Advanced Computational Approaches to Biomedical Engineering

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Editors

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To my late grandmother Manorama Saha
Punam Kumar Saha

To Sanghamitra and Utsav
Ujjwal Maulik

To my parents Shyamal Kumar Basu and Rita Basu, my wife Koel, and my daughter Aishiki
Subhadip Basu

Preface

Over the last few decades, advancements in biomedical imaging, modeling, and sensing systems, coupled with rapid growth in computational and networking technologies, analytic approaches, visualization and virtual-reality, man–machine interaction, and automation, have led to growing interest in biomedical engineering. While research interest in this field is rapidly emerging among international communities, most leading universities around the globe have already adopted academic curricula on biomedical engineering and related subjects.

In general, biomedical engineering relates to the application of engineering principles to advance the medical and biological sciences. It comprises several topics, including biomedicine, medical imaging, physiological modeling and sensing, instrumentation, real-time systems, microtechniques, automation and control, signal processing, image reconstruction, visualization, processing and analysis, pattern recognition and data mining, and biomechanics.

Biomedical engineering holds great promise for advancing clinical research in medicine, pharmaceuticals, and public health services focusing on prevention, diagnosis, and treatment of complex medical conditions and understanding the etiologies of different biological processes. In recent years, biomedical engineering has taken on a significant role in clinical research, facilitating the development of new drugs, innovative implants and prosthetics, novel imaging technologies, and improved tools for diagnostic and therapeutic mechanisms.

This book brings together contributions from leading research groups presenting recent advances in various active fields of biomedical engineering, including different imaging technologies, image processing and visualization, pattern recognition and data mining, and their clinical applications. Major sources of biomedical imaging data include X-ray computed tomography, magnetic resonance imaging, ultrasound imaging, and positron emission tomography. Often, biomedical data are associated with several significant challenges including limited signal-to-noise ratios and spatial and temporal resolution, misregistration of deformable data in cross-sectional and longitudinal imaging studies, the inherently complex and fuzzy nature of the target objects or information, and large image and data volumes. The overarching goal of most medical imaging research programs is to overcome these challenges with a focus on accurate and reproducible information gathering, enhanced automation at various levels of imaging and data analysis, and the integration of multidisciplinary expertise toward facilitating diagnostic and therapeutic practices.

The chapters in this book are divided into two parts: Part I includes chapters primarily dedicated to computational approaches to medical imaging, while Part II consists of chapters devoted to task-specific biomedical imaging applications. The methods and algorithms presented in this book include medical image segmentation, information-theoretic clustering, multiobjective differential-evolution-based fuzzy clustering, spectral and nonlinear analysis, and metalearning approaches. The second part of this book covers a number of biomedical applications across various imaging modalities, including 3D ultrasound, fluorescent confocal microscopy, magnetic resonance imaging, and X-ray computed tomography.

Five chapters on advanced computational methods of biomedical engineering are included in the first part of this book. In the chapter "Graph Algorithmic Techniques for Biomedical Image Segmentation," Garvin and Wu present an in-depth overview of two state-of-the-art graph-based methods, viz., graph cuts as well as the layered optimal graph image segmentation of multiple objects and surfaces (LOGISMOS) approach, for segmenting three-dimensional structures in medical images. In each case, an overview of the underlying optimization problem is presented first, followed by the graph-based representation of the problem which enables the globally optimal solution to be found in polynomial time.

In the chapter "Information Theoretic Clustering for Medical Image Segmentation," Hill et al. review a recent approach to clustering under an information-theoretic framework that efficiently finds the suitable number of clusters in a medical image representing different tissue characteristics. The proposed clustering approach optimizes an objective function quantifying the quality of a given cluster configuration. In the chapter "Multiobjective Differential Evolution Based Fuzzy Clustering for MR Brain Image Segmentation," Saha and Maulik present a multiobjective differential-evolution-based fuzzy clustering technique for simultaneous optimization of multiple clustering measures. Here differential evolution is used as the underlying optimization technique and cluster centers are encoded in vectors in differential evolution. The technique is evaluated on several simulated T1-weighted, T2-weighted, and proton density-weighted magnetic resonance (MR) brain images for classifying normal and multiple sclerosis lesions.

In the chapter "Spectral and Non-linear Analysis of Thalamocortical Neural Mass Model Oscillatory Dynamics," Sen-Bhattacharya et al. first present the multimodal analytical techniques for investigating abnormal brain oscillations in Alzheimer's disease. They focus on a combined power spectral and nonlinear behavioral analysis of a neural mass model of the thalamocortical circuitry. They also present the power spectral analysis on a model that implements feedforward and feedback connectivities in a thalamocorticothalamic circuitry.

In the chapter "A Meta-learning Approach for Protein Function Prediction," Plewczynski and Basu present a review of multiscale protein biological function prediction algorithms. They also highlight the advantages of using a metalearning approach for protein function prediction, particularly related to protein sequence analysis, 3D structure comparison, biological function annotation, and molecular interaction predictions. They include diverse computational methods for predicting the biological function for a given biomolecule using multiscale features and a metalearning prediction system to analyze the impact of microdynamics on the global behavior of selected biological systems.

The second part of the book contains four chapters on important biomedical applications. In the chapter “Segmentation of the Carotid Arteries from 3D Ultrasound Images,” Ukwatta and Fenster present an accurate and robust method for segmentation of the carotid arteries from 3D ultrasound images allowing efficient quantification of carotid atherosclerosis. They describe the carotid vessel segmentation algorithm and demonstrate that 3D ultrasound is a viable technique for quantifying the progression and regression of carotid atherosclerosis. In the chapter “Contemporary Problems in Quantitative Image Analysis in Structural Neuronal Plasticity,” Ruszczycki et al. study the brain structure at the microscopic level to elucidate the processes of structural neuronal plasticity to understand various neurodegenerative diseases. They used fluorescent confocal microscopy images for quantitative analysis of brain tissues.

In the chapter “Advanced MRI of Cartilage and Subchondral Bone in Osteoarthritis,” Chang and Regatte provide an overview of MR imaging techniques to evaluate cartilage and subchondral bone microstructure, and cartilage biochemical composition, in order to provide a noninvasive alternative to detect pathological alterations in these two tissues for early diagnosis of osteoarthritis in at-risk subjects. The derived knowledge and capabilities should ultimately accelerate the discovery and testing of novel therapies to treat osteoarthritis, a disease that represents an enormous socioeconomic and health burden on society.

In the final chapter of the book, Chowdhury et al. address the problem of detection of hairline mandibular fractures from computed tomography (CT) images. It has been observed that such fractures are difficult to detect manually due to the absence of sharp surface and contour discontinuities and the presence of intensity inhomogeneity in the CT images. In the presented work, a two-stage method is adopted to first identify the 2D CT image slices of a mandible with hairline fractures from a fractured craniofacial skeleton. In the second stage, the hairline fracture is detected using a maximum-flow minimum-cut algorithm from the previously identified subset of images.

Overall, the book chapters cover a wide spectrum of biomedical engineering research related to advanced computational methods and their applications. Currently there are not many books available that address these important research discipline in one volume. This edited book, which is unique in its character, will be useful to graduate students and researchers in computer science, biomedical engineering, computational and molecular biology, electrical engineering, system science, and information technology, both as a text and a reference book for some parts of the curriculum. Researchers and practitioners in industrial and research laboratories will also benefit.

Finally, we take this opportunity to thank all the authors for contributing chapters related to their current research work that explain the state of the art in advanced computational approaches to biomedical engineering. Thanks are due to Indrajit Saha and Ayatullah Faruk Mollah who provided technical support in preparing this volume, as well as to our students who incessantly provided us with the necessary academic stimulus to go on. We are also grateful to Ronan Nugent of Springer for his constant support toward this project.

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Contents