIT Thyrrenian Symposium
S. Pupolin

Adaptive Nonlinear System Identification: The Volterra and Wiener Model Approaches
T. Ogunfunmi

Wireless Network Security
Y. Xiao, X. Shen, and D.Z. Du (Eds.)
ISBN 978-0-387-28040-0

Satellite Communications and Navigation Systems
E. Del Re and M. Ruggieri

Wireless Ad Hoc and Sensor Networks
A Cross-Layer Design Perspective
R. Jurdak
ISBN 0-387-39022-7

Cryptographic Algorithms on Reconfigurable Hardware
F. Rodriguez-Henriquez, N.A. Saqib, A. Diaz Pérez, and C.K. Koc
ISBN 0-387-33956-6

Multimedia Database Retrieval
A Human-Centered Approach
P. Muneesawang and L. Guan

Broadband Fixed Wireless Access
A System Perspective
M. Engels and F. Petre
ISBN 0-387-33956-6

Distributed Cooperative Laboratories
Networking, Instrumentation, and Measurements
F. Davoli, S. Palazzo and S. Zappatore (Eds.)
ISBN 0-387-29811-8

The Variational Bayes Method in Signal Processing
V. Šmídl and A. Quinn
ISBN 3-540-28819-8

Topics in Acoustic Echo and Noise Control
Selected Methods for the Cancellation of Acoustical Echoes, the Reduction of Background Noise, and Speech Processing
E. Händler and G. Schmidt (Eds.)
ISBN 3-540-33212-6

EM Modeling of Antennas and RF Components for Wireless Communication Systems
F. Gustrau, D. Manteuffel
ISBN 3-540-28614-4

Interactive Video Methods and Applications
R. I Hammoud (Ed.)
ISBN 3-540-33214-6

Continuous Time Signals
Y. Shmaliy
ISBN 1-4020-4817-3

Voice and Speech Quality Perception: Assessment and Evaluation
U. Jekosch
ISBN 3-540-24095-0

Advanced Man-Machine Interaction
Fundamentals and Implementation
K.-F. Kraiss
ISBN 3-540-30618-8

Orthogonal Frequency Division Multiplexing for Wireless Communications
Y. (Geoffrey) Li and G.L. Stüber (Eds.)
ISBN 0-387-29095-8

Circuits and Systems Based on Delta Modulation
Linear, Nonlinear and Mixed Mode Processing
D.G. Zrilic
ISBN 3-540-23751-8

Functional Structures in Networks
AML—in—A Language for Model Driven Development of Telecom Systems
T. Muth
ISBN 3-540-22545-5

Radio Wave Propagation for Telecommunication Applications
H. Sizun
ISBN 3-540-40758-8

Electronic Noise and Interfering Signals
Principles and Applications
G. Vasilescu
ISBN 3-540-40741-3

DVB
U. Reimers
ISBN 3-540-43545-X

(continued after index)
Preface

This book grew out of a two day workshop that was held in May 2005 and was funded by the U.S. Defense Advanced Projects Research Agency (DARPA) and the U.S. National Science Foundation (NSF). The express purpose of this workshop was to gather together key contributors to the field of active sensing and sensor management to discuss the state-of-the-art in research, the main mathematical approaches to design and performance approximation, the problems solved and the problems remaining. At the end of the workshop the participants had generated an outline and agreed on writing assignments.

The intended audience for this book are graduate students, engineers and scientists in the fields of signal processing, control, and applied mathematics. Readers would benefit from a rudimentary background in statistical signal processing or stochastic control but the book is largely self contained. Appendices cover background material in information theory, Markov processes, and stopping times. A symbol index and a subject index are also included to facilitate the reader’s navigation through the book.

Thus the book lies somewhere between a coherent textbook and a loose collection of papers typical of many recent edited collections on emerging topics in engineering. Like an edited collection, the chapters were written by some of the principal architects of recent advances in sensor management and active sensing. However, authors and editors attempted to adopt a common notation, cross reference other chapters, provide index terms, and adhere to an outline established at the NSF workshop. We hope the reader will find that the book has benefited from this extra planning and coordination.

Alfred Hero, David Castañoñ, Douglas Cochran, and Keith Kastella

Ann Arbor, Boston, Tempe, Ypsilanti
July 2007
Acknowledgments

The editors wish to acknowledge the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. National Science Foundation (NSF) for supporting a workshop, NSF grant number CCF 0524865, at which the structure of this volume was initially worked out.
Contents

Preface v
Acknowledgments vii
Contributing Authors xv
Symbol Index xvii

1 Overview of Book

Alfred O. Hero III, David A. Castañón, Douglas Cochran, Keith Kastella

1. Introduction 1
2. Scope of Book 2
3. Book Organization 3

2 Stochastic Control Theory for Sensor Management

David A. Castañón, Lawrence Carin

1. Introduction 7
2. Markov Decision Problems 10
3. Partially Observed Markov Decision Problems 19
4. Approximate Dynamic Programming 26
5. Example 27
6. Conclusion 32
3

Information Theoretic Approaches to Sensor Management

Alfred O. Hero III, Christopher M. Kreucher, Doron Blatt

1. Introduction 33
2. Background 35
3. Information-Optimal Policy Search 40
4. Information Gain Via Classification Reduction 43
5. A Near Universal Proxy 44
6. Information Theoretic Sensor Management for Multi-target Tracking 47
7. Terrain Classification in Hyperspectral Satellite Imagery 53
8. Conclusion and Perspectives 57

4

Joint Multi-target Particle Filtering

Christopher M. Kreucher, Mark Morelande, Keith Kastella, Alfred O. Hero III

1. Introduction 59
2. The Joint Multi-target Probability Density 62
3. Particle Filter Implementation of JMPD 71
4. Multi-target Tracking Experiments 85
5. Conclusions 91

5

POMDP Approximation Using Simulation and Heuristics

Edwin K. P. Chong, Christopher M. Kreucher, Alfred O. Hero III

1. Introduction 95
2. Motivating Example 97
3. Basic Principle: Q-value Approximation 98
4. Control Architecture 101
5. Q-value Approximation Methods 104
6. Simulation Result 116
1. Introduction 201
2. Analytical Forms of the Classifier 203
3. Pre-labeling Selection of Basis Functions $\phi$ 204
4. Pre-labeling Selection of Data $\mathcal{X}_{tr}$ 209
5. Connection to Theory of Optimal Experiments 210
6. Application to UXO Detection 212
7. Chapter Summary 219

10
Sensor Scheduling in Radar
William Moran, Sofia Suvorova, Stephen Howard
1. Introduction 221
2. Basic Radar 222
3. Measurement in Radar 233
4. Basic Scheduling of Waveforms in Target Tracking 234
5. Measures of Effectiveness for Waveforms 239
6. Scheduling of Beam Steering and Waveforms 245
7. Waveform Libraries 250
8. Conclusion 255

11
Defense Applications
Stanton H. Musick
1. Introduction 257
2. Background 259
3. The Contemporary Situation 260
4. Dynamic Tactical Targeting (DTT) 262
5. Conclusion 266
**Contents**

12

Appendices

*Alfred O. Hero, Aditya Mahajan, Demosthenis Teneketzis, Edwin Chong*

1. Information Theory 269
2. Markov Processes 273
3. Stopping Times 278

References 283

Index 305
Contributing Authors

Doron Blatt, DRW Holdings, Chicago, IL, USA

Lawrence Carin, Duke University, Durham, NC, USA

David A. Castañón, Boston University, Boston, MA, USA

Rui Castro, University of Wisconsin, Madison, WI, USA

Douglas Cochran, Arizona State University, Tempe, AZ, USA

Edwin K. P. Chong, Colorado State University, Fort Collins, CO, USA

Alfred O. Hero III, University of Michigan, Ann Arbor, MI, USA

Stephen Howard, Defence Science and Technology Organisation, Edinburgh, Australia

Keith Kastella, General Dynamics Michigan Research and Development Center, Ypsilanti, MI, USA

Christopher M. Kreucher, General Dynamics Michigan Research and Development Center, Ypsilanti, MI, USA
Xuejun Liao, Duke University, Durham, NC, USA

Aditya Mahajan, University of Michigan, Ann Arbor, MI, USA

William Moran, University of Melbourne, Melbourne, Australia

Mark Morelande, University of Melbourne, Melbourne, Australia

Stanton H. Musick, Sensors Directorate, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, USA

Robert Nowak, University of Wisconsin, Madison, WI, USA

Sofia Suvorova, University of Melbourne, Melbourne, Australia

Demosthenis Teneketzis, University of Michigan, Ann Arbor, MI, USA

Robert B. Washburn, Parietal Systems, Inc., North Andover, MA, USA

Yan Zhang, Innovation Center of Humana, Inc., Louisville, KY, USA
Symbol Index

General notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{R}$</td>
<td>the real line</td>
</tr>
<tr>
<td>$\mathbb{R}^2$</td>
<td>the real plane</td>
</tr>
<tr>
<td>$\mathbf{x}$</td>
<td>bold lowercase letter denotes a vector as in $\mathbf{x} = [x_1, \ldots, x_2]$</td>
</tr>
<tr>
<td>$s$</td>
<td>complex variable, a vector $\Re(s) + j\Im(s)$ in the complex plane</td>
</tr>
<tr>
<td>$s^*$</td>
<td>complex conjugate $\Re(s) - j\Im(s)$ of complex variable $s$</td>
</tr>
<tr>
<td>$\mathbf{J}$</td>
<td>bold uppercase letter near beginning of alphabet denotes a matrix</td>
</tr>
<tr>
<td>$\mathbf{I}$</td>
<td>the identity matrix</td>
</tr>
<tr>
<td>$\mathbf{\tau}$</td>
<td>vector or matrix transpose as in $\mathbf{x}^\top$</td>
</tr>
<tr>
<td>$\mathbf{H}$</td>
<td>Hermitian transpose of a complex vector or matrix, $\mathbf{x}^H = (\mathbf{x}^*)^\top$</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>permutation operator as in $\Pi([x_1, \ldots, x_M]) = [x_M, \ldots, x_1]$</td>
</tr>
<tr>
<td>$\langle \mathbf{x}, \mathbf{y} \rangle$</td>
<td>inner product between two vectors $\mathbf{x}$ and $\mathbf{y}$ in $\mathbb{R}^d$</td>
</tr>
<tr>
<td>$|\mathbf{x}|$</td>
<td>norm of a vector</td>
</tr>
<tr>
<td>$</td>
<td>\mathbf{x}</td>
</tr>
<tr>
<td>$</td>
<td>S</td>
</tr>
<tr>
<td>$I_A(x)$</td>
<td>indicator function of set $A$</td>
</tr>
</tbody>
</table>

Statistical notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$</td>
<td>uppercase letter near end of alphabet usually denotes a random variable</td>
</tr>
<tr>
<td>$y$</td>
<td>lowercase letter near end of alphabet usually denotes a realization</td>
</tr>
<tr>
<td>$\mathbf{Y}$</td>
<td>bold uppercase letter usually denotes a random vector</td>
</tr>
<tr>
<td>$\mathbb{E}$</td>
<td>statistical expectation as in $\mathbb{E}[\mathbf{Y}\mathbf{Y}^\top]$</td>
</tr>
<tr>
<td>$\mathbb{P}$</td>
<td>probability measure as in $\mathbb{P}(X \in [0, 1])$</td>
</tr>
<tr>
<td>$p_X$</td>
<td>probability density or probability mass function of random variable $X$</td>
</tr>
<tr>
<td>$p(x)$</td>
<td>shorthand for $p_X(x)$</td>
</tr>
<tr>
<td>$\mathcal{D}$</td>
<td>information divergence as in $\alpha$-divergence $\mathcal{D}_\alpha(p_X</td>
</tr>
<tr>
<td>$\mathbf{J}$</td>
<td>Fisher information matrix</td>
</tr>
</tbody>
</table>
\( \pi_k \) belief state (information state)
\( \pi \) the belief state space, a space of density functions \( \pi \)
\( P_d, P_f \) probability of detection, probability of false alarm
\( P_e \) Bayes probability of error

**Scheduling notation**

\( a \) a sensor action
\( \mathcal{A} \) the space of sensor actions \( a \)
\( Y_k \) measured sensor output at time \( k \)
\( \mathbf{Y}^k \) vector of measurements, \( \mathbf{Y}^k = [Y_1, \ldots, Y_k]^\top \)
\( S_k \) the state of nature to be determined from past sensor measurements
\( X_k \) state vector of a target in the plane, a special case of \( S_k \)
\( R(S, a) \) reward due to taking action \( a \) in state \( s \)
\( \gamma_k \) policy, a mapping from available measurements to sensor actions
\( \mathcal{A} \) at time \( k \)
\( V_{\gamma} \) value function associated with policy \( \gamma \)
\( E_{\gamma} \) statistical expectation under a given policy \( \gamma \)
\( < g, \pi > \) conditional expectation of \( g \) given the posterior density \( \pi \)
\( \beta \) scheduling discount factor
\( Q_k \) Q-function of reinforcement learning; an empirical approximation to value function