Preface xv
Acknowledgements xviii
About the Authors xix

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 30
References and Further Reading 31

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