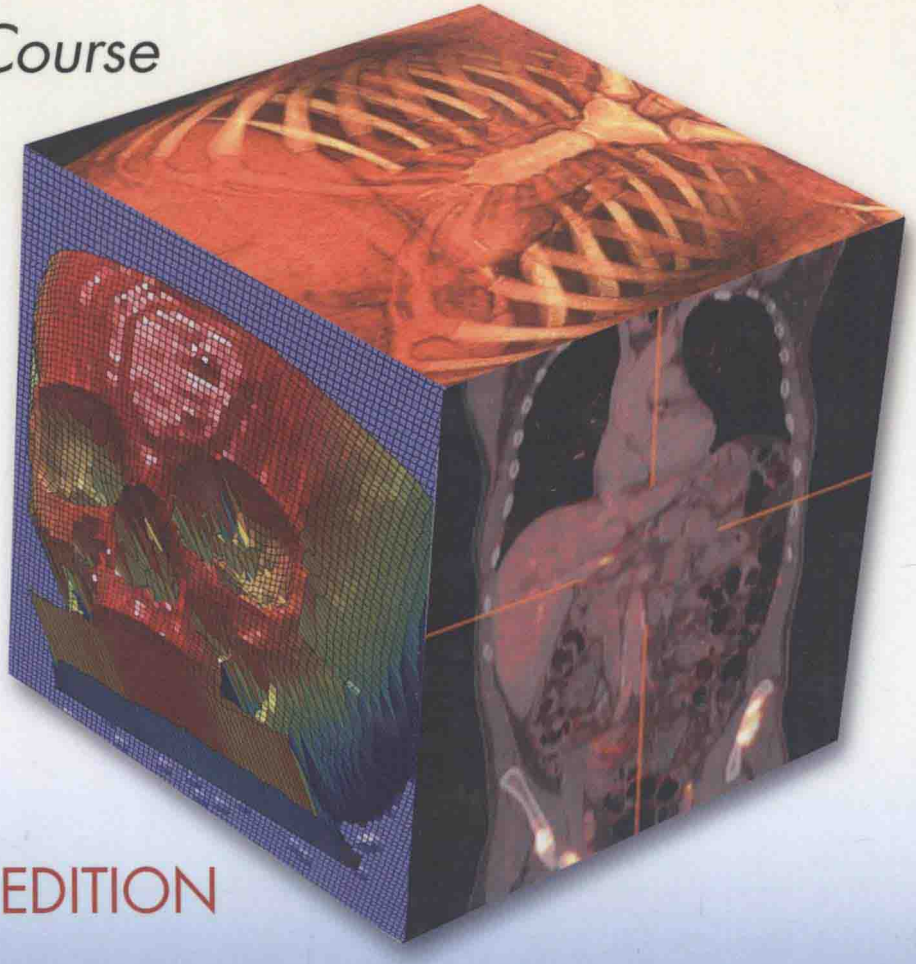
Applied Medical Image Processing

A Basic Course



SECOND EDITION

Wolfgang Birkfellner

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A Basic Course

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I dedicate this book to Katharina, Joseph, Carl and Anton – the most important people in the world to me – and to my academic mentor and advisor, Helmar Bergmann – WB

Foreword

Applied Medical Image Processing: A Basic Course is a superbly measured introduction to the field of medical imaging. Albert Einstein is purported to have said "The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses and axioms". I think Einstein might have been pleased with this wonderful work by Wolfgang Birkfellner (with contributions by Michael Figl and Johann Hummel) who have adroitly tackled the challenge of "less is more" with their basic course on medical image processing. This author is intimately familiar with such a challenge, having published two similar books. As with those works, these authors have attempted to find the elusive compromise between sufficient detail and simple formulations to produce a useful reference in the field that will stand the test of time. I believe this work will meet that test.

The discipline of modern medical imaging is really quite young, having its landmark launch in the early 1970s with the development of CT scanning. With that advent, imaging became fully digital, and three-dimensional. This heralded a rich future for imaging in the healthcare industry facilitated by computers. Computers are so embedded in medical imaging that we have lost sight of them as the enabling technology which has made multi-modality, multi-dimensional, multi-faceted medical imaging possible to do and, indeed, impossible to be without. The roots of this remarkable revolution remain important. A basic understanding of the fundamental principles, tenets and concepts underlying modern medical imaging is critically important in order to advance and realize its full future potential.

That is why this book is significant and timely. It provides a cogent, not overly simplified, not excessively mathematical treatise of basic principles that the student, trainee, young scientist, and junior practitioner can readily grasp and apply. Such empowerment will inevitably lead to advancing the state of the art in medical imaging science. This will be the opportunity presented to those students whose college or university professors select this book as a basic text in their imaging courses. It will enable the diligent student who studies and peruses it to implement the principles and concepts outlined. It will permit him or her to become an active participant, contributor and perhaps even a "new Godfrey Hounsfield".[1]

The authors, based on their personal experience, have established the goal for this introductory volume to teach undergraduate and first year Ph.D. students what they need to know in order to consider and pursue a career in medical imaging, or at least to work productively with those who do. They address four specific aims to achieve this goal:

> produce an essential overview of relevant basic methods in applied medical image processing (the emphasis is on "applied", suggesting the underlying goal that the outcome have practical, useful consequences);

[1] Godfrey Hounsfield was a Nobel prize winner in medicine for his invention of the first CT scanner.

little prior knowledge beyond basic scientific principles is required to grasp the concepts and methods of the work;

promote hands-on learning by providing working programs that demonstrate algorithms and methods rather than mere recital of the theoretical and sometimes complex mathematical underpinnings of these capabilities; and

learning would not be constrained by need for or access to expensive software or sophisticated programming capabilities.

This latter aim is admirably met by providing in the book more than 70 scripts and examples of algorithmic code to be developed, tested, applied and learned by the student using readily available software. The extrapolation from fundamental theory and concepts to working testable code will make the learning experience satisfying and the acquired domain knowledge enduring.

The chapters in the book provide a logical, necessary and quite sufficient coverage of the basics in medical image processing. They include cogent treatments of image acquisition from multiple sources, various image formats and representations, basic image intensity-based transforms, elegant image filtering transforms, image segmentation methods (arguably one of the most challenging, complex, and important capabilities needed in medical image processing), image registration methods (to bring multi-modal images into coherent spatial alignment), rendering and surface modeling approaches to object visualization, and finally (a circular return to the beginning chapter) the closing chapter on CT reconstruction, the same basic principles used by Godfrey Hounsfield over 40 years ago to launch the era of 3D digital imaging of which this book speaks. Throughout this sequence of chapters, the references to prior relevant work, the images used to demonstrate principles and applications, and the clarity of explanation generously included throughout the text, make the learning experience not only memorable, but enjoyable.

This reviewer thinks that the authors of *Applied Medical Image Processing: A Basic Course* should be proud of their work, and derive satisfaction from its publication. It will help facilitate the ongoing, almost magical evolution of modern medical imaging. It will ground the young scientists, engineers and physicians engaged in the field with a solid foundation from which to launch their aspirations to forge and shape the promising future. I believe the book will find its way into the curriculum of science and engineering departments in reputable college undergraduate programs and in seminal university graduate programs. In addition to the matriculated students and learners, other beneficiaries will be faculty and practicing professionals who may use it as a refresher course, returning them to the basics in order to soundly develop new approaches and advances. They, like the great artist Henri Matisse, will be driven to say "I want to reach a point of condensation of sensations to make a picture". I add that they who read this book will be able to make "a truly useful picture".

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Preface to the First Edition

Given the rapid evolution of radiological imaging in the past four decades, medical image processing nowadays is an essential tool for clinical research. Applications range from research in neuroscience, biomechanics and biomedical engineering to clinical routine tasks such as the visualization of huge datasets provided by modern computed tomography systems in radiology, the manufacturing of patient-specific prostheses for orthopedic surgery, the precise planning of dose distributions in radiation oncology, the fusion of multimodal image data for therapy monitoring in internal medicine, and computer-aided neurosurgical interventions.

For more than a decade, we have been working as scientists in this vital field of research at various institutions and hospitals; and still, it is a fascinating subject. We have also taught the subject of medical image processing to undergraduate and graduate students of medical physics, biomedical engineering, medicine and computer science; our audience usually also was at least interested and some students even shared our sense of fascination.

However, besides our own enthusiasm, we always felt a little bit unsatisfied with the available textbooks on the subject of medical image processing. Some of them we found very formal, others were discontinuous due to the fact that they were written by a multitude of authors; some are not very useful as an introduction since they are too specialized, and a few are of little use at all.

On the other hand, there are a number of good introductions to image processing in general, but the requirements of the medical community differ in some important aspects; above all, we do not deal with images in a common sense since most of our imaging machines acquire their data outside the visual spectrum. Furthermore, many modern imaging methods are three-dimensional. The problems of handling voxels and 3D datasets, spatial transforms in 3D, and data fusion are usually not being dealt with to a sufficient extent in these works.

Based on our own experience, we came to the conclusion that an introductory textbook for undergraduate and first year Ph.D. students should have the following features:

> It should give an overview of the relevant basic methods in applied medical image processing.
>
> It should assume little prior knowledge beyond basic applied mathematics, physics and programming.
>
> It should be tangible; rather than giving theoretic derivations, it would be nice to demonstrate how things work in real life.
>
> It should be accessible. The use of expensive software or highly sophisticated programming techniques is to be avoided.

You hold the outcome of such an effort in your hands. Whether we met our own demands is to be judged by you. If you find errors – quite likely, there are a number of them – or if you have suggestions for improvement, we would be grateful if you would point those out to us. Have fun!

Wolfgang Birkfellner, Michael Figl, and Johann Hummel

Preface to the Second Edition

Four years after completing the first edition of our textbook, which resulted from a series of lectures given by us in courses at the Medical University of Vienna as well as other institutions, we now present a second edition of our work. The general outline and the topics of the book have stayed the same, but with growing experience in using the teaching materials presented here, we felt that a little update would be warranted. We've come up with a few additional MATLAB® examples, for instance on using color (Examples 4.5.2 and 8.5.4), on advanced histogram-based image intensity operations (Example 4.5.6), on signal processing using Fourier series (Example 5.4.6.2) and on cone beam computed tomography reconstruction (Example 10.6.5).

Beyond that, we have added a few examples where two popular, freely available 2D and 3D image processing programs, *ImageJ*[2] and *3D Slicer*[3] are used to illustrate how the algorithms and methods discussed are used in "real" software – Examples 3.7.3, 4.5.7, 5.4.2 and 8.5.7 are the result of this effort.

Aside from additional examples and various changes in the text, which mainly give additional illustrative examples and clarifications, we have also written two new chapters for this edition. Chapter 2 was added to give a connection between the algorithms and methods presented and the application of these methods in clinical software from radiology, nuclear medicine and radiotherapy. And our friends Özgür Güler and Ziv Yaniv were kind enough to add Chapter 11 – an image-guided therapy tutorial that allows for 3D tracking of a stylus using a webcam and for "image-guided surgery" on a widely available "patient". We are proud to have this exceptional piece of work in this textbook now, and we strongly encourage all readers and lecturers to utilize this work in class since it builds on many of the techniques introduced in the book and gives an excellent illustrative hands-on example.

Other additional efforts are more of an administrative nature, but we hope that these increase the usefulness of the book as well – above all, we have now named the JPEG images of the illustrations, which are found on the book's website at `www.crcpress.com` under supplementary materials in the folder "JPGs", in the same fashion as in the text. Lecturers may feel free to use these images in their presentations, and now it should be easier to assign these images to corresponding parts of the text.

Since a few more color images became necessary, we have also added a special folder "ColorImages" which holds these illustrations while they are still in grayscale in the book in order to keep the total cost of the volume to reasonable limits.

We were happy to see that the first edition of our textbook was well accepted, and we wish to thank you – the students and lecturers using this volume – for your support. We

[2] Available at the time of printing from `http://rsbweb.nih.gov/ij/` for all major platforms.

[3] See `http://www.slicer.org/`.

hope that the second edition continues to serve the purpose of providing a basic introduction to the world of medical image processing.

Wolfgang Birkfellner, Michael Figl, and Johann Hummel

User Guide

This is an introductory book for those who want to learn about the inner mechanics of medical image processing algorithms. Most likely, the course is not suitable for those who are interested in simply using available medical image processing software. An appropriate reference for this audience is given at the end of this section.

We have organized the course in such a manner that it gives an overview of the physics of medical imaging, which is followed by eight chapters that cover the most important aspects of medical image processing, from image file formats to reconstruction of volumetric images from projection data. Each chapter contains a rather short introduction of the basic concepts and several simple scripts for the Mathworks MATLAB® programming environment (`http://www.mathworks.com`). MATLAB is an interpreted environment for matrix computations, and does not require sophisticated programming skills.

All scripts provided on the accompanying CD were tested using MATLAB 7.7.0 (R2008b) under Microsoft Windows XP and Ubuntu 9.04 Linux. Furthermore, we made sure that all scripts also work with Octave, a freely available MATLAB clone that can be downloaded from `http://www.octave.org`. The scripts were therefore also tested using Octave 3.0.5 under various Linux brands and Microsoft Windows XP. A few tests were also successfully carried out with MATLAB under MacOS X. Some simple 2D image processing tasks are also demonstrated using the freely available GNU image manipulation program GIMP (`http://www.gimp.org`), although commercial programs such as Adobe Photoshop may be used as well. Furthermore, a number of image examples were made using the commercially available AnalyzeAVW software – however, AnalyzeAVW is not required to work with this volume. Public domain software – namely Octave and GIMP, which are both available for Microsoft Windows and Linux operation systems – is all you need. In a few examples, 3DSlicer and ImageJ, two more programs also available in the public domain, are used as well.

To a large extent, we have avoided the excessive use of mathematical formalisms, although a working knowledge of engineering mathematics, especially numerical mathematics and linear algebra, is inevitable. The other prerequisite is some knowledge of basic physics and a little bit of experience in programming, although the scripts are kept very simple. Furthermore, it is inevitable to have some knowledge about basic anatomy and medical terminology if one wants to start a career in medical imaging.

Furthermore, we have also abdicated the use of good MATLAB programming manners for the sake of simplicity, and we do only use very basic functionality of the MATLAB environment.[4] Above all, we do *not* use the *Image Processing Toolbox* of MATLAB. All algorithms are implemented from scratch. Good MATLAB programming would require the use of fast internal procedures and vector notations for optimum performance in such an interpreted environment. For instance, the use of multiple `for` loops, which you will encounter very often in this volume, is a classic example of bad MATLAB programming. Using such a structure in favor of the MATLAB specific vector notation tends to slow down the code. On the other hand, we wanted to keep our code as simple and readable as

[4] An exception is seen in Examples 9.9.5 and 9.9.6, where some functions from the Optimization Toolbox of MATLAB are used.

possible, and therefore we had to make a compromise here. The advantage of this approach lies in the fact that the resulting code is easy to understand, even for students not familiar with MATLAB. Basically speaking, it is more or less so-called *pseudo code*; for some arcane reason, this pseudo code works under MATLAB and Octave. If you are interested in proper MATLAB programming (which unfortunately is of limited use in medical imaging because of the sheer size of modern 3D datasets) you may resort to some of the references given below.

Since we have had the experience that experimenting with small code snippets is a more efficient approach to teaching the details of medical image processing compared to lengthy explanations, we have provided more than 70 MATLAB scripts illustrating the algorithms presented in a simple and straightforward manner. You can find those scripts, together with the associated images, in the `LessonData` folder on the accompanying CD. Working with those lectures and the associated additional tasks is a crucial part of studying this volume. Each script is well documented within the volume.

If the course is to be used in class, one may also use the illustrations from the book, which are provided separately on the CD in a folder `JPGs` – some of them in color, whereas they are printed in grayscale. We have to point out that the algorithms are provided for teaching purposes only. They are not suitable for clinical work; all datasets were completely anonymized, and while the illustrations are made by us, we have indicated the source of the image data in the text where applicable.

LITERATURE

S. Attaway: MATLAB: A Practical Introduction to Programming and Problem Solving, Butterworth-Heinemann, (2009)

G. Dougherty: Digital Image Processing for Medical Applications, Cambridge University Press, (2009)

E. Berry: A Practical Approach to Medical Image Processing, Taylor & Francis, (2007)

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