

Contents

<i>Preface</i>	<i>xv</i>
<i>Acknowledgments</i>	<i>xix</i>
<i>The Book Web Site</i>	<i>xx</i>
<i>About the Authors</i>	<i>xxi</i>

1 Introduction 1

1.1	What Is Digital Image Processing?	1
1.2	The Origins of Digital Image Processing	3
1.3	Examples of Fields that Use Digital Image Processing	7
1.3.1	Gamma-Ray Imaging	8
1.3.2	X-Ray Imaging	9
1.3.3	Imaging in the Ultraviolet Band	11
1.3.4	Imaging in the Visible and Infrared Bands	12
1.3.5	Imaging in the Microwave Band	18
1.3.6	Imaging in the Radio Band	20
1.3.7	Examples in which Other Imaging Modalities Are Used	20
1.4	Fundamental Steps in Digital Image Processing	25
1.5	Components of an Image Processing System	28
	Summary	31
	References and Further Reading	31

2 Digital Image Fundamentals 35

2.1	Elements of Visual Perception	36
2.1.1	Structure of the Human Eye	36
2.1.2	Image Formation in the Eye	38
2.1.3	Brightness Adaptation and Discrimination	39
2.2	Light and the Electromagnetic Spectrum	43
2.3	Image Sensing and Acquisition	46
2.3.1	Image Acquisition Using a Single Sensor	48
2.3.2	Image Acquisition Using Sensor Strips	48
2.3.3	Image Acquisition Using Sensor Arrays	50
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	55
2.4.3	Spatial and Intensity Resolution	59
2.4.4	Image Interpolation	65

- 2.5 **Some Basic Relationships between Pixels** 68
 - 2.5.1 Neighbors of a Pixel 68
 - 2.5.2 Adjacency, Connectivity, Regions, and Boundaries 68
 - 2.5.3 Distance Measures 71
- 2.6 **An Introduction to the Mathematical Tools Used in Digital Image Processing** 72
 - 2.6.1 Array versus Matrix Operations 72
 - 2.6.2 Linear versus Nonlinear Operations 73
 - 2.6.3 Arithmetic Operations 74
 - 2.6.4 Set and Logical Operations 80
 - 2.6.5 Spatial Operations 85
 - 2.6.6 Vector and Matrix Operations 92
 - 2.6.7 Image Transforms 93
 - 2.6.8 Probabilistic Methods 96
- Summary** 98
- References and Further Reading** 98
- Problems** 99

3 *Intensity Transformations and Spatial Filtering* 104

- 3.1 **Background** 105
 - 3.1.1 The Basics of Intensity Transformations and Spatial Filtering 105
 - 3.1.2 About the Examples in This Chapter 107
- 3.2 **Some Basic Intensity Transformation Functions** 107
 - 3.2.1 Image Negatives 108
 - 3.2.2 Log Transformations 109
 - 3.2.3 Power-Law (Gamma) Transformations 110
 - 3.2.4 Piecewise-Linear Transformation Functions 115
- 3.3 **Histogram Processing** 120
 - 3.3.1 Histogram Equalization 122
 - 3.3.2 Histogram Matching (Specification) 128
 - 3.3.3 Local Histogram Processing 139
 - 3.3.4 Using Histogram Statistics for Image Enhancement 139
- 3.4 **Fundamentals of Spatial Filtering** 144
 - 3.4.1 The Mechanics of Spatial Filtering 145
 - 3.4.2 Spatial Correlation and Convolution 146
 - 3.4.3 Vector Representation of Linear Filtering 150
 - 3.4.4 Generating Spatial Filter Masks 151
- 3.5 **Smoothing Spatial Filters** 152
 - 3.5.1 Smoothing Linear Filters 152
 - 3.5.2 Order-Statistic (Nonlinear) Filters 156
- 3.6 **Sharpening Spatial Filters** 157
 - 3.6.1 Foundation 158
 - 3.6.2 Using the Second Derivative for Image Sharpening—The Laplacian 160

- 3.6.3 Unsharp Masking and Highboost Filtering 162
- 3.6.4 Using First-Order Derivatives for (Nonlinear) Image Sharpening—The Gradient 165
- 3.7 **Combining Spatial Enhancement Methods 169**
- 3.8 **Using Fuzzy Techniques for Intensity Transformations and Spatial Filtering 173**
 - 3.8.1 Introduction 173
 - 3.8.2 Principles of Fuzzy Set Theory 174
 - 3.8.3 Using Fuzzy Sets 178
 - 3.8.4 Using Fuzzy Sets for Intensity Transformations 186
 - 3.8.5 Using Fuzzy Sets for Spatial Filtering 189
- Summary 192**
- References and Further Reading 192**
- Problems 193**

4 *Filtering in the Frequency Domain* 199

- 4.1 **Background 200**
 - 4.1.1 A Brief History of the Fourier Series and Transform 200
 - 4.1.2 About the Examples in this Chapter 201
- 4.2 **Preliminary Concepts 202**
 - 4.2.1 Complex Numbers 202
 - 4.2.2 Fourier Series 203
 - 4.2.3 Impulses and Their Sifting Property 203
 - 4.2.4 The Fourier Transform of Functions of One Continuous Variable 205
 - 4.2.5 Convolution 209
- 4.3 **Sampling and the Fourier Transform of Sampled Functions 211**
 - 4.3.1 Sampling 211
 - 4.3.2 The Fourier Transform of Sampled Functions 212
 - 4.3.3 The Sampling Theorem 213
 - 4.3.4 Aliasing 217
 - 4.3.5 Function Reconstruction (Recovery) from Sampled Data 219
- 4.4 **The Discrete Fourier Transform (DFT) of One Variable 220**
 - 4.4.1 Obtaining the DFT from the Continuous Transform of a Sampled Function 221
 - 4.4.2 Relationship Between the Sampling and Frequency Intervals 223
- 4.5 **Extension to Functions of Two Variables 225**
 - 4.5.1 The 2-D Impulse and Its Sifting Property 225
 - 4.5.2 The 2-D Continuous Fourier Transform Pair 226
 - 4.5.3 Two-Dimensional Sampling and the 2-D Sampling Theorem 227
 - 4.5.4 Aliasing in Images 228
 - 4.5.5 The 2-D Discrete Fourier Transform and Its Inverse 235

- 4.6 Some Properties of the 2-D Discrete Fourier Transform 236**
 - 4.6.1 Relationships Between Spatial and Frequency Intervals 236
 - 4.6.2 Translation and Rotation 236
 - 4.6.3 Periodicity 237
 - 4.6.4 Symmetry Properties 239
 - 4.6.5 Fourier Spectrum and Phase Angle 245
 - 4.6.6 The 2-D Convolution Theorem 249
 - 4.6.7 Summary of 2-D Discrete Fourier Transform Properties 253
- 4.7 The Basics of Filtering in the Frequency Domain 255**
 - 4.7.1 Additional Characteristics of the Frequency Domain 255
 - 4.7.2 Frequency Domain Filtering Fundamentals 257
 - 4.7.3 Summary of Steps for Filtering in the Frequency Domain 263
 - 4.7.4 Correspondence Between Filtering in the Spatial and Frequency Domains 263
- 4.8 Image Smoothing Using Frequency Domain Filters 269**
 - 4.8.1 Ideal Lowpass Filters 269
 - 4.8.2 Butterworth Lowpass Filters 273
 - 4.8.3 Gaussian Lowpass Filters 276
 - 4.8.4 Additional Examples of Lowpass Filtering 277
- 4.9 Image Sharpening Using Frequency Domain Filters 280**
 - 4.9.1 Ideal Highpass Filters 281
 - 4.9.2 Butterworth Highpass Filters 284
 - 4.9.3 Gaussian Highpass Filters 285
 - 4.9.4 The Laplacian in the Frequency Domain 286
 - 4.9.5 Unsharp Masking, Highboost Filtering, and High-Frequency-Emphasis Filtering 288
 - 4.9.6 Homomorphic Filtering 289
- 4.10 Selective Filtering 294**
 - 4.10.1 Bandreject and Bandpass Filters 294
 - 4.10.2 Notch Filters 294
- 4.11 Implementation 298**
 - 4.11.1 Separability of the 2-D DFT 298
 - 4.11.2 Computing the IDFT Using a DFT Algorithm 299
 - 4.11.3 The Fast Fourier Transform (FFT) 299
 - 4.11.4 Some Comments on Filter Design 303
- Summary 303**
- References and Further Reading 304**
- Problems 304**

5 *Image Restoration and Reconstruction* 311

- 5.1 A Model of the Image Degradation/Restoration Process 312**
- 5.2 Noise Models 313**
 - 5.2.1 Spatial and Frequency Properties of Noise 313
 - 5.2.2 Some Important Noise Probability Density Functions 314

- 5.2.3 Periodic Noise 318
- 5.2.4 Estimation of Noise Parameters 319
- 5.3 **Restoration in the Presence of Noise Only—Spatial Filtering** 322
 - 5.3.1 Mean Filters 322
 - 5.3.2 Order-Statistic Filters 325
 - 5.3.3 Adaptive Filters 330
- 5.4 **Periodic Noise Reduction by Frequency Domain Filtering** 335
 - 5.4.1 Bandreject Filters 335
 - 5.4.2 Bandpass Filters 336
 - 5.4.3 Notch Filters 337
 - 5.4.4 Optimum Notch Filtering 338
- 5.5 **Linear, Position-Invariant Degradations** 343
- 5.6 **Estimating the Degradation Function** 346
 - 5.6.1 Estimation by Image Observation 346
 - 5.6.2 Estimation by Experimentation 347
 - 5.6.3 Estimation by Modeling 347
- 5.7 **Inverse Filtering** 351
- 5.8 **Minimum Mean Square Error (Wiener) Filtering** 352
- 5.9 **Constrained Least Squares Filtering** 357
- 5.10 **Geometric Mean Filter** 361
- 5.11 **Image Reconstruction from Projections** 362
 - 5.11.1 Introduction 362
 - 5.11.2 Principles of Computed Tomography (CT) 365
 - 5.11.3 Projections and the Radon Transform 368
 - 5.11.4 The Fourier-Slice Theorem 374
 - 5.11.5 Reconstruction Using Parallel-Beam Filtered Backprojections 375
 - 5.11.6 Reconstruction Using Fan-Beam Filtered Backprojections 381
- Summary** 387
- References and Further Reading** 388
- Problems** 389

6 *Color Image Processing* 394

- 6.1 **Color Fundamentals** 395
- 6.2 **Color Models** 401
 - 6.2.1 The RGB Color Model 402
 - 6.2.2 The CMY and CMYK Color Models 406
 - 6.2.3 The HSI Color Model 407
- 6.3 **Pseudocolor Image Processing** 414
 - 6.3.1 Intensity Slicing 415
 - 6.3.2 Intensity to Color Transformations 418
- 6.4 **Basics of Full-Color Image Processing** 424
- 6.5 **Color Transformations** 426
 - 6.5.1 Formulation 426
 - 6.5.2 Color Complements 430

- 6.5.3 Color Slicing 431
- 6.5.4 Tone and Color Corrections 433
- 6.5.5 Histogram Processing 438
- 6.6 Smoothing and Sharpening 439**
 - 6.6.1 Color Image Smoothing 439
 - 6.6.2 Color Image Sharpening 442
- 6.7 Image Segmentation Based on Color 443**
 - 6.7.1 Segmentation in HSI Color Space 443
 - 6.7.2 Segmentation in RGB Vector Space 445
 - 6.7.3 Color Edge Detection 447
- 6.8 Noise in Color Images 451**
- 6.9 Color Image Compression 454**
 - Summary 455
 - References and Further Reading 456
 - Problems 456

7 *Wavelets and Multiresolution Processing* 461

- 7.1 Background 462**
 - 7.1.1 Image Pyramids 463
 - 7.1.2 Subband Coding 466
 - 7.1.3 The Haar Transform 474
- 7.2 Multiresolution Expansions 477**
 - 7.2.1 Series Expansions 477
 - 7.2.2 Scaling Functions 479
 - 7.2.3 Wavelet Functions 483
- 7.3 Wavelet Transforms in One Dimension 486**
 - 7.3.1 The Wavelet Series Expansions 486
 - 7.3.2 The Discrete Wavelet Transform 488
 - 7.3.3 The Continuous Wavelet Transform 491
- 7.4 The Fast Wavelet Transform 493**
- 7.5 Wavelet Transforms in Two Dimensions 501**
- 7.6 Wavelet Packets 510**
 - Summary 520
 - References and Further Reading 520
 - Problems 521

8 *Image Compression* 525

- 8.1 Fundamentals 526**
 - 8.1.1 Coding Redundancy 528
 - 8.1.2 Spatial and Temporal Redundancy 529
 - 8.1.3 Irrelevant Information 530
 - 8.1.4 Measuring Image Information 531
 - 8.1.5 Fidelity Criteria 534

- 8.1.6 Image Compression Models 536
- 8.1.7 Image Formats, Containers, and Compression Standards 538
- 8.2 Some Basic Compression Methods 542**
 - 8.2.1 Huffman Coding 542
 - 8.2.2 Golomb Coding 544
 - 8.2.3 Arithmetic Coding 548
 - 8.2.4 LZW Coding 551
 - 8.2.5 Run-Length Coding 553
 - 8.2.6 Symbol-Based Coding 559
 - 8.2.7 Bit-Plane Coding 562
 - 8.2.8 Block Transform Coding 566
 - 8.2.9 Predictive Coding 584
 - 8.2.10 Wavelet Coding 604
- 8.3 Digital Image Watermarking 614**
 - Summary 621**
 - References and Further Reading 622**
 - Problems 623**

9 *Morphological Image Processing* 627

- 9.1 Preliminaries 628**
- 9.2 Erosion and Dilation 630**
 - 9.2.1 Erosion 631
 - 9.2.2 Dilation 633
 - 9.2.3 Duality 635
- 9.3 Opening and Closing 635**
- 9.4 The Hit-or-Miss Transformation 640**
- 9.5 Some Basic Morphological Algorithms 642**
 - 9.5.1 Boundary Extraction 642
 - 9.5.2 Hole Filling 643
 - 9.5.3 Extraction of Connected Components 645
 - 9.5.4 Convex Hull 647
 - 9.5.5 Thinning 649
 - 9.5.6 Thickening 650
 - 9.5.7 Skeletons 651
 - 9.5.8 Pruning 654
 - 9.5.9 Morphological Reconstruction 656
 - 9.5.10 Summary of Morphological Operations on Binary Images 664
- 9.6 Gray-Scale Morphology 665**
 - 9.6.1 Erosion and Dilation 666
 - 9.6.2 Opening and Closing 668
 - 9.6.3 Some Basic Gray-Scale Morphological Algorithms 670
 - 9.6.4 Gray-Scale Morphological Reconstruction 676
 - Summary 679**
 - References and Further Reading 679**
 - Problems 680**

10 *Image Segmentation* 689

10.1 **Fundamentals** 690

10.2 **Point, Line, and Edge Detection** 692

10.2.1 Background 692

10.2.2 Detection of Isolated Points 696

10.2.3 Line Detection 697

10.2.4 Edge Models 700

10.2.5 Basic Edge Detection 706

10.2.6 More Advanced Techniques for Edge Detection 714

10.2.7 Edge Linking and Boundary Detection 725

10.3 **Thresholding** 738

10.3.1 Foundation 738

10.3.2 Basic Global Thresholding 741

10.3.3 Optimum Global Thresholding Using Otsu's Method 742

10.3.4 Using Image Smoothing to Improve Global Thresholding 747

10.3.5 Using Edges to Improve Global Thresholding 749

10.3.6 Multiple Thresholds 752

10.3.7 Variable Thresholding 756

10.3.8 Multivariable Thresholding 761

10.4 **Region-Based Segmentation** 763

10.4.1 Region Growing 763

10.4.2 Region Splitting and Merging 766

10.5 **Segmentation Using Morphological Watersheds** 769

10.5.1 Background 769

10.5.2 Dam Construction 772

10.5.3 Watershed Segmentation Algorithm 774

10.5.4 The Use of Markers 776

10.6 **The Use of Motion in Segmentation** 778

10.6.1 Spatial Techniques 778

10.6.2 Frequency Domain Techniques 782

Summary 785

References and Further Reading 785

Problems 787

11 *Representation and Description* 795

11.1 **Representation** 796

11.1.1 Boundary (Border) Following 796

11.1.2 Chain Codes 798

11.1.3 Polygonal Approximations Using Minimum-Perimeter Polygons 801

11.1.4 Other Polygonal Approximation Approaches 807

11.1.5 Signatures 808

- 11.1.6 Boundary Segments 810
- 11.1.7 Skeletons 812
- 11.2 Boundary Descriptors 815**
 - 11.2.1 Some Simple Descriptors 815
 - 11.2.2 Shape Numbers 816
 - 11.2.3 Fourier Descriptors 818
 - 11.2.4 Statistical Moments 821
- 11.3 Regional Descriptors 822**
 - 11.3.1 Some Simple Descriptors 822
 - 11.3.2 Topological Descriptors 823
 - 11.3.3 Texture 827
 - 11.3.4 Moment Invariants 839
- 11.4 Use of Principal Components for Description 842**
- 11.5 Relational Descriptors 852**
 - Summary 856
 - References and Further Reading 856
 - Problems 857

12 *Object Recognition* 861

- 12.1 Patterns and Pattern Classes 861**
- 12.2 Recognition Based on Decision-Theoretic Methods 866**
 - 12.2.1 Matching 866
 - 12.2.2 Optimum Statistical Classifiers 872
 - 12.2.3 Neural Networks 882
- 12.3 Structural Methods 903**
 - 12.3.1 Matching Shape Numbers 903
 - 12.3.2 String Matching 904
 - Summary 906
 - References and Further Reading 906
 - Problems 907

Appendix A 910

Bibliography 915

Index 943