

Digital Image Processing

Third Edition

Rafael C. Gonzalez

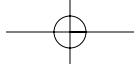
University of Tennessee

Richard E. Woods

MedData Interactive



Upper Saddle River, NJ 07458

**Library of Congress Cataloging-in-Publication Data on File**

Vice President and Editorial Director, ECS: *Marcia J. Horton*
Executive Editor: *Michael McDonald*
Associate Editor: *Alice Dworkin*
Editorial Assistant: *William Opaluch*
Managing Editor: *Scott Disanno*
Production Editor: *Rose Kernan*
Director of Creative Services: *Paul Belfanti*
Creative Director: *Juan Lopez*
Art Director: *Heather Scott*
Art Editors: *Gregory Dulles* and *Thomas Benfatti*
Manufacturing Manager: *Alexis Heydt-Long*
Manufacturing Buyer: *Lisa McDowell*
Senior Marketing Manager: *Tim Galligan*



© 2008 by Pearson Education, Inc.
Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

All rights reserved. No part of this book may be reproduced, in any form, or by any means, without permission in writing from the publisher.

Pearson Prentice Hall® is a trademark of Pearson Education, Inc.

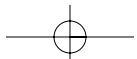
The authors and publisher of this book have used their best efforts in preparing this book. These efforts include the development, research, and testing of the theories and programs to determine their effectiveness. The authors and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The authors and publisher shall not be liable in any event for incidental or consequential damages with, or arising out of, the furnishing, performance, or use of these programs.

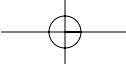
Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-168728-x
978-0-13-168728-8

Pearson Education Ltd., London
Pearson Education Australia Pty. Ltd., Sydney
Pearson Education Singapore, Pte., Ltd.
Pearson Education North Asia Ltd., Hong Kong
Pearson Education Canada, Inc., Toronto
Pearson Educación de Mexico, S.A. de C.V.
Pearson Education—Japan, Tokyo
Pearson Education Malaysia, Pte. Ltd.
Pearson Education, Inc., Upper Saddle River, New Jersey





Preface

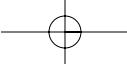
When something can be read without effort,
great effort has gone into its writing.

Enrique Jardiel Poncela

This edition of *Digital Image Processing* is a major revision of the book. As in the 1977 and 1987 editions by Gonzalez and Wintz, and the 1992 and 2002 editions by Gonzalez and Woods, this fifth-generation edition was prepared with students and instructors in mind. The principal objectives of the book continue to be to provide an introduction to basic concepts and methodologies for digital image processing, and to develop a foundation that can be used as the basis for further study and research in this field. To achieve these objectives, we focused again on material that we believe is fundamental and whose scope of application is not limited to the solution of specialized problems. The mathematical complexity of the book remains at a level well within the grasp of college seniors and first-year graduate students who have introductory preparation in mathematical analysis, vectors, matrices, probability, statistics, linear systems, and computer programming. The book Web site provides tutorials to support readers needing a review of this background material.

One of the principal reasons this book has been the world leader in its field for more than 30 years is the level of attention we pay to the changing educational needs of our readers. The present edition is based on the most extensive survey we have ever conducted. The survey involved faculty, students, and independent readers of the book in 134 institutions from 32 countries. The major findings of the survey indicated a need for:

- A more comprehensive introduction early in the book to the mathematical tools used in image processing.
- An expanded explanation of histogram processing techniques.
- Stating complex algorithms in step-by-step summaries.
- An expanded explanation of spatial correlation and convolution.
- An introduction to fuzzy set theory and its application to image processing.
- A revision of the material dealing with the frequency domain, starting with basic principles and showing how the discrete Fourier transform follows from data sampling.
- Coverage of computed tomography (CT).
- Clarification of basic concepts in the wavelets chapter.
- A revision of the data compression chapter to include more video compression techniques, updated standards, and watermarking.
- Expansion of the chapter on morphology to include morphological reconstruction and a revision of gray-scale morphology.



- Expansion of the coverage on image segmentation to include more advanced edge detection techniques such as Canny's algorithm, and a more comprehensive treatment of image thresholding.
- An update of the chapter dealing with image representation and description.
- Streamlining the material dealing with structural object recognition.

The new and reorganized material that resulted in the present edition is our attempt at providing a reasonable degree of balance between rigor, clarity of presentation, and the findings of the market survey, while at the same time keeping the length of the book at a manageable level. The major changes in this edition of the book are as follows.

Chapter 1: A few figures were updated and part of the text was rewritten to correspond to changes in later chapters.

Chapter 2: Approximately 50% of this chapter was revised to include new images and clearer explanations. Major revisions include a new section on image interpolation and a comprehensive new section summarizing the principal mathematical tools used in the book. Instead of presenting "dry" mathematical concepts one after the other, however, we took this opportunity to bring into Chapter 2 a number of image processing applications that were scattered throughout the book. For example, image averaging and image subtraction were moved to this chapter to illustrate arithmetic operations. This follows a trend we began in the second edition of the book to move as many applications as possible early in the discussion not only as illustrations, but also as motivation for students. After finishing the newly organized Chapter 2, a reader will have a basic understanding of how digital images are manipulated and processed. This is a solid platform upon which the rest of the book is built.

Chapter 3: Major revisions of this chapter include a detailed discussion of spatial correlation and convolution, and their application to image filtering using spatial masks. We also found a consistent theme in the market survey asking for numerical examples to illustrate histogram equalization and specification, so we added several such examples to illustrate the mechanics of these processing tools. Coverage of fuzzy sets and their application to image processing was also requested frequently in the survey. We included in this chapter a new section on the foundation of fuzzy set theory, and its application to intensity transformations and spatial filtering, two of the principal uses of this theory in image processing.

Chapter 4: The topic we heard most about in comments and suggestions during the past four years dealt with the changes we made in Chapter 4 from the first to the second edition. Our objective in making those changes was to simplify the presentation of the Fourier transform and the frequency domain. Evidently, we went too far, and numerous users of the book complained that the new material was too superficial. We corrected that problem in the present edition. The material now begins with the Fourier transform of one continuous variable and proceeds to derive the discrete Fourier transform starting with basic concepts of sampling and convolution. A byproduct of the flow of this

material is an intuitive derivation of the sampling theorem and its implications. The 1-D material is then extended to 2-D, where we give a number of examples to illustrate the effects of sampling on digital images, including aliasing and moiré patterns. The 2-D discrete Fourier transform is then illustrated and a number of important properties are derived and summarized. These concepts are then used as the basis for filtering in the frequency domain. Finally, we discuss implementation issues such as transform decomposition and the derivation of a fast Fourier transform algorithm. At the end of this chapter, the reader will have progressed from sampling of 1-D functions through a clear derivation of the foundation of the discrete Fourier transform and some of its most important uses in digital image processing.

Chapter 5: The major revision in this chapter was the addition of a section dealing with image reconstruction from projections, with a focus on computed tomography (CT). Coverage of CT starts with an intuitive example of the underlying principles of image reconstruction from projections and the various imaging modalities used in practice. We then derive the Radon transform and the Fourier slice theorem and use them as the basis for formulating the concept of filtered backprojections. Both parallel- and fan-beam reconstruction are discussed and illustrated using several examples. Inclusion of this material was long overdue and represents an important addition to the book.

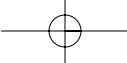
Chapter 6: Revisions to this chapter were limited to clarifications and a few corrections in notation. No new concepts were added.

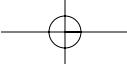
Chapter 7: We received numerous comments regarding the fact that the transition from previous chapters into wavelets was proving difficult for beginners. Several of the foundation sections were rewritten in an effort to make the material clearer.

Chapter 8: This chapter was rewritten completely to bring it up to date. New coding techniques, expanded coverage of video, a revision of the section on standards, and an introduction to image watermarking are among the major changes. The new organization will make it easier for beginning students to follow the material.

Chapter 9: The major changes in this chapter are the inclusion of a new section on morphological reconstruction and a complete revision of the section on gray-scale morphology. The inclusion of morphological reconstruction for both binary and gray-scale images made it possible to develop more complex and useful morphological algorithms than before.

Chapter 10: This chapter also underwent a major revision. The organization is as before, but the new material includes greater emphasis on basic principles as well as discussion of more advanced segmentation techniques. Edge models are discussed and illustrated in more detail, as are properties of the gradient. The Marr-Hildreth and Canny edge detectors are included to illustrate more advanced edge detection techniques. The section on thresholding was rewritten also to include Otsu's method, an optimum thresholding technique whose popularity has increased significantly over the past few years. We introduced this approach in favor of optimum thresholding based on the Bayes classification rule, not only because it is easier to understand and implement, but also





because it is used considerably more in practice. The Bayes approach was moved to Chapter 12, where the Bayes decision rule is discussed in more detail. We also added a discussion on how to use edge information to improve thresholding and several new adaptive thresholding examples. Except for minor clarifications, the sections on morphological watersheds and the use of motion for segmentation are as in the previous edition.

Chapter 11: The principal changes in this chapter are the inclusion of a boundary-following algorithm, a detailed derivation of an algorithm to fit a minimum-perimeter polygon to a digital boundary, and a new section on co-occurrence matrices for texture description. Numerous examples in Sections 11.2 and 11.3 are new, as are all the examples in Section 11.4.

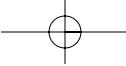
Chapter 12: Changes in this chapter include a new section on matching by correlation and a new example on using the Bayes classifier to recognize regions of interest in multispectral images. The section on structural classification now limits discussion only to string matching.

All the revisions just mentioned resulted in over 400 new images, over 200 new line drawings and tables, and more than 80 new homework problems. Where appropriate, complex processing procedures were summarized in the form of step-by-step algorithm formats. The references at the end of all chapters were updated also.

The book Web site, established during the launch of the second edition, has been a success, attracting more than 20,000 visitors each month. The site was redesigned and upgraded to correspond to the launch of this edition. For more details on features and content, see *The Book Web Site*, following the *Acknowledgments*.

This edition of *Digital Image Processing* is a reflection of how the educational needs of our readers have changed since 2002. As is usual in a project such as this, progress in the field continues after work on the manuscript stops. One of the reasons why this book has been so well accepted since it first appeared in 1977 is its continued emphasis on fundamental concepts—an approach that, among other things, attempts to provide a measure of stability in a rapidly-evolving body of knowledge. We have tried to follow the same principle in preparing this edition of the book.

R. C. G.
R. E. W.



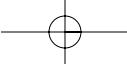
Acknowledgments

We are indebted to a number of individuals in academic circles as well as in industry and government who have contributed to this edition of the book. Their contributions have been important in so many different ways that we find it difficult to acknowledge them in any other way but alphabetically. In particular, we wish to extend our appreciation to our colleagues Mongi A. Abidi, Steven L. Eddins, Yongmin Kim, Bryan Morse, Andrew Oldroyd, Ali M. Reza, Edgardo Felipe Riveron, Jose Ruiz Shulcloper, and Cameron H. G. Wright for their many suggestions on how to improve the presentation and/or the scope of coverage in the book.

Numerous individuals and organizations provided us with valuable assistance during the writing of this edition. Again, we list them alphabetically. We are particularly indebted to Courtney Esposito and Naomi Fernandes at The Mathworks for providing us with MATLAB software and support that were important in our ability to create or clarify many of the examples and experimental results included in this edition of the book. A significant percentage of the new images used in this edition (and in some cases their history and interpretation) were obtained through the efforts of individuals whose contributions are sincerely appreciated. In particular, we wish to acknowledge the efforts of Serge Beucher, Melissa D. Binde, James Blankenship, Uwe Boos, Ernesto Bribiesca, Michael E. Casey, Michael W. Davidson, Susan L. Forsburg, Thomas R. Gest, Lalit Gupta, Daniel A. Hammer, Zhong He, Roger Heady, Juan A. Herrera, John M. Hudak, Michael Hurwitz, Chris J. Johannsen, Rhonda Knighton, Don P. Mitchell, Ashley Mohamed, A. Morris, Curtis C. Ober, Joseph E. Pascente, David. R. Pickens, Michael Robinson, Barrett A. Schaefer, Michael Shaffer, Pete Sites, Sally Stowe, Craig Watson, David K. Wehe, and Robert A. West. We also wish to acknowledge other individuals and organizations cited in the captions of numerous figures throughout the book for their permission to use that material.

Special thanks go to Vince O'Brien, Rose Kernan, Scott Disanno, Michael McDonald, Joe Ruddick, Heather Scott, and Alice Dworkin, at Prentice Hall. Their creativity, assistance, and patience during the production of this book are truly appreciated.

R.C.G.
R.E.W.



The Book Web Site

www.prenhall.com/gonzalezwoods

or its mirror site,

www.imageprocessingplace.com

Digital Image Processing is a completely self-contained book. However, the companion Web site offers additional support in a number of important areas.

For the Student or Independent Reader the site contains

- Reviews in areas such as probability, statistics, vectors, and matrices.
- Complete solutions to selected problems.
- Computer projects.
- A Tutorials section containing dozens of tutorials on most of the topics discussed in the book.
- A database containing all the images in the book.

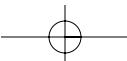
For the Instructor the site contains

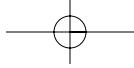
- An *Instructor's Manual* with complete solutions to all the problems in the book, as well as course and laboratory teaching guidelines. The manual is available free of charge to instructors who have adopted the book for classroom use.
- Classroom presentation materials in PowerPoint format.
- Material removed from previous editions, downloadable in convenient PDF format.
- Numerous links to other educational resources.

For the Practitioner the site contains additional specialized topics such as

- Links to commercial sites.
- Selected new references.
- Links to commercial image databases.

The Web site is an ideal tool for keeping the book current between editions by including new topics, digital images, and other relevant material that has appeared after the book was published. Although considerable care was taken in the production of the book, the Web site is also a convenient repository for any errors that may be discovered between printings. References to the book Web site are designated in the book by the following icon:





About the Authors

Rafael C. Gonzalez

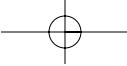
R. C. Gonzalez received the B.S.E.E. degree from the University of Miami in 1965 and the M.E. and Ph.D. degrees in electrical engineering from the University of Florida, Gainesville, in 1967 and 1970, respectively. He joined the Electrical and Computer Engineering Department at the University of Tennessee, Knoxville (UTK) in 1970, where he became Associate Professor in 1973, Professor in 1978, and Distinguished Service Professor in 1984. He served as Chairman of the department from 1994 through 1997. He is currently a Professor Emeritus at UTK.

Gonzalez is the founder of the Image & Pattern Analysis Laboratory and the Robotics & Computer Vision Laboratory at the University of Tennessee. He also founded Perceptics Corporation in 1982 and was its president until 1992. The last three years of this period were spent under a full-time employment contract with Westinghouse Corporation, who acquired the company in 1989.

Under his direction, Perceptics became highly successful in image processing, computer vision, and laser disk storage technology. In its initial ten years, Perceptics introduced a series of innovative products, including: The world's first commercially-available computer vision system for automatically reading license plates on moving vehicles; a series of large-scale image processing and archiving systems used by the U.S. Navy at six different manufacturing sites throughout the country to inspect the rocket motors of missiles in the Trident II Submarine Program; the market-leading family of imaging boards for advanced Macintosh computers; and a line of trillion-byte laser disk products.

He is a frequent consultant to industry and government in the areas of pattern recognition, image processing, and machine learning. His academic honors for work in these fields include the 1977 UTK College of Engineering Faculty Achievement Award; the 1978 UTK Chancellor's Research Scholar Award; the 1980 Magnavox Engineering Professor Award; and the 1980 M.E. Brooks Distinguished Professor Award. In 1981 he became an IBM Professor at the University of Tennessee and in 1984 he was named a Distinguished Service Professor there. He was awarded a Distinguished Alumnus Award by the University of Miami in 1985, the Phi Kappa Phi Scholar Award in 1986, and the University of Tennessee's Nathan W. Dougherty Award for Excellence in Engineering in 1992.

Honors for industrial accomplishment include the 1987 IEEE Outstanding Engineer Award for Commercial Development in Tennessee; the 1988 Albert Rose Nat'l Award for Excellence in Commercial Image Processing; the 1989 B. Otto Wheeley Award for Excellence in Technology Transfer; the 1989 Coopers and Lybrand Entrepreneur of the Year Award; the 1992 IEEE Region 3 Outstanding Engineer Award; and the 1993 Automated Imaging Association National Award for Technology Development.



Gonzalez is author or co-author of over 100 technical articles, two edited books, and four textbooks in the fields of pattern recognition, image processing, and robotics. His books are used in over 1000 universities and research institutions throughout the world. He is listed in the prestigious Marquis Who's Who in America, Marquis Who's Who in Engineering, Marquis Who's Who in the World, and in 10 other national and international biographical citations. He is the co-holder of two U.S. Patents, and has been an associate editor of the *IEEE Transactions on Systems, Man and Cybernetics*, and the *International Journal of Computer and Information Sciences*. He is a member of numerous professional and honorary societies, including Tau Beta Pi, Phi Kappa Phi, Eta Kappa Nu, and Sigma Xi. He is a Fellow of the IEEE.

Richard E. Woods

Richard E. Woods earned his B.S., M.S., and Ph.D. degrees in Electrical Engineering from the University of Tennessee, Knoxville. His professional experiences range from entrepreneurial to the more traditional academic, consulting, governmental, and industrial pursuits. Most recently, he founded MedData Interactive, a high technology company specializing in the development of handheld computer systems for medical applications. He was also a founder and Vice President of Perceptics Corporation, where he was responsible for the development of many of the company's quantitative image analysis and autonomous decision-making products.

Prior to Perceptics and MedData, Dr. Woods was an Assistant Professor of Electrical Engineering and Computer Science at the University of Tennessee and prior to that, a computer applications engineer at Union Carbide Corporation. As a consultant, he has been involved in the development of a number of special-purpose digital processors for a variety of space and military agencies, including NASA, the Ballistic Missile Systems Command, and the Oak Ridge National Laboratory.

Dr. Woods has published numerous articles related to digital signal processing and is a member of several professional societies, including Tau Beta Pi, Phi Kappa Phi, and the IEEE. In 1986, he was recognized as a Distinguished Engineering Alumnus of the University of Tennessee.