THE ELECTRICAL ENGINEERING
AND APPLIED SIGNAL PROCESSING SERIES

ADVANCED SIGNAL PROCESSING

Theory and Implementation for Sonar, Radar, and Non-Invasive Medical Diagnostic Systems

SECOND EDITION

Edited by
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Advanced Signal Processing: Theory and Implementation for Sonar, Radar, and Non-Invasive Medical Diagnostic Systems, Second Edition
Stergios Stergiopoulos

To my son Sotirios and my daughter Erene

Preface to Second Edition

This handbook emerged from the Editor's most recent investigations at Defence R&D Canada (DRDC) in implementing defence oriented research from sonar and radar system applications into non-invasive medical diagnostic R&D to address difficult diagnostic problems relevant with the protection of members of the Canadian Forces serving in hostile fields of operations. The development of these medical technologies has proven to be equally applicable for civilian use and as a result a private company has been established to commercialize them. Thus, the writing of this handbook was prompted by a desire to bring together some of the most recent theoretical developments on advanced signal processing; and to provide a glimpse on how modern technology can be applied to the development of current and next generation real-time sonar and medical diagnostic systems.

The first edition focused on advances in digital signal processing algorithms and on their implementation in PC-based computing architectures that can provide the ability to produce real-time systems that have capabilities far exceeding those of a few years ago. It included also a generic concept for implementing successfully adaptive schemes with near-instantaneous convergence in 2-dimensional (2D) and 3-dimensional (3D) array of sensors, such as planar, circular, cylindrical and spherical arrays of sensors.

The present edition preserves the form of the more mathematical part of the previous edition, but contains a number of major changes and much new material, especially in the first and third parts of the handbook that focus on the emerging medical technologies in the areas of non-invasive tomography imaging, biometrics, and monitoring vital signs. The earlier chapters give essential background theory on the basic elements of signal processing for practical system applications that are the scope of the handbook. More specifically, the material in Chapters 2 through 4 on 'Adaptive Systems in Signal Processing', 'Advanced Beamformers' and 'Volume Visualization Methods in Medicine' remain the same since it was found to be helpful to the general graduate students of engineering and applied physics and to system engineers specializing on sonar and medical technology developments. However, Chapters 5 and 6 are new and their material addresses topics on recent advances on image segmentation, registration and fusion techniques for 3D/4D ultrasound and other tomography imaging modalities. The material in Chapters 7 and 8 is also new and expands to include aspects of the handbook in the areas of diffraction computed tomography for non-destructive 3D tomography imaging and biometrics, respectively, for security screening applications.

In the second part of the handbook on sonar and radar system applications, apart from only minor changes in Chapters 10 and 11 on sonar systems, Chapter 9 on phased array radar signal processing has been completely re-written to address issues of space—time adaptive processing and detection of targets in interference intense backgrounds comprised of clutter and jamming.

Finally, the changes in the third part of the handbook on non-invasive medical diagnostic system applications have been considerable, resulting in a substantially different set of chapters from the first edition. In particular, Chapter 12 introduces the concept of a fully digital 3D/(4D: 3D+time) ultrasound system technology, computing architecture requirements and the relevant implementation issues for a set of 3D adaptive ultrasound beamformers that have been discussed in detail in Chapter 3. The material of Chapters 13 and 14 on magnetic resonance imaging (MRI) and on organ motion correction issues for single slice CT scanners, respectively, remains the same, while the new material of Chapter 15 extends the topic of cardiac motion correction in the emerging field of multi-slice X-ray CT imaging. Further new topics on vital signs technologies and dispersive ultrasound for monitoring non-visible traumatic brain injuries have been included in Chapter 16. The next two chapters (Chapters 17 and 18) introduce new topics on MRI diagnostic applications. More specifically, Chapter 17 focuses on contrast agent kinetic analysis that has applications in medical diagnostics by helping to characterize the functional state of a tissue and in drug discovery by offering insight into the behavior of the contrast agent itself. Contrast agent kinetic analysis is used often in conjunction with an imaging device, such as MRI, that can measure non-invasively the concentration of the contrast agent, at one or more locations, as a function of time. Chapter 18 discusses arterial spin labeling (ASL) methods that can be interpreted using the same classical tracer kinetic theory to generate quantitative cerebral blood flow MRI diagnostic applications; and the final Chapter 19 presents the importance of automatic diagnosis of microcalcifications in early detection and diagnostic procedures for breast cancer using computer aided diagnosis (CAD) in mammography.

I wish to thank my colleagues and contributing authors for their valuable assistance in forming the material of this handbook.

Stergios Stergiopoulos
Toronto, Ontario, Canada

Preface to First Edition

Recent advances in digital signal processing algorithms and computer technology have combined to provide the ability to produce real-time systems that have capabilities far exceeding those of a few years ago. The writing of this handbook was prompted by a desire to bring together some of the recent theoretical developments on advanced signal processing; and to provide a glimpse of how modern technology can be applied to the development of current and next generation active and passive real-time systems.

The handbook is intended to serve as an introduction to the principles and applications of advanced signal processing. It will focus on the development of a generic processing structure that exploits the great degree of processing concept similarities existing among the radar, sonar, and medical imaging systems. A high-level view of the above real-time systems consists of a high-speed *Signal Processor* to provide mainstream signal processing for detection and initial parameter estimation, a *Data Manager* which supports the data and information processing functionality of the system and a *Display Sub-System* through which the system operator can interact with the data structures in the data manager to make the most effective use of the resources at his command.

The *Signal Processor* normally incorporates a few fundamental operations. For example, the sonar and radar signal processors include beamforming, 'matched' filtering, data normalization and image processing. The first two processes are used to improve both the signal-to-noise ratio (SNR) and parameter estimation capability through spatial and temporal processing techniques. Data normalization is required to map the resulting data into the dynamic range of the display devices in a manner which provides a CFAR (constant false alarm rate) capability across the analysis cells.

The processing algorithms for spatial and temporal spectral analysis in real-time systems are based on conventional FFT and vector dot product operations because they are computationally cheaper and very robust than the modern non-linear high resolution adaptive methods. However, these non-linear algorithms trade robustness for improved array gain performance. Thus, the challenge is to develop a concept which allows an appropriate mixture of these algorithms to be implemented in practical real-time systems.

The non-linear processing schemes are adaptive and synthetic aperture beamformers that have been shown experimentally to provide improvements in array gain for signals embedded in partially correlated noise fields. Using system image outputs, target tracking and localization results as performance criteria, the impact and merits of these techniques are contrasted with those obtained using the conventional processing schemes. The reported real data results show that the advaned processing schemes provide improvements in array gain for signals embedded in anisotropic noise fields. However, the same set of results demonstrates that these processing schemes are not adequate enough to be considered as a replacement for conventional processing. This restriction adds an additional element in our generic signal processing structure, in that the conventional and the advanced signal processing schemes should run in parallel in a real-time system in order to achieve optimum use of the advanced signal processing schemes of this study.

The handbook will include also a generic concept for implementing successfully adaptive schemes with near-instantaneous convergence in 2-dimensional (2D) and 3-dimensional (3D) arrays of sensors, such as planar, circular, cylindrical, and spherical arrays of sensors. It will be shown that the basic step is to minimize the number of degrees of freedom associated with the adaptation process. This step will minimize the adaptive scheme's convergence period and achieve near-instantaneous convergence for integrated active and passive sonar applications. The reported results are part of a major research project, which includes the definition of a generic signal processing structure that allows the implementation of adaptive and synthetic aperture signal processing schemes in real-time radar, sonar, and medical tomography (CT, MRI, ultrasound) systems that have 2D and 3D arrays of sensors.

The material in the handbook will bridge a number of related fields: detection and estimation theory; filter theory (finite impulse response filters); 1D, 2D, and 3D sensor array processing that includes conventional, adaptive, synthetic aperture beamforming and imaging; spatial and temporal spectral analysis; and data normalization. Emphasis will be be placed on topics that have been found to be particularly useful in practice. These are several interrelated topics of interest such as the influence of medium on array gain system performance, detection and estimation theory, filter theory, spaceñtime processing, conventional, adaptive processing and model-based signal processing concepts. Moreover, the system concept similarities between sonar and ultrasound problems are identified in order to exploit the use of advanced sonar and model-based signal processing concepts in ultrasound systems.

Furthermore, issues of information post-processing functionality supported by the data manager and the display units of real-time systems of interest are addressed in the relevant chapters that discuss normalizers, target tracking, target motion analysis, image post-processing and volume visualization methods.

The presentation of the subject matter has been influenced by the authors' practical experience, and it is hoped that the volume will be useful to scientists and system engineers as a textbook for a graduate course on sonar, radar, and medical imaging digital signal processing. In particular, a number of chapters summarize the state-of-the-art application of advanced processing concepts in sonar, radar, and medical imaging X-ray CT scanners, magnetic resonance imaging, 2D and 3D ultrasound systems. The focus of these chapters is to point out their applicability, benefits, and potential in the sonar, radar, and medical environments. Although an all-encompassing general approach to a subject is mathematically elegant, practical insight and understanding may be sacrificed. To avoid this problem and to keep the handbook to a reasonable size, only a modest introduction is provided. In consequence, the reader is expected to be familiar with the basics of linear and sampled systems and the principles of probability theory. Furthermore, since modern real-time systems entail sampled signals that are digitized at the sensor level, our signals are assumed to be discrete in time and the subsystems that perform the processing are assumed to be digital.

It has been a pleasure for me to edit this book and to have the relevant technical exchanges with so many experts on advanced signal processing. I take this opportunity to thank all authors for their response to my invitation to contribute. I am also greatful to CRC Press LLC and in particular to Bob Stern for his truly professional cooperation; and to Dr. George Metakides, Director in the IST-Program of the European Commission, for his efforts to initiate the European Canadian exchange that resulted in a number of major collaborative R&D projects. The preparation of this handbook is the result of this initiative. Finally, the support by the European Commission is acknowledged for awarding Professor Uzunonglu and myself with the Fourier Euroworkshop grant (HPCF-1999-00034) to organize two workshops that enabled the contributing authors to refine and coherently integrate the material of their chapters as a handbook on advanced signal processing for sonar, radar, and medical imaging system applications.

Stergios Stergiopoulos

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Editor

Stergios Stergiopoulos received a BSc (Hon.) from the University of Athens in 1976 and the MSc and PhD in Physics in 1977 and 1982, respectively, from York University, Toronto, Canada. Presently, he is a defence scientist at the Defence R&D Canada (DRDC) Toronto, an adjunct professor at the Edward S. Rogers Sr. Department of Electrical and Computer Engineering of the University of Toronto, and the main innovator of the Defence R&D Canada (DRDC) medical diagnostic technologies and patents that have been licensed to a Canadian company for commercialization. These innovation include a number of non-invasive 3D imaging (i.e. cardiac 3D CT, portable 3D/4D ultrasound) and vital signs monitoring (i.e. motion and noise tolerant automated blood pressure and intracranial dispersive-ultrasound) technologies. To complete their development and their commercialization process, Dr. Stergiopoulos raised approximately $11 million from private investors and Government grants. He has an extensive background in science and research. Since 1991 he is with DRDC, a Research Agency for the Canadian Department of National Defence. From 1988 to 1991, he was with the NATO SACLANT Centre in La Spezia, Italy, where he performed both theoretical and experimental research in sonar signal processing. At SACLANTCEN, he developed jointly with Dr. Edmund J. Sullivan from NUWC an acoustic synthetic aperture technique that has been patented by the US Navy. From 1984 to 1988, he developed an underwater fixed array surveillance system for the Hellenic Navy in Greece and there, he was appointed also senior advisor to the Greek Minister of Defence. From 1982 to 1984, he worked as a research associate at York University and in collaboration with the US Army Ballistic Research Lab (BRL), Aberdeen, MD, on projects related to the stability of liquid filled spin stabilized projectiles. In 1984, he was awarded a US NRC Research Fellowship for BRL. He was associate editor for the *IEEE Journal of Oceanic Engineering* and for this journal he has prepared two special issues on Acoustic Synthetic Aperture and Sonar System Technology. He has published numerous scientific articles and a handbook (i.e. CRC Press) in the areas of advanced signal processing for sonar and medical non-invasive system applications. His present interests are associated with the implementation of advanced processing schemes in multi-dimensional arrays of sensors for sonar and medical tomography (CT, MRI, and ultrasound) systems. His research activities are supported by Canadian-DND Grants, by Research and Strategic Grants (NSERC-CANADA), the Ontario Challenge Fund and NATO Collaborative Research Grant. He has been awarded with European Commission-IST grants as technical manager of several projects that included as project partners major European corporations and institutes (i.e. Siemens, Nucletron, Philips, Sema Group, Esaote, Atmel, Fraunhofer). These project were entitled 'New Roentgen', 'MITTUG', 'ADUMS', 'MRI-MARCB', 'DUST' and Euroworkshop 'Fourier', with an average budget level of the order of €1.5 million per project. Dr. Stergiopoulos is a fellow of the Acoustical Society of America and a senior member of the IEEE. He has been a consultant to a number of companies, including Atlas Elektronik in Germany, Hellenic Arms Industry, and Hellenic Aerospace Industry.

Contributors

Bhashyam Balaji
Defence R&D Canada Ottawa
Ottawa, Ontario, Canada

G. Clifford Carter
Naval Undersea Warfare Center
Newport, Rhode Island

Ian Cunningham
The John Robarts Research Institute
University of Western Ontario
London, Ontario, Canada

Anthony Damini
Defence R&D Canada Ottawa,
Ottawa, Ontario, Canada

Amar Dhanantwari
Defence R&D Canada Toronto
Toronto, Ontario, Canada

Geoffrey Edelson
Advanced Systems & Technology
Nashua, New Hampshire

Marius Erdt
Department of Cognitive Computing & Medical Imaging
Fraunhofer Institute for Computer Graphics
Darmstadt, Germany

Andreas Freibert
Defence R&D Canada Toronto,
Toronto, Ontario, Canada

Julius Grodski
Defence R&D Canada Toronto
Toronto, Ontario, Canada

Dimitrios Hatzinakos
The Edward S. Rogers Sr. Department of ECE
University of Toronto
Toronto, Ontario, Canada

David Havelock
National Research Council
Ottawa, Ontario, Canada

Simon Haykin
Communications Research Laboratory
McMaster University
Hamilton, Ontario, Canada

Michael Jerosch-Herold
Department of Radiology
Brigham & Women's Hospital
Boston, Massachussets

Sung Ho Jin
Multimedia Group
Information Communication University
Yuseong-gu
Daejon, Korea

Grigorios Karangelis
Department of Cognitive Computing and Medical Imaging
Fraunhofer Institute for Computer Graphics
Darmstadt, Germany

Benoit Lewden
Lawson Health Research Institute
London, Ontario, Canada

Haiping Lu
The Edward S. Rogers Sr. Department of ECE
University of Toronto
Toronto, Ontario, Canada

George K. Matsopoulos
Department of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece

Michael K. McDonald
Defence R&D Canada Ottawa
Ottawa, Ontario, Canada

Bernard E. McTaggart
Naval Undersea Warfare Center
Newport, Rhode Island

Sanjay K. Mehta
Naval Undersea Warfare Center
Newport, Rhode Island

Arnulf Oppelt
Siemens AG
Erlangen, Germany

Daron G. Owen
Imaging Division
Lawson Health Research Institute
London, Ontario, Canada

and

Department of Medical Biophysics
University of Western Ontario
London, Ontario, Canada

Konstantinos N. Plataniotis
The Edward S. Rogers Sr. Department of ECE
University of Toronto
Toronto, Ontario, Canada

Andreas Pommert
Institute of Mathematics and Computer Science in Medicine (IMDM)
University Hospital Eppendorf
Hamburg, Germany

Frank S. Prato
Imaging Division
Lawson Health Research Institute
London, Ontario, Canada

Department of Medical Biophysics
University of Western Ontario
London, Ontario, Canada

Department of Diagnostic Radiology and Nuclear Medicine
University of Western Ontario
London, Ontario, Canada

and

Department of Diagnostic Imaging
St Joseph's Health Care
London, Ontario, Canada

Yong Man Ro
Multimedia Group
Information Communication University
Yuseong-gu
Daejon, Korea

Eric Sabondjian
Lawson Health Research Institute
University of Western Ontario
London, Ontario, Canada

Georgios Sakas
Department of Cognitive Computing and Medical Imaging
Fraunhofer Institute for Computer Graphics
Darmstadt, Germany

and

Technical University Darmstadt
Darmstadt, Germany

Keith St. Lawrence
Imaging Division
Lawson Health Research Institute
London, Ontario, Canada

Department of Medical Biophysics
University of Western Ontario
London, Ontario, Canada

and

Department of Diagnostic Radiology and Nuclear Medicine
University of Western Ontario
London, Ontario, Canada

Stergios Stergiopoulos
Defence R&D Canada Toronto,
Toronto, Ontario, Canada

The Edward S. Rogers Sr. Department of ECE
University of Toronto
Toronto, Ontario, Canada

and

Department of Medical Biophysics
Schulich School of Medicine
University of Western Ontario
London, Ontario, Canada

Robert Z. Stodilka
University of Western Ontario
Lawson Health Research Institute
London, Ontario, Canada

Jie Wang
Epson Edge
Toronto, Ontario, Canada

Waheed A. Younis
Defence R&D Canada Toronto
Toronto, Ontario, Canada

Jason Zhang
Defence R&D Canada Toronto
Toronto, Ontario, Canada

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