

Bernd Jähne

Digital Image Processing

Bernd Jähne

Digital Image Processing

6th revised and extended edition

With 248 Figures , 155 Exercises, and CD-ROM

 Springer

Professor Dr. Bernd Jähne
Interdisciplinary Center for Scientific Computing
University of Heidelberg
Im Neuenheimer Feld 368
69120 Heidelberg
Germany
Bernd.Jaehne@iwr.uni-heidelberg.de
www.bernd-jaehne.de
<http://klimt.uni-heidelberg.de>

Library of Congress Control Number: 2005920591

ISBN 3-540-24035-7 Springer Berlin Heidelberg New York
ISBN 978-3-540-24035-8 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in other ways, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution act under German Copyright Law.

Springer is a part of Springer Science + Business Media
springeronline.com

© Springer-Verlag Berlin Heidelberg 2005
Printed in The Netherlands

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: Digital data supplied by author
Cover-Design: Struve & Partner, Heidelberg
Production: medionet AG, Berlin

Printed on acid-free paper 62/3141 Rw 5 4 3 2 1 0

Preface

The sixth edition of this worldwide used textbook was thoroughly revised and extended. Throughout the whole text you will find numerous improvements, extensions, and updates. Above all, I would like to draw your attention to two major changes.

Firstly, the whole textbook is now clearly partitioned into basic and advanced material in order to cope with the ever-increasing field of digital image processing. The most important equations are put into framed boxes. The advanced sections are located in the second part of each chapter and are marked by italic headlines and by a smaller typeface. In this way, you can first work your way through the basic principles of digital image processing without getting overwhelmed by the wealth of the material. You can extend your studies later to selected topics of interest.

The second most notable extension are exercises that are now included at the end of each chapter. These exercise help you to test your understanding, train your skills, and introduce you to real-world image processing tasks. The exercises are marked with one to three stars to indicate their difficulty. An important part of the exercises is a wealth of interactive computer exercises, which cover all topics of this textbook. These exercises are performed with the image processing software **heurisko**[®] (<http://www.heurisko.de>), which is included on the accompanying CD-ROM. In this way you can get own practical experience with almost all topics and algorithms covered by this book. The CD-ROM also includes a large collection of images, image sequences, and volumetric images that can be used together with the computer exercises. Information about the solutions of the exercises and updates of the computer exercises can be found on the homepage of the author at <http://www.bernd-jahne.de>.

Each chapter closes with a section “Further Reading” that guides the interested reader to further references. The appendix includes two chapters. Appendix A gives a quick access to a collection of often used reference material and Appendix B details the notation used throughout the book. The complete text of the book is now available on the accompanying CD-ROM. It is hyperlinked so that it can be used in a very flexible way.

You can jump from the table of contents to the corresponding section, from citations to the bibliography, from the index to the corresponding page, and to any other cross-references. It is also possible to execute the computer exercises directly from the PDF document.

I would like to thank all individuals and organizations who have contributed visual material for this book. The corresponding acknowledgements can be found where the material is used. I would also like to express my sincere thanks to the staff of Springer-Verlag for their constant interest in this book and their professional advice. Special thanks are due to my friends at AEON Verlag & Studio, Hanau, Germany. Without their dedication and professional knowledge it would not have been possible to produce this book and, in particular, the accompanying CD-ROM.

Finally, I welcome any constructive input from you, the reader. I am grateful for comments on improvements or additions and for hints on errors, omissions, or typing errors, which — despite all the care taken — may have slipped attention.

Heidelberg, January 2005

Bernd Jähne

From the preface of the fifth edition

As the fourth edition, the fifth edition is completely revised and extended. The whole text of the book is now arranged in 20 instead of 16 chapters. About one third of text is marked as advanced material. In this way, you will find a quick and systematic way through the basic material and you can extend your studies later to special topics of interest.

The most notable extensions include a detailed discussion on random variables and fields (Chapter 3), 3-D imaging techniques (Chapter 8) and an approach to regularized parameter estimation unifying techniques including inverse problems, adaptive filter techniques such as anisotropic diffusion, and variational approaches for optimal solutions in image restoration, tomographic reconstruction, segmentation, and motion determination (Chapter 17). Each chapter now closes with a section “Further Reading” that guides the interested reader to further references.

The complete text of the book is now available on the accompanying CD-ROM. It is hyperlinked so that it can be used in a very flexible way. You can jump from the table of contents to the corresponding section, from citations to the bibliography, from the index to the corresponding page, and to any other cross-references.

Heidelberg, November 2001

Bernd Jähne

From the preface of the fourth edition

In a fast developing area such as digital image processing a book that appeared in its first edition in 1991 required a complete revision just six years later. But what has not changed is the proven concept, offering a systematic approach to

digital image processing with the aid of concepts and general principles also used in other areas of natural science. In this way, a reader with a general background in natural science or an engineering discipline is given fast access to the complex subject of image processing. The book covers the basics of image processing. Selected areas are treated in detail in order to introduce the reader both to the way of thinking in digital image processing and to some current research topics. Whenever possible, examples and image material are used to illustrate basic concepts. It is assumed that the reader is familiar with elementary matrix algebra and the Fourier transform.

The new edition contains four parts. Part 1 summarizes the basics required for understanding image processing. Thus there is no longer a mathematical appendix as in the previous editions. Part 2 on image acquisition and preprocessing has been extended by a detailed discussion of image formation. Motion analysis has been integrated into Part 3 as one component of feature extraction. Object detection, object form analysis, and object classification are put together in Part 4 on image analysis.

Generally, this book is not restricted to 2-D image processing. Wherever possible, the subjects are treated in such a manner that they are also valid for higher-dimensional image data (volumetric images, image sequences). Likewise, color images are considered as a special case of multichannel images.

Heidelberg, May 1997

Bernd Jähne

From the preface of the first edition

Digital image processing is a fascinating subject in several aspects. Human beings perceive most of the information about their environment through their visual sense. While for a long time images could only be captured by photography, we are now at the edge of another technological revolution which allows image data to be captured, manipulated, and evaluated electronically with computers. With breathtaking pace, computers are becoming more powerful and at the same time less expensive, so that widespread applications for digital image processing emerge. In this way, image processing is becoming a tremendous tool for analyzing image data in all areas of natural science. For more and more scientists digital image processing will be the key to study complex scientific problems they could not have dreamed of tackling only a few years ago. A door is opening for new interdisciplinary cooperation merging computer science with the corresponding research areas.

Many students, engineers, and researchers in all natural sciences are faced with the problem of needing to know more about digital image processing. This book is written to meet this need. The author — himself educated in physics — describes digital image processing as a new tool for scientific research. The book starts with the essentials of image processing and leads — in selected areas — to the state-of-the art. This approach gives an insight as to how image processing really works. The selection of the material is guided by the needs of a researcher who wants to apply image-processing techniques in his or her field. In this sense, this book tries to offer an integral view of image processing from image acquisition to the extraction of the data of interest. Many concepts and mathematical tools that find widespread application in natural sciences are

also applied in digital image processing. Such analogies are pointed out, since they provide an easy access to many complex problems in digital image processing for readers with a general background in natural sciences. The discussion of the general concepts is supplemented with examples from applications on PC-based image processing systems and ready-to-use implementations of important algorithms.

I am deeply indebted to the many individuals who helped me to write this book. I do this by tracing its history. In the early 1980s, when I worked on the physics of small-scale air-sea interaction at the Institute of Environmental Physics at Heidelberg University, it became obvious that these complex phenomena could not be adequately treated with point measuring probes. Consequently, a number of area extended measuring techniques were developed. Then I searched for techniques to extract the physically relevant data from the images and sought for colleagues with experience in digital image processing. The first contacts were established with the Institute for Applied Physics at Heidelberg University and the German Cancer Research Center in Heidelberg. I would like to thank Prof. Dr. J. Bille, Dr. J. Dengler and Dr. M. Schmidt cordially for many eye-opening conversations and their cooperation.

I would also like to thank Prof. Dr. K. O. Münnich, director of the Institute for Environmental Physics. From the beginning, he was open-minded about new ideas on the application of digital image processing techniques in environmental physics. It is due to his farsightedness and substantial support that the research group "Digital Image Processing in Environmental Physics" could develop so fruitfully at his institute. Many of the examples shown in this book are taken from my research at Heidelberg University and the Scripps Institution of Oceanography. I gratefully acknowledge financial support for this research from the German Science Foundation, the European Community, the US National Science Foundation, and the US Office of Naval Research.

La Jolla, California, and Heidelberg, spring 1991

Bernd Jähne

Contents

I Foundation

1 Applications and Tools	3
1.1 A Tool for Science and Technique	3
1.2 Examples of Applications	4
1.3 Hierarchy of Image Processing Operations	15
1.4 Image Processing and Computer Graphics	17
1.5 Cross-disciplinary Nature of Image Processing	17
1.6 Human and Computer Vision	18
1.7 Components of an Image Processing System	21
1.8 <i>Exercises</i>	26
1.9 <i>Further Readings</i>	28
2 Image Representation	31
2.1 Introduction	31
2.2 Spatial Representation of Digital Images	31
2.3 Wave Number Space and Fourier Transform	41
2.4 <i>Discrete Unitary Transforms</i>	63
2.5 <i>Fast Algorithms for Unitary Transforms</i>	67
2.6 <i>Exercises</i>	77
2.7 <i>Further Readings</i>	80
3 Random Variables and Fields	81
3.1 Introduction	81
3.2 Random Variables	83
3.3 Multiple Random Variables	87
3.4 Probability Density Functions	91
3.5 <i>Stochastic Processes and Random Fields</i>	98
3.6 <i>Exercises</i>	102
3.7 <i>Further Readings</i>	104
4 Neighborhood Operations	105
4.1 Basic Properties and Purpose	105
4.2 Linear Shift-Invariant Filters	108
4.3 Rank Value Filters	119
4.4 <i>LSI-Filters: Further Properties</i>	120
4.5 <i>Recursive Filters</i>	122

4.6	<i>Exercises</i>	131
4.7	<i>Further Readings</i>	134
5	Multiscale Representation	135
5.1	Scale	135
5.2	Multigrid Representations	138
5.3	<i>Scale Spaces</i>	144
5.4	<i>Exercises</i>	152
5.5	<i>Further Readings</i>	153
 II Image Formation and Preprocessing 		
6	Quantitative Visualization	157
6.1	Introduction	157
6.2	Radiometry, Photometry, Spectroscopy, and Color	159
6.3	<i>Waves and Particles</i>	168
6.4	<i>Interactions of Radiation with Matter</i>	174
6.5	<i>Exercises</i>	186
6.6	<i>Further Readings</i>	187
7	Image Formation	189
7.1	Introduction	189
7.2	World and Camera Coordinates	189
7.3	Ideal Imaging: Perspective Projection	192
7.4	Real Imaging	195
7.5	Radiometry of Imaging	201
7.6	<i>Linear System Theory of Imaging</i>	205
7.7	<i>Homogeneous Coordinates</i>	212
7.8	<i>Exercises</i>	214
7.9	<i>Further Readings</i>	215
8	3-D Imaging	217
8.1	Basics	217
8.2	<i>Depth from Triangulation</i>	221
8.3	<i>Depth from Time-of-Flight</i>	228
8.4	<i>Depth from Phase: Interferometry</i>	229
8.5	<i>Shape from Shading</i>	229
8.6	<i>Depth from Multiple Projections: Tomography</i>	235
8.7	<i>Exercises</i>	241
8.8	<i>Further Readings</i>	242
9	Digitization, Sampling, Quantization	243
9.1	Definition and Effects of Digitization	243
9.2	Image Formation, Sampling, Windowing	245
9.3	Reconstruction from Samples	249
9.4	<i>Multidimensional Sampling on Nonorthogonal Grids</i>	251
9.5	<i>Quantization</i>	253
9.6	<i>Exercises</i>	254

9.7	<i>Further Readings</i>	255
10	Pixel Processing	257
10.1	Introduction	257
10.2	Homogeneous Point Operations	258
10.3	Inhomogeneous Point Operations	268
10.4	Geometric Transformations	275
10.5	Interpolation	279
10.6	<i>Optimized Interpolation</i>	286
10.7	<i>Multichannel Point Operations</i>	291
10.8	<i>Exercises</i>	293
10.9	<i>Further Readings</i>	295
 III Feature Extraction 		
11	Averaging	299
11.1	Introduction	299
11.2	General Properties of Averaging Filters	299
11.3	Box Filter	302
11.4	Binomial Filter	306
11.5	Efficient Large-Scale Averaging	312
11.6	<i>Nonlinear Averaging</i>	321
11.7	<i>Averaging in Multichannel Images</i>	326
11.8	<i>Exercises</i>	328
11.9	<i>Further Readings</i>	330
12	Edges	331
12.1	Introduction	331
12.2	Differential Description of Signal Changes	332
12.3	General Properties of Edge Filters	335
12.4	Gradient-Based Edge Detection	338
12.5	Edge Detection by Zero Crossings	345
12.6	<i>Optimized Edge Detection</i>	347
12.7	<i>Regularized Edge Detection</i>	349
12.8	<i>Edges in Multichannel Images</i>	353
12.9	<i>Exercises</i>	355
12.10	<i>Further Readings</i>	357
13	Simple Neighborhoods	359
13.1	Introduction	359
13.2	Properties of Simple Neighborhoods	360
13.3	First-Order Tensor Representation	364
13.4	<i>Local Wave Number and Phase</i>	375
13.5	<i>Further Tensor Representations</i>	384
13.6	<i>Exercises</i>	395
13.7	<i>Further Readings</i>	396

14 Motion	397
14.1 Introduction	397
14.2 Basics	398
14.3 First-Order Differential Methods	413
14.4 Tensor Methods	418
14.5 Correlation Methods	423
14.6 <i>Phase Method</i>	426
14.7 <i>Additional Methods</i>	428
14.8 <i>Exercises</i>	434
14.9 <i>Further Readings</i>	434
15 Texture	435
15.1 Introduction	435
15.2 First-Order Statistics	438
15.3 Rotation and Scale Variant Texture Features	442
15.4 <i>Exercises</i>	446
15.5 <i>Further Readings</i>	446
IV Image Analysis	
16 Segmentation	449
16.1 Introduction	449
16.2 Pixel-Based Segmentation	449
16.3 Edge-Based Segmentation	453
16.4 Region-Based Segmentation	454
16.5 Model-Based Segmentation	458
16.6 <i>Exercises</i>	461
16.7 <i>Further Readings</i>	462
17 Regularization and Modeling	463
17.1 Introduction	463
17.2 <i>Continuous Modeling I: Variational Approach</i>	466
17.3 <i>Continuous Modeling II: Diffusion</i>	473
17.4 <i>Discrete Modeling: Inverse Problems</i>	478
17.5 <i>Inverse Filtering</i>	486
17.6 <i>Further Equivalent Approaches</i>	492
17.7 <i>Exercises</i>	498
17.8 <i>Further Readings</i>	500
18 Morphology	501
18.1 Introduction	501
18.2 Neighborhood Operations on Binary Images	501
18.3 General Properties	503
18.4 Composite Morphological Operators	506
18.5 <i>Exercises</i>	512
18.6 <i>Further Readings</i>	514

19 Shape Presentation and Analysis	515
19.1 Introduction	515
19.2 Representation of Shape	515
19.3 Moment-Based Shape Features	520
19.4 Fourier Descriptors	522
19.5 Shape Parameters	528
19.6 <i>Exercises</i>	531
19.7 <i>Further Readings</i>	532
20 Classification	533
20.1 Introduction	533
20.2 Feature Space	536
20.3 Simple Classification Techniques	543
20.4 <i>Exercises</i>	548
20.5 <i>Further Readings</i>	549
V Reference Part	
A Reference Material	553
B Notation	577
Bibliography	585
Index	597

Part I

Foundation