

Contents

<i>Preface</i>	15
<i>Acknowledgments</i>	19
<i>The Book Web Site</i>	20
<i>About the Authors</i>	21

1 Introduction 23

1.1	What Is Digital Image Processing?	23
1.2	The Origins of Digital Image Processing	25
1.3	Examples of Fields that Use Digital Image Processing	29
1.3.1	Gamma-Ray Imaging	30
1.3.2	X-Ray Imaging	31
1.3.3	Imaging in the Ultraviolet Band	33
1.3.4	Imaging in the Visible and Infrared Bands	34
1.3.5	Imaging in the Microwave Band	40
1.3.6	Imaging in the Radio Band	42
1.3.7	Examples in which Other Imaging Modalities Are Used	42
1.4	Fundamental Steps in Digital Image Processing	47
1.5	Components of an Image Processing System	50
	Summary	53
	References and Further Reading	53

2 Digital Image Fundamentals 57

2.1	Elements of Visual Perception	58
2.1.1	Structure of the Human Eye	58
2.1.2	Image Formation in the Eye	60
2.1.3	Brightness Adaptation and Discrimination	61
2.2	Light and the Electromagnetic Spectrum	65
2.3	Image Sensing and Acquisition	68
2.3.1	Image Acquisition Using a Single Sensor	70
2.3.2	Image Acquisition Using Sensor Strips	70
2.3.3	Image Acquisition Using Sensor Arrays	72
2.3.4	A Simple Image Formation Model	72
2.4	Image Sampling and Quantization	74
2.4.1	Basic Concepts in Sampling and Quantization	74
2.4.2	Representing Digital Images	77
2.4.3	Spatial and Intensity Resolution	81
2.4.4	Image Interpolation	87

- 2.5 Some Basic Relationships between Pixels 90**
 - 2.5.1 Neighbors of a Pixel 90
 - 2.5.2 Adjacency, Connectivity, Regions, and Boundaries 90
 - 2.5.3 Distance Measures 93
- 2.6 An Introduction to the Mathematical Tools Used in Digital Image Processing 94**
 - 2.6.1 Array versus Matrix Operations 94
 - 2.6.2 Linear versus Nonlinear Operations 95
 - 2.6.3 Arithmetic Operations 96
 - 2.6.4 Set and Logical Operations 102
 - 2.6.5 Spatial Operations 107
 - 2.6.6 Vector and Matrix Operations 114
 - 2.6.7 Image Transforms 115
 - 2.6.8 Probabilistic Methods 118
 - Summary 120
 - References and Further Reading 120
 - Problems 121

3 *Intensity Transformations and Spatial Filtering 126*

- 3.1 Background 127**
 - 3.1.1 The Basics of Intensity Transformations and Spatial Filtering 127
 - 3.1.2 About the Examples in This Chapter 129
- 3.2 Some Basic Intensity Transformation Functions 129**
 - 3.2.1 Image Negatives 130
 - 3.2.2 Log Transformations 131
 - 3.2.3 Power-Law (Gamma) Transformations 132
 - 3.2.4 Piecewise-Linear Transformation Functions 137
- 3.3 Histogram Processing 142**
 - 3.3.1 Histogram Equalization 144
 - 3.3.2 Histogram Matching (Specification) 150
 - 3.3.3 Local Histogram Processing 161
 - 3.3.4 Using Histogram Statistics for Image Enhancement 161
- 3.4 Fundamentals of Spatial Filtering 166**
 - 3.4.1 The Mechanics of Spatial Filtering 167
 - 3.4.2 Spatial Correlation and Convolution 168
 - 3.4.3 Vector Representation of Linear Filtering 172
 - 3.4.4 Generating Spatial Filter Masks 173
- 3.5 Smoothing Spatial Filters 174**
 - 3.5.1 Smoothing Linear Filters 174
 - 3.5.2 Order-Statistic (Nonlinear) Filters 178
- 3.6 Sharpening Spatial Filters 179**
 - 3.6.1 Foundation 180
 - 3.6.2 Using the Second Derivative for Image Sharpening—The Laplacian 182

- 3.6.3 Unsharp Masking and Highboost Filtering 184
- 3.6.4 Using First-Order Derivatives for (Nonlinear) Image Sharpening—The Gradient 187
- 3.7 Combining Spatial Enhancement Methods 191**
- 3.8 Using Fuzzy Techniques for Intensity Transformations and Spatial Filtering 195**
 - 3.8.1 Introduction 195
 - 3.8.2 Principles of Fuzzy Set Theory 196
 - 3.8.3 Using Fuzzy Sets 200
 - 3.8.4 Using Fuzzy Sets for Intensity Transformations 208
 - 3.8.5 Using Fuzzy Sets for Spatial Filtering 211
 - Summary 214**
 - References and Further Reading 214**
 - Problems 215**

4 *Filtering in the Frequency Domain* 221

- 4.1 Background 222**
 - 4.1.1 A Brief History of the Fourier Series and Transform 222
 - 4.1.2 About the Examples in this Chapter 223
- 4.2 Preliminary Concepts 224**
 - 4.2.1 Complex Numbers 224
 - 4.2.2 Fourier Series 225
 - 4.2.3 Impulses and Their Sifting Property 225
 - 4.2.4 The Fourier Transform of Functions of One Continuous Variable 227
 - 4.2.5 Convolution 231
- 4.3 Sampling and the Fourier Transform of Sampled Functions 233**
 - 4.3.1 Sampling 233
 - 4.3.2 The Fourier Transform of Sampled Functions 234
 - 4.3.3 The Sampling Theorem 235
 - 4.3.4 Aliasing 239
 - 4.3.5 Function Reconstruction (Recovery) from Sampled Data 241
- 4.4 The Discrete Fourier Transform (DFT) of One Variable 242**
 - 4.4.1 Obtaining the DFT from the Continuous Transform of a Sampled Function 243
 - 4.4.2 Relationship Between the Sampling and Frequency Intervals 245
- 4.5 Extension to Functions of Two Variables 247**
 - 4.5.1 The 2-D Impulse and Its Sifting Property 247
 - 4.5.2 The 2-D Continuous Fourier Transform Pair 248
 - 4.5.3 Two-Dimensional Sampling and the 2-D Sampling Theorem 249
 - 4.5.4 Aliasing in Images 250
 - 4.5.5 The 2-D Discrete Fourier Transform and Its Inverse 257

- 4.6 Some Properties of the 2-D Discrete Fourier Transform 258**
 - 4.6.1 Relationships Between Spatial and Frequency Intervals 258
 - 4.6.2 Translation and Rotation 258
 - 4.6.3 Periodicity 259
 - 4.6.4 Symmetry Properties 261
 - 4.6.5 Fourier Spectrum and Phase Angle 267
 - 4.6.6 The 2-D Convolution Theorem 271
 - 4.6.7 Summary of 2-D Discrete Fourier Transform Properties 275
- 4.7 The Basics of Filtering in the Frequency Domain 277**
 - 4.7.1 Additional Characteristics of the Frequency Domain 277
 - 4.7.2 Frequency Domain Filtering Fundamentals 279
 - 4.7.3 Summary of Steps for Filtering in the Frequency Domain 285
 - 4.7.4 Correspondence Between Filtering in the Spatial and Frequency Domains 285
- 4.8 Image Smoothing Using Frequency Domain Filters 291**
 - 4.8.1 Ideal Lowpass Filters 291
 - 4.8.2 Butterworth Lowpass Filters 295
 - 4.8.3 Gaussian Lowpass Filters 298
 - 4.8.4 Additional Examples of Lowpass Filtering 299
- 4.9 Image Sharpening Using Frequency Domain Filters 302**
 - 4.9.1 Ideal Highpass Filters 303
 - 4.9.2 Butterworth Highpass Filters 306
 - 4.9.3 Gaussian Highpass Filters 307
 - 4.9.4 The Laplacian in the Frequency Domain 308
 - 4.9.5 Unsharp Masking, Highboost Filtering, and High-Frequency-Emphasis Filtering 310
 - 4.9.6 Homomorphic Filtering 311
- 4.10 Selective Filtering 316**
 - 4.10.1 Bandreject and Bandpass Filters 316
 - 4.10.2 Notch Filters 316
- 4.11 Implementation 320**
 - 4.11.1 Separability of the 2-D DFT 320
 - 4.11.2 Computing the IDFT Using a DFT Algorithm 321
 - 4.11.3 The Fast Fourier Transform (FFT) 321
 - 4.11.4 Some Comments on Filter Design 325
 - Summary 325**
 - References and Further Reading 326**
 - Problems 326**

5 *Image Restoration and Reconstruction* 333

- 5.1 A Model of the Image Degradation/Restoration Process 334**
- 5.2 Noise Models 335**
 - 5.2.1 Spatial and Frequency Properties of Noise 335
 - 5.2.2 Some Important Noise Probability Density Functions 336

- 5.2.3 Periodic Noise 340
- 5.2.4 Estimation of Noise Parameters 341
- 5.3 Restoration in the Presence of Noise Only—Spatial Filtering 344**
 - 5.3.1 Mean Filters 344
 - 5.3.2 Order-Statistic Filters 347
 - 5.3.3 Adaptive Filters 352
- 5.4 Periodic Noise Reduction by Frequency Domain Filtering 357**
 - 5.4.1 Bandreject Filters 357
 - 5.4.2 Bandpass Filters 358
 - 5.4.3 Notch Filters 359
 - 5.4.4 Optimum Notch Filtering 360
- 5.5 Linear, Position-Invariant Degradations 365**
- 5.6 Estimating the Degradation Function 368**
 - 5.6.1 Estimation by Image Observation 368
 - 5.6.2 Estimation by Experimentation 369
 - 5.6.3 Estimation by Modeling 369
- 5.7 Inverse Filtering 373**
- 5.8 Minimum Mean Square Error (Wiener) Filtering 374**
- 5.9 Constrained Least Squares Filtering 379**
- 5.10 Geometric Mean Filter 383**
- 5.11 Image Reconstruction from Projections 384**
 - 5.11.1 Introduction 384
 - 5.11.2 Principles of Computed Tomography (CT) 387
 - 5.11.3 Projections and the Radon Transform 390
 - 5.11.4 The Fourier-Slice Theorem 396
 - 5.11.5 Reconstruction Using Parallel-Beam Filtered Backprojections 397
 - 5.11.6 Reconstruction Using Fan-Beam Filtered Backprojections 403
- Summary 409**
- References and Further Reading 410**
- Problems 411**

6 *Color Image Processing* 416

- 6.1 Color Fundamentals 417**
- 6.2 Color Models 423**
 - 6.2.1 The RGB Color Model 424
 - 6.2.2 The CMY and CMYK Color Models 428
 - 6.2.3 The HSI Color Model 429
- 6.3 Pseudocolor Image Processing 436**
 - 6.3.1 Intensity Slicing 437
 - 6.3.2 Intensity to Color Transformations 440
- 6.4 Basics of Full-Color Image Processing 446**
- 6.5 Color Transformations 448**
 - 6.5.1 Formulation 448
 - 6.5.2 Color Complements 452

- 6.5.3 Color Slicing 453
- 6.5.4 Tone and Color Corrections 455
- 6.5.5 Histogram Processing 460
- 6.6 Smoothing and Sharpening 461**
 - 6.6.1 Color Image Smoothing 461
 - 6.6.2 Color Image Sharpening 464
- 6.7 Image Segmentation Based on Color 465**
 - 6.7.1 Segmentation in HSI Color Space 465
 - 6.7.2 Segmentation in RGB Vector Space 467
 - 6.7.3 Color Edge Detection 469
- 6.8 Noise in Color Images 473**
- 6.9 Color Image Compression 476**
 - Summary 477
 - References and Further Reading 478
 - Problems 478

7 *Wavelets and Multiresolution Processing* 483

- 7.1 Background 484**
 - 7.1.1 Image Pyramids 485
 - 7.1.2 Subband Coding 488
 - 7.1.3 The Haar Transform 496
- 7.2 Multiresolution Expansions 499**
 - 7.2.1 Series Expansions 499
 - 7.2.2 Scaling Functions 501
 - 7.2.3 Wavelet Functions 505
- 7.3 Wavelet Transforms in One Dimension 508**
 - 7.3.1 The Wavelet Series Expansions 508
 - 7.3.2 The Discrete Wavelet Transform 510
 - 7.3.3 The Continuous Wavelet Transform 513
- 7.4 The Fast Wavelet Transform 515**
- 7.5 Wavelet Transforms in Two Dimensions 523**
- 7.6 Wavelet Packets 532**
 - Summary 542
 - References and Further Reading 542
 - Problems 543

8 *Image Compression* 547

- 8.1 Fundamentals 548**
 - 8.1.1 Coding Redundancy 550
 - 8.1.2 Spatial and Temporal Redundancy 551
 - 8.1.3 Irrelevant Information 552
 - 8.1.4 Measuring Image Information 553
 - 8.1.5 Fidelity Criteria 556

- 8.1.6 Image Compression Models 558
- 8.1.7 Image Formats, Containers, and Compression Standards 560
- 8.2 Some Basic Compression Methods 564**
 - 8.2.1 Huffman Coding 564
 - 8.2.2 Golomb Coding 566
 - 8.2.3 Arithmetic Coding 570
 - 8.2.4 LZW Coding 573
 - 8.2.5 Run-Length Coding 575
 - 8.2.6 Symbol-Based Coding 581
 - 8.2.7 Bit-Plane Coding 584
 - 8.2.8 Block Transform Coding 588
 - 8.2.9 Predictive Coding 606
 - 8.2.10 Wavelet Coding 626
- 8.3 Digital Image Watermarking 636**
 - Summary 643**
 - References and Further Reading 644**
 - Problems 645**

9 *Morphological Image Processing* 649

- 9.1 Preliminaries 650**
- 9.2 Erosion and Dilation 652**
 - 9.2.1 Erosion 653
 - 9.2.2 Dilation 655
 - 9.2.3 Duality 657
- 9.3 Opening and Closing 657**
- 9.4 The Hit-or-Miss Transformation 662**
- 9.5 Some Basic Morphological Algorithms 664**
 - 9.5.1 Boundary Extraction 664
 - 9.5.2 Hole Filling 665
 - 9.5.3 Extraction of Connected Components 667
 - 9.5.4 Convex Hull 669
 - 9.5.5 Thinning 671
 - 9.5.6 Thickening 672
 - 9.5.7 Skeletons 673
 - 9.5.8 Pruning 676
 - 9.5.9 Morphological Reconstruction 678
 - 9.5.10 Summary of Morphological Operations on Binary Images 684
- 9.6 Gray-Scale Morphology 687**
 - 9.6.1 Erosion and Dilation 688
 - 9.6.2 Opening and Closing 690
 - 9.6.3 Some Basic Gray-Scale Morphological Algorithms 692
 - 9.6.4 Gray-Scale Morphological Reconstruction 698
 - Summary 701**
 - References and Further Reading 701**
 - Problems 702**

10 *Image Segmentation* 711

- 10.1 **Fundamentals** 712
- 10.2 **Point, Line, and Edge Detection** 714
 - 10.2.1 Background 714
 - 10.2.2 Detection of Isolated Points 718
 - 10.2.3 Line Detection 719
 - 10.2.4 Edge Models 722
 - 10.2.5 Basic Edge Detection 728
 - 10.2.6 More Advanced Techniques for Edge Detection 736
 - 10.2.7 Edge Linking and Boundary Detection 747
- 10.3 **Thresholding** 760
 - 10.3.1 Foundation 760
 - 10.3.2 Basic Global Thresholding 763
 - 10.3.3 Optimum Global Thresholding Using Otsu's Method 764
 - 10.3.4 Using Image Smoothing to Improve Global Thresholding 769
 - 10.3.5 Using Edges to Improve Global Thresholding 771
 - 10.3.6 Multiple Thresholds 774
 - 10.3.7 Variable Thresholding 778
 - 10.3.8 Multivariable Thresholding 783
- 10.4 **Region-Based Segmentation** 785
 - 10.4.1 Region Growing 785
 - 10.4.2 Region Splitting and Merging 788
- 10.5 **Segmentation Using Morphological Watersheds** 791
 - 10.5.1 Background 791
 - 10.5.2 Dam Construction 794
 - 10.5.3 Watershed Segmentation Algorithm 796
 - 10.5.4 The Use of Markers 798
- 10.6 **The Use of Motion in Segmentation** 800
 - 10.6.1 Spatial Techniques 800
 - 10.6.2 Frequency Domain Techniques 804
- Summary** 807
- References and Further Reading** 807
- Problems** 809

11 *Representation and Description* 817

- 11.1 **Representation** 818
 - 11.1.1 Boundary (Border) Following 818
 - 11.1.2 Chain Codes 820
 - 11.1.3 Polygonal Approximations Using Minimum-Perimeter Polygons 823
 - 11.1.4 Other Polygonal Approximation Approaches 829
 - 11.1.5 Signatures 830

- 11.1.6 Boundary Segments 832
- 11.1.7 Skeletons 834
- 11.2 Boundary Descriptors 837**
 - 11.2.1 Some Simple Descriptors 837
 - 11.2.2 Shape Numbers 838
 - 11.2.3 Fourier Descriptors 840
 - 11.2.4 Statistical Moments 843
- 11.3 Regional Descriptors 844**
 - 11.3.1 Some Simple Descriptors 844
 - 11.3.2 Topological Descriptors 845
 - 11.3.3 Texture 849
 - 11.3.4 Moment Invariants 861
- 11.4 Use of Principal Components for Description 864**
- 11.5 Relational Descriptors 874**
 - Summary 878
 - References and Further Reading 878
 - Problems 879

12 *Object Recognition* 883

- 12.1 Patterns and Pattern Classes 883**
- 12.2 Recognition Based on Decision-Theoretic Methods 888**
 - 12.2.1 Matching 888
 - 12.2.2 Optimum Statistical Classifiers 894
 - 12.2.3 Neural Networks 904
- 12.3 Structural Methods 925**
 - 12.3.1 Matching Shape Numbers 925
 - 12.3.2 String Matching 926
 - Summary 928
 - References and Further Reading 928
 - Problems 929

Appendix A 932

Bibliography 937

Index 965