



Digital Image Processing

Second Edition

Rafael C. Gonzalez

University of Tennessee

Richard E. Woods

MedData Interactive



Prentice Hall
Upper Saddle River, New Jersey 07458

Library of Congress Cataloging-in-Publication Data

Gonzalez, Rafael C.

Digital Image Processing / Richard E. Woods

p. cm.

Includes bibliographical references

ISBN 0-201-18075-8

1. Digital Imaging. 2. Digital Techniques. I. Title.

TA1632.G66 2001

621.3—dc21

2001035846

CIP

Vice-President and Editorial Director, ECS: *Marcia J. Horton*

Publisher: *Tom Robbins*

Associate Editor: *Alice Dworkin*

Editorial Assistant: *Jody McDonnell*

Vice President and Director of Production and Manufacturing, ESM: *David W. Riccardi*

Executive Managing Editor: *Vince O'Brien*

Managing Editor: *David A. George*

Production Editor: *Rose Kernan*

Composition: *Prepare, Inc.*

Director of Creative Services: *Paul Belfanti*

Creative Director: *Carole Anson*

Art Director and Cover Designer: *Heather Scott*

Art Editor: *Greg Dulles*

Manufacturing Manager: *Trudy Piscioti*

Manufacturing Buyer: *Lisa McDowell*

Senior Marketing Manager: *Jennie Burger*



© 2002 by Prentice-Hall, 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.

The author 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 author and publisher make no warranty of any kind, expressed or implied, with regard to these programs or the documentation contained in this book. The author and publisher shall not be liable in any event for incidental or consequential damages in connection 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: 0-201-18075-8

Pearson Education Ltd., *London*

Pearson Education Australia Pty., Limited, *Sydney*

Pearson Education Singapore, Pte. Ltd.

Pearson Education North Asia Ltd., *Hong Kong*

Pearson Education Canada, Ltd., *Toronto*

Pearson Education de Mexico, S.A. de C.V.

Pearson Education—Japan, *Tokyo*

Pearson Education Malaysia, Pte. Ltd.

Pearson Education, *Upper Saddle River, New Jersey*

Contents

Preface xv

Acknowledgements xviii

About the Authors xix

1 Introduction 15

- 1.1 What Is Digital Image Processing? 15
- 1.2 The Origins of Digital Image Processing 17
- 1.3 Examples of Fields that Use Digital Image Processing 21
 - 1.3.1 Gamma-Ray Imaging 22
 - 1.3.2 X-ray Imaging 23
 - 1.3.3 Imaging in the Ultraviolet Band 25
 - 1.3.4 Imaging in the Visible and Infrared Bands 26
 - 1.3.5 Imaging in the Microwave Band 32
 - 1.3.6 Imaging in the Radio Band 34
 - 1.3.7 Examples in which Other Imaging Modalities Are Used 34
- 1.4 Fundamental Steps in Digital Image Processing 39
- 1.5 Components of an Image Processing System 42
 - Summary 44
 - References and Further Reading 45

2 Digital Image Fundamentals 34

- 2.1 Elements of Visual Perception 34
 - 2.1.1 Structure of the Human Eye 35
 - 2.1.2 Image Formation in the Eye 37
 - 2.1.3 Brightness Adaptation and Discrimination 38
- 2.2 Light and the Electromagnetic Spectrum 42
- 2.3 Image Sensing and Acquisition 45
 - 2.3.1 Image Acquisition Using a Single Sensor 47
 - 2.3.2 Image Acquisition Using Sensor Strips 48
 - 2.3.3 Image Acquisition Using Sensor Arrays 49
 - 2.3.4 A Simple Image Formation Model 50
- 2.4 Image Sampling and Quantization 52
 - 2.4.1 Basic Concepts in Sampling and Quantization 52
 - 2.4.2 Representing Digital Images 54
 - 2.4.3 Spatial and Gray-Level Resolution 57
 - 2.4.4 Aliasing and Moiré Patterns 62
 - 2.4.5 Zooming and Shrinking Digital Images 64

- 2.5 Some Basic Relationships Between Pixels 66**
 - 2.5.1 Neighbors of a Pixel 66
 - 2.5.2 Adjacency, Connectivity, Regions, and Boundaries 66
 - 2.5.3 Distance Measures 68
 - 2.5.4 Image Operations on a Pixel Basis 69
- 2.6 Linear and Nonlinear Operations 70**
 - Summary 70
 - References and Further Reading 70
 - Problems 71

3 *Image Enhancement in the Spatial Domain* 75

- 3.1 Background 76**
- 3.2 Some Basic Gray Level Transformations 78**
 - 3.2.1 Image Negatives 78
 - 3.2.2 Log Transformations 79
 - 3.2.3 Power-Law Transformations 80
 - 3.2.4 Piecewise-Linear Transformation Functions 85
- 3.3 Histogram Processing 88**
 - 3.3.1 Histogram Equalization 91
 - 3.3.2 Histogram Matching (Specification) 94
 - 3.3.3 Local Enhancement 103
 - 3.3.4 Use of Histogram Statistics for Image Enhancement 103
- 3.4 Enhancement Using Arithmetic/Logic Operations 108**
 - 3.4.1 Image Subtraction 110
 - 3.4.2 Image Averaging 112
- 3.5 Basics of Spatial Filtering 116**
- 3.6 Smoothing Spatial Filters 119**
 - 3.6.1 Smoothing Linear Filters 119
 - 3.6.2 Order-Statistics Filters 123
- 3.7 Sharpening Spatial Filters 125**
 - 3.7.1 Foundation 125
 - 3.7.2 Use of Second Derivatives for Enhancement—The Laplacian 128
 - 3.7.3 Use of First Derivatives for Enhancement—The Gradient 134
- 3.8 Combining Spatial Enhancement Methods 137**
 - Summary 141
 - References and Further Reading 142
 - Problems 142

4 *Image Enhancement in the Frequency Domain* 147

- 4.1 Background 148**

4.2	Introduction to the Fourier Transform and the Frequency Domain	149
4.2.1	The One-Dimensional Fourier Transform and its Inverse	150
4.2.2	The Two-Dimensional DFT and Its Inverse	154
4.2.3	Filtering in the Frequency Domain	156
4.2.4	Correspondence between Filtering in the Spatial and Frequency Domains	161
4.3	Smoothing Frequency-Domain Filters	167
4.3.1	Ideal Lowpass Filters	167
4.3.2	Butterworth Lowpass Filters	173
4.3.3	Gaussian Lowpass Filters	175
4.3.4	Additional Examples of Lowpass Filtering	178
4.4	Sharpening Frequency Domain Filters	180
4.4.1	Ideal Highpass Filters	182
4.4.2	Butterworth Highpass Filters	183
4.4.3	Gaussian Highpass Filters	184
4.4.4	The Laplacian in the Frequency Domain	185
4.4.5	Unsharp Masking, High-Boost Filtering, and High-Frequency Emphasis Filtering	187
4.5	Homomorphic Filtering	191
4.6	Implementation	194
4.6.1	Some Additional Properties of the 2-D Fourier Transform	194
4.6.2	Computing the Inverse Fourier Transform Using a Forward Transform Algorithm	198
4.6.3	More on Periodicity: the Need for Padding	199
4.6.4	The Convolution and Correlation Theorems	205
4.6.5	Summary of Properties of the 2-D Fourier Transform	208
4.6.6	The Fast Fourier Transform	208
4.6.7	Some Comments on Filter Design	213
	Summary	214
	References	214
	Problems	215

5 *Image Restoration* 220

5.1	A Model of the Image Degradation/Restoration Process	221
5.2	Noise Models	222
5.2.1	Spatial and Frequency Properties of Noise	222
5.2.2	Some Important Noise Probability Density Functions	222
5.2.3	Periodic Noise	227
5.2.4	Estimation of Noise Parameters	227
5.3	Restoration in the Presence of Noise Only—Spatial Filtering	230
5.3.1	Mean Filters	231
5.3.2	Order-Statistics Filters	233
5.3.3	Adaptive Filters	237

- 5.4 Periodic Noise Reduction by Frequency Domain Filtering 243**
 - 5.4.1 Bandreject Filters 244
 - 5.4.2 Bandpass Filters 245
 - 5.4.3 Notch Filters 246
 - 5.4.4 Optimum Notch Filtering 248
- 5.5 Linear, Position-Invariant Degradations 254**
- 5.6 Estimating the Degradation Function 256**
 - 5.6.1 Estimation by Image Observation 256
 - 5.6.2 Estimation by Experimentation 257
 - 5.6.3 Estimation by Modeling 258
- 5.7 Inverse Filtering 261**
- 5.8 Minimum Mean Square Error (Wiener) Filtering 262**
- 5.9 Constrained Least Squares Filtering 266**
- 5.10 Geometric Mean Filter 270**
- 5.11 Geometric Transformations 270**
 - 5.11.1 Spatial Transformations 271
 - 5.11.2 Gray-Level Interpolation 272
- Summary 276**
- References and Further Reading 277**
- Problems 278**

6 *Color Image Processing* 282

- 6.1 Color Fundamentals 283**
- 6.2 Color Models 289**
 - 6.2.1 The RGB Color Model 290
 - 6.2.2 The CMY and CMYK Color Models 294
 - 6.2.3 The HSI Color Model 295
- 6.3 Pseudocolor Image Processing 302**
 - 6.3.1 Intensity Slicing 303
 - 6.3.2 Gray Level to Color Transformations 308
- 6.4 Basics of Full-Color Image Processing 313**
- 6.5 Color Transformations 315**
 - 6.5.1 Formulation 315
 - 6.5.2 Color Complements 318
 - 6.5.3 Color Slicing 320
 - 6.5.4 Tone and Color Corrections 322
 - 6.5.5 Histogram Processing 326
- 6.6 Smoothing and Sharpening 327**
 - 6.6.1 Color Image Smoothing 328
 - 6.6.2 Color Image Sharpening 330
- 6.7 Color Segmentation 331**
 - 6.7.1 Segmentation in HSI Color Space 331
 - 6.7.2 Segmentation in RGB Vector Space 333
 - 6.7.3 Color Edge Detection 335

- 6.8 Noise in Color Images 339
- 6.9 Color Image Compression 342
 - Summary 343
 - References and Further Reading 344
 - Problems 344

7 *Wavelets and Multiresolution Processing* 349

- 7.1 Background 350
 - 7.1.1 Image Pyramids 351
 - 7.1.2 Subband Coding 354
 - 7.1.3 The Haar Transform 360
- 7.2 Multiresolution Expansions 363
 - 7.2.1 Series Expansions 364
 - 7.2.2 Scaling Functions 365
 - 7.2.3 Wavelet Functions 369
- 7.3 Wavelet Transforms in One Dimension 372
 - 7.3.1 The Wavelet Series Expansions 372
 - 7.3.2 The Discrete Wavelet Transform 375
 - 7.3.3 The Continuous Wavelet Transform 376
- 7.4 The Fast Wavelet Transform 379
- 7.5 Wavelet Transforms in Two Dimensions 386
- 7.6 Wavelet Packets 394
 - Summary 402
 - References and Further Reading 404
 - Problems 404

8 *Image Compression* 409

- 8.1 Fundamentals 411
 - 8.1.1 Coding Redundancy 412
 - 8.1.2 Interpixel Redundancy 414
 - 8.1.3 Psychovisual Redundancy 417
 - 8.1.4 Fidelity Criteria 419
- 8.2 Image Compression Models 421
 - 8.2.1 The Source Encoder and Decoder 421
 - 8.2.2 The Channel Encoder and Decoder 423
- 8.3 Elements of Information Theory 424
 - 8.3.1 Measuring Information 424
 - 8.3.2 The Information Channel 425
 - 8.3.3 Fundamental Coding Theorems 430
 - 8.3.4 Using Information Theory 437
- 8.4 Error-Free Compression 440
 - 8.4.1 Variable-Length Coding 440

- 8.4.2 LZW Coding 446
- 8.4.3 Bit-Plane Coding 448
- 8.4.4 Lossless Predictive Coding 456
- 8.5 Lossy Compression 459**
 - 8.5.1 Lossy Predictive Coding 459
 - 8.5.2 Transform Coding 467
 - 8.5.3 Wavelet Coding 486
- 8.6 Image Compression Standards 492**
 - 8.6.1 Binary Image Compression Standards 493
 - 8.6.2 Continuous Tone Still Image Compression Standards 498
 - 8.6.3 Video Compression Standards 510
- Summary 513**
- References and Further Reading 513**
- Problems 514**

9 *Morphological Image Processing* 519

- 9.1 Preliminaries 520**
 - 9.1.1 Some Basic Concepts from Set Theory 520
 - 9.1.2 Logic Operations Involving Binary Images 522
- 9.2 Dilation and Erosion 523**
 - 9.2.1 Dilation 523
 - 9.2.2 Erosion 525
- 9.3 Opening and Closing 528**
- 9.4 The Hit-or-Miss Transformation 532**
- 9.5 Some Basic Morphological Algorithms 534**
 - 9.5.1 Boundary Extraction 534
 - 9.5.2 Region Filling 535
 - 9.5.3 Extraction of Connected Components 536
 - 9.5.4 Convex Hull 539
 - 9.5.5 Thinning 541
 - 9.5.6 Thickening 541
 - 9.5.7 Skeletons 543
 - 9.5.8 Pruning 545
 - 9.5.9 Summary of Morphological Operations on Binary Images 547
- 9.6 Extensions to Gray-Scale Images 550**
 - 9.6.1 Dilation 550
 - 9.6.2 Erosion 552
 - 9.6.3 Opening and Closing 554
 - 9.6.4 Some Applications of Gray-Scale Morphology 556
- Summary 560**
- References and Further Reading 560**
- Problems 560**

10 *Image Segmentation* 567

- 10.1 Detection of Discontinuities** 568
 - 10.1.1 Point Detection 569
 - 10.1.2 Line Detection 570
 - 10.1.3 Edge Detection 572
- 10.2 Edge Linking and Boundary Detection** 585
 - 10.2.1 Local Processing 585
 - 10.2.2 Global Processing via the Hough Transform 587
 - 10.2.3 Global Processing via Graph-Theoretic Techniques 591
- 10.3 Thresholding** 595
 - 10.3.1 Foundation 595
 - 10.3.2 The Role of Illumination 596
 - 10.3.3 Basic Global Thresholding 598
 - 10.3.4 Basic Adaptive Thresholding 600
 - 10.3.5 Optimal Global and Adaptive Thresholding 602
 - 10.3.6 Use of Boundary Characteristics for Histogram Improvement and Local Thresholding 608
 - 10.3.7 Thresholds Based on Several Variables 611
- 10.4 Region-Based Segmentation** 612
 - 10.4.1 Basic Formulation 612
 - 10.4.2 Region Growing 613
 - 10.4.3 Region Splitting and Merging 615
- 10.5 Segmentation by Morphological Watersheds** 617
 - 10.5.1 Basic Concepts 617
 - 10.5.2 Dam Construction 620
 - 10.5.3 Watershed Segmentation Algorithm 622
 - 10.5.4 The Use of Markers 624
- 10.6 The Use of Motion in Segmentation** 626
 - 10.6.1 Spatial Techniques 626
 - 10.6.2 Frequency Domain Techniques 630
- Summary** 634
- References and Further Reading** 634
- Problems** 636

11 *Representation and Description* 643

- 11.1 Representation** 644
 - 11.1.1 Chain Codes 644
 - 11.1.2 Polygonal Approximations 646
 - 11.1.3 Signatures 648
 - 11.1.4 Boundary Segments 649
 - 11.1.5 Skeletons 650

- 11.2 Boundary Descriptors 653**
 - 11.2.1 Some Simple Descriptors 653
 - 11.2.2 Shape Numbers 654
 - 11.2.3 Fourier Descriptors 655
 - 11.2.4 Statistical Moments 659
- 11.3 Regional Descriptors 660**
 - 11.3.1 Some Simple Descriptors 661
 - 11.3.2 Topological Descriptors 661
 - 11.3.3 Texture 665
 - 11.3.4 Moments of Two-Dimensional Functions 672
- 11.4 Use of Principal Components for Description 675**
- 11.5 Relational Descriptors 683**
 - Summary 687**
 - References and Further Reading 687**
 - Problems 689**

12 *Object Recognition* 693

- 12.1 Patterns and Pattern Classes 693**
- 12.2 Recognition Based on Decision-Theoretic Methods 698**
 - 12.2.1 Matching 698
 - 12.2.2 Optimum Statistical Classifiers 704
 - 12.2.3 Neural Networks 712
- 12.3 Structural Methods 732**
 - 12.3.1 Matching Shape Numbers 732
 - 12.3.2 String Matching 734
 - 12.3.3 Syntactic Recognition of Strings 735
 - 12.3.4 Syntactic Recognition of Trees 740
 - Summary 750**
 - References and Further Reading 750**
 - Problems 750**

Bibliography 755

Index 779

