CAMBRIDGE
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Excerpt
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1 Overview of biomedical image analysis

1.1 Introduction

Image analysis is a vibrant field in research, applications, and technologies. Any image is a representation of data gathered by sensors from a physical environment. Biomedical image analysis deals with biological systems; this book focuses on analysis of images that describe the structure or function of the human body. Broadly speaking, biomedical image analysis includes three major components: segmentation, registration, and visualization. Each of these components is a science and art in its own right, with considerable literature spanning over four decades of theory, algorithms, and applications. Each component has been documented in books, conference proceedings, archived journals, technologies, and commercial products.

So a new book on this subject faces two questions: what can it add to the sea of progress, and what distinguishes it from similar books on the subject? The first of these is not a problem per se. This book addresses the common denominator in theory, algorithms and applications that has resulted from this sea of progress, tailored towards a particular audience. To answer the second question, the book covers what is not currently available in textbooks in terms of subjects and educational material. It aims to be a friendly welcome for newcomers to the field, treating it in a rigorous manner, yet without becoming overwhelmed by details. Specifically, the intended audience includes seniors and first-year graduate students in engineering, mathematics, and physics. Those who are experts in the field may also find the book appropriate as a refresher.

The original plan for this book was to focus on statistical methods of biomedical image analysis. However, given current developments in this vibrant field and its multidisciplinary nature, a strictly statistical framework might be too dry. Likewise, the popularity of variational calculus methods in image analysis might make it appealing to have that as the sole focus. But my experience with students taking this subject matter is that they start off very excited about the subject; then their enthusiasm decreases on realizing the prerequisite knowledge of stochastic processes, differential calculus, and algorithms. Hence, a reassessment was necessary, which required a change of plan.

I have therefore added a review of image modalities and the basics of signals and systems, as an overview of the basic information needed for biomedical image analysis. Uncertainties in the imaging process include noise, motion, and occlusion. Hence, some statistical background on random variables, random processes, and random fields has been introduced, as prerequisites to analysis steps such as segmentation, model building, and registration. The same strategy was followed with variational calculus approaches. An introductory chapter on level-set methods has been added, in order to offer the background necessary for deploying elastic deformable models in biomedical image analysis. Statistical and level-set methods may share some shape models, so some basic concepts of topology and shape models have been introduced. With background in statistics, level sets, and computational geometry, the processes of segmentation, registration and visualization become more purposeful, and it becomes possible to extract information and build a hypothesis. Indeed, complete front-end systems for interpreting biomedical imaging data may be established based on this background. For example, computer-assisted diagnosis (CAD) systems, image-guided surgical simulation, and telemedicine require knowledge of statistical, variational, and geometric techniques; they also require an understanding of algorithms and numerical methods.

The risk of this ambitious scope is obvious: the book may become too big and the material may seem too disparate. Every effort has been made to curtail the appetite for comprehensiveness and keep the focus on the fundamentals.

I aim to present the subjects in a standard framework, augmented with examples, computer simulations and exercises, which include computer projects. Advanced seniors and first-year graduates, with basic knowledge of probability, calculus and college algebra, and basic programming skills in a procedural language or MATLAB and Mathematica, should find the book user-friendly and easy to follow. Teachers and educators will appreciate its scope and coverage, and can carve out different strategies for its use based on background and interests. Likewise, researchers will find the book a refresher or a guide to many of the tools in modern biomedical image analysis. Of course, there are chapters that may be skipped by experienced readers and advanced students, who have the requisite background from other classwork.

1.2 The scope of the book

The book contains five basic building blocks: (a) signals and systems, image formation and image modality; (b) stochastic models; (c) computational geometry methods; (d) level-set methods; and (e) tools and CAD models. These blocks are intertwined and are not necessarily in sequence.

1.2.1 Signals and systems, image formation, and image modality

Systems theory has been of great benefit for the development of signal processing and analysis in multiple dimensions. Chapter 2 is an overview of the basics of signals and systems for image representation and processing. I have attempted to make it a succinct briefing on the terminologies, theories and tools of two-dimensional (2D) signal processing, a field that is well established and based on solid theoretical and algorithmic foundation.

Biomedical imaging modalities are numerous. Chapter 3 aims to cover the physics and mathematics of the image formation processes most used in modern medicine, with focus on X-ray, computed tomography (CT), nuclear medicine, ultrasound, and magnetic resonance imaging (MRI). Knowledge of the image formation and its sources of uncertainties serves as a prelude to the mathematical approaches that form the backbone of the image analysis process.

1.2.2 Stochastic models

Statistical models are an essential part of the engineering, mathematics and physics curricula. They are broad and far-reaching. A focused presentation of the essential background for image analysis allows the reader to understand optimal filtering, segmentation, and construction of CAD models. Chapters 4 to 6 are on random variables, random processes, and random fields, respectively. They serve as a rigorous overview of the main topics on which typical statistical models for image analysis are based. Examples, computer projects, and exercises are listed to help crystallize these concepts, which are traditionally hard to appreciate in isolation. Chapter 7 is dedicated to the problem of probability density estimation, which comes into play as we study various image analysis problems, including segmentation, object detection, and classification.

1.2.3 Computational geometry

The shape of objects in a biomedical image may be described by various methods. We are interested in models of shape that are invariant to size, orientation, and translation. To achieve this, proper approaches for definition and extraction of features are needed. Shape models are embedded in segmentation, registration, and recognition methodologies. In Chapter 8, we discuss basics of topology and computational geometry. Chapter 9 deals with object models in the sense of features and their descriptors. There is a rich computer vision literature on this subject matter, which is crucial for object modeling and the intertwined operations of segmentation and registration.

1.2.4 Variational calculus and level-set methods

Deformable models are based on calculus of variations, and partial differential equations govern their mathematical description. They are hard to understand and implement. Application-oriented treatment, for example in the context of image segmentation, is not very beneficial, as it teaches trickery more than fundamentals. While mathematics can be abstract and may seem “over the head” of those interested in applications and “real-world” problem solving, the fact is: mathematics is mathematics. If we do not treat a mathematical concept properly, this only results in ambiguities and inability to interpret the results of an algorithm.

A general framework for deformable models is attempted in Chapter 10. The level-set method (LSM) for implicit object modeling is examined. We also examine the active contours (or “snake”) model, which is useful for a class of objects that have distinct boundaries. Energy models for the LSM and active contour models are constructed, and the optimization methods for their solution are discussed.

1.2.5 Image analysis tools

We examine in detail the problems of image segmentation and registration and provide examples of an entire image analysis system used to design CAD models. Chapter 11 examines statistical methods for image segmentation. Chapter 12 examines variational and level-set approaches for segmentation. Chapter 13 examines the problem of image registration, with focus on distance-based rigid registration and image-based mutual information methods. Chapter 14 examines elastic registration with focus on "shape registration." These chapters contain the basic theory and various examples of synthetic as well as real-world images. Chapter 15 examines statistical models for shape and appearance. These models are very popular in various problems in computer vision and biomedical image analysis. Some case studies are considered for analysis of spinal imaging, lung nodules, and reconstruction of the human jaw using images and statistics.

1.3 Options for class work

Image analysis is an art and a science combined. It is impossible to enumerate all the approaches that one may use for analysis of biomedical images. There is no substitute for the talent acquired by experimentation and immersion in a particular biomedical problem; this talent defines the "prior knowledge" which is used in the mathematical framework of segmentation and registration, for example. Typically, the engineering curriculum may contain a series of courses on signals and systems in which image processing, biomedical imaging, and computer vision are taught. Some institutions may have many courses on imaging, computer vision, and machine learning; others only a few. This book is intended for use in both environments.

Depending on the background of the students enrolled in the class, this book may be used for a two-semester or a two-quarter sequence on biomedical imaging. Single-semester coverage may be possible with appropriate prerequisites. Instructors have considerable flexibility based on their circumstances. The review chapters (Chapters 2–5) may be skimmed through for students of engineering who have experience with signals and systems, and the basics of probabilistic modeling. A one-semester course on statistical methods could focus on Chapters 4–9, plus 11, 13, and 15. A one-semester course on variational methods might focus on Chapters 8–10, 12 and 14. A one-semester course for advanced students with appropriate background image processing and statistical modeling might focus on Chapters 3 and 6–15. To assist the reader, a set of homework and computer projects is included, and the website for the book is planned to contain updates and extra material. For instructors, course slides and a solution manual are available.

1.4 Other references

Biomedical imaging is multidisciplinary. It involves three major components: modalities, image analysis, and decision-making. There are many books and periodicals on imaging modalities and imaging sensors. There are also a number of proceedings, annual meetings, and periodicals focused on the analysis and applications of biomedical imaging. Such material is readily available through the World Wide Web. In particular, the following annual meetings promote the basics, research, and technologies of biomedical imaging:

1. Radiological Society of North America (RSNA)
2. Magnetic Resonance Imaging
3. Journal of Radiology
4. IEEE Transactions on Medical Imaging – IEEE-TMI
5. Medical Image Analysis – MedIA
6. Computer-Assisted Radiology and Surgery – CARS
7. International Symposium on Biomedical Imaging – ISBI
8. Medical Imaging, Computing and Computer-Assisted Intervention – MICCAI

There are also a number of books that specialize in particular topics of medical imaging. A listing of these books is also accessible by searching the World Wide Web. In each chapter, I include sample references and make every effort to point to the appropriate follow-up reading material.

Part I

Signals and systems, image formation, and image modality

2 Overview of two-dimensional signals and systems

Signals and systems approaches are based on fundamental theory and form the backbone of various disciplines in engineering and physics. Because of their importance, signals and systems are a well-established component of the engineering curriculum. In this chapter we review some of the basics of signals and systems as they pertain to image representation, processing, and analysis. Specifically, we study Fourier methods, which are fundamental to image reconstruction. We also study some systems methodologies of image processing and analysis. In all, the focus of the chapter is on the basics without plunging into the details of mathematical properties. For the expert reader, the chapter may act as a refresher and a quick overview of some of the well-known results of signals and systems. Otherwise, the intent of the chapter is to form a prelude to generalized model-based approaches of biomedical image analysis.

2.1 Definitions

A signal is a functional representation of a physical phenomenon captured by a sensor. That is, a signal may be defined as a transformation from a physical environment into a mathematical domain. The sensors are assumed to be capable of producing a meaningful description of the physical phenomenon. Signals theory deals, in the abstract sense, with the mathematical characterization of the functional forms of the signal, without regard to the phenomenon that generated it. In this chapter, however, we are interested in using the signal properties to infer information about the physical phenomenon. For example, if the signal is generated from an X-ray sensor directed at biological tissue, we are interested in a representation that describes the characteristics of the tissue. Similarly, in an MRI reconstruction application, we are most interested in signal representations that can describe the process of image formation from MRI. In short, we need to keep the physics of the problem in mind as we discuss signal theory.

We may formally define a signal $x(t)$ as a mapping from a sensor's output to the measurement domain, the N-dimensional space R^N. Figure 2.1 illustrates a basic framework for signal generation and representation.

For numerical manipulation of the representation in the computer, a numerical form (digital) of the signal $x(t)$ is needed. The theory of signals and systems deals with signal representations in analog and digital form, and with its manipulation

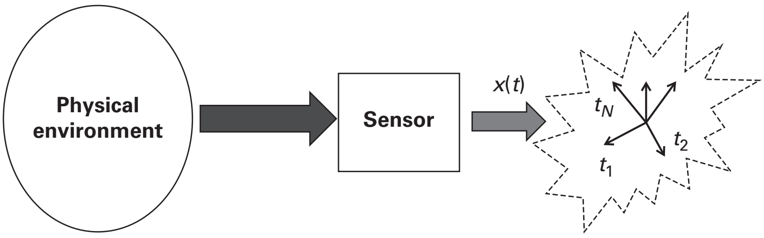

Figure 2.1 Model of signal generation and representation.

to achieve desired characteristics, or to extract particular information. Below we state the basic definitions from signals and systems theory that pertain to biomedical image analysis.

DEFINITION 2.1 *A system is a number of interconnected components, while a system function is a mapping from an input* x(.) $\in R^N$ *to an output* y(.) $\in R^M$*, where the dimensions* N *and* M *need not be the same.*

From the above definition, a system may be a physical entity or a set of steps involved in achieving a particular task. We may consider the process of transforming an *analog* or continuous-time signal (or image) into a *digital* or discrete form as a system. In particular, we are interested in the mapping: $x(t_1,t_2)\rightarrow x[n_1,n_2]$ where the domains of t_1, $t_2,n_1,n_2 \in R$, and so is the range or norm $||x||$. The discrete form may be obtained by a sampling and quantization processes which transforms uniformly sampled values of $x(t_1,t_2)$ into a finite form. That is, in the digitization process, both time and amplitude must be sampled. For the case of band-limited signals (i.e., signals with energy within a finite frequency range), time-sampling is governed by the sampling theorem (Nyquist theorem), which requires that the time-sampling be conducted at a rate at least twice the bandwidth. The amplitude-sampling is determined by the desired accuracy and robustness against spurious noise associated with the signal or the time-sampling apparatus. Books on signals and systems are abundant, and the theory of digital signal/image processing is well established in curricula for engineering, physics and computer science. We refer to the classic books of Oppenheim and Shafer [2.1]; Dudgeon and Mersereau [2.2]; and Lim [2.3]. Below we highlight the fundamental equations of signal representations and the process of sampling a band-limited signal. While our focus is on images (i.e., 2D signals), the results also apply to 1D and to higher dimensions.

2.2 Signal representations

Signals take different forms. They may be deterministic or stochastic (random or non-reproducible); and for either case they may be periodic (amplitude repeats every specific period of the indexing parameter) or aperiodic (has no periodic behavior),