Contents

Preface vii
About the Author xiii
Acknowledgments xv

Symbols and Abbreviations xxix

1 The Nature of Biomedical Images 1
1.1 Body Temperature as an Image 2
1.2 Transillumination 6
1.3 Light Microscopy 6
1.4 Electron Microscopy 10
1.5 X-ray Imaging 15
1.5.1 Breast cancer and mammography 22
1.6 Tomography 27
1.7 Nuclear Medicine Imaging 36
1.8 Ultrasonography 43
1.9 Magnetic Resonance Imaging 47
1.10 Objectives of Biomedical Image Analysis 53
1.11 Computer-aided Diagnosis 55
1.12 Remarks 57
1.13 Study Questions and Problems 57
1.14 Laboratory Exercises and Projects 58

2 Image Quality and Information Content 61
2.1 Difficulties in Image Acquisition and Analysis 61
2.2 Characterization of Image Quality 64
2.3 Digitization of Images 65
2.3.1 Sampling 65
2.3.2 Quantization 66
2.3.3 Array and matrix representation of images 69
2.4 Optical Density 72
2.5 Dynamic Range 73
2.6 Contrast 75
2.7 Histogram 78
2.8 Entropy 84
2.9 Blur and Spread Functions 90
2.10 Resolution 99

2.11 The Fourier Transform and Spectral Content 99
2.11.1 Important properties of the Fourier transform 110
2.12 Modulation Transfer Function 122
2.13 Signal-to-Noise Ratio 131
2.14 Error-based Measures 138
2.15 Application: Image Sharpness and Acutance 139
2.16 Remarks 145
2.17 Study Questions and Problems 145
2.18 Laboratory Exercises and Projects 149

3 Removal of Artifacts **151**
3.1 Characterization of Artifacts 151
3.1.1 Random noise 151
3.1.2 Examples of noise PDFs 159
3.1.3 Structured noise 164
3.1.4 Physiological interference 165
3.1.5 Other types of noise and artifact 166
3.1.6 Stationary versus nonstationary processes 166
3.1.7 Covariance and cross-correlation 168
3.1.8 Signal-dependent noise 169
3.2 Synchronized or Multiframe Averaging 171
3.3 Space-domain Local-statistics-based Filters 174
3.3.1 The mean filter 176
3.3.2 The median filter 177
3.3.3 Order-statistic filters 181
3.4 Frequency-domain Filters 193
3.4.1 Removal of high-frequency noise 194
3.4.2 Removal of periodic artifacts 199
3.5 Matrix Representation of Image Processing 202
3.5.1 Matrix representation of images 203
3.5.2 Matrix representation of transforms 206
3.5.3 Matrix representation of convolution 212
3.5.4 Illustrations of convolution 215
3.5.5 Diagonalization of a circulant matrix 218
3.5.6 Block-circulant matrix representation of a 2D filter . . 221
3.6 Optimal Filtering 224
3.6.1 The Wiener filter 225
3.7 Adaptive Filters 228
3.7.1 The local LMMSE filter 228
3.7.2 The noise-updating repeated Wiener filter 234
3.7.3 The adaptive 2D LMS filter 235
3.7.4 The adaptive rectangular window LMS filter 237
3.7.5 The adaptive-neighborhood filter 241
3.8 Comparative Analysis of Filters for Noise Removal 251
3.9 Application: Multiframe Averaging in Confocal Microscopy . 270

3.10 Application: Noise Reduction in Nuclear Medicine Imaging . 271
3.11 Remarks 277
3.12 Study Questions and Problems 281
3.13 Laboratory Exercises and Projects 283

4 Image Enhancement 285
4.1 Digital Subtraction Angiography 286
4.2 Dual-energy and Energy-subtraction X-ray Imaging 287
4.3 Temporal Subtraction 291
4.4 Gray-scale Transforms 291
4.4.1 Gray-scale thresholding 291
4.4.2 Gray-scale windowing 292
4.4.3 Gamma correction 294
4.5 Histogram Transformation 301
4.5.1 Histogram equalization 301
4.5.2 Histogram specification 305
4.5.3 Limitations of global operations 310
4.5.4 Local-area histogram equalization 310
4.5.5 Adaptive-neighborhood histogram equalization 311
4.6 Convolution Mask Operators 314
4.6.1 Unsharp masking 314
4.6.2 Subtracting Laplacian 316
4.6.3 Limitations of fixed operators 323
4.7 High-frequency Emphasis 325
4.8 Homomorphic Filtering for Enhancement 328
4.8.1 Generalized linear filtering 328
4.9 Adaptive Contrast Enhancement 338
4.9.1 Adaptive-neighborhood contrast enhancement 338
4.10 Objective Assessment of Contrast Enhancement 346
4.11 Application: Contrast Enhancement of Mammograms 350
4.11.1 Clinical evaluation of contrast enhancement 354
4.12 Remarks 357
4.13 Study Questions and Problems 358
4.14 Laboratory Exercises and Projects 361

5 Detection of Regions of Interest 363
5.1 Thresholding and Binarization 364
5.2 Detection of Isolated Points and Lines 365
5.3 Edge Detection 367
5.3.1 Convolution mask operators for edge detection 367
5.3.2 The Laplacian of Gaussian 370
5.3.3 Scale-space methods for multiscale edge detection . . 380
5.3.4 Canny's method for edge detection 390
5.3.5 Fourier-domain methods for edge detection 390
5.3.6 Edge linking 392

5.4 Segmentation and Region Growing 393
5.4.1 Optimal thresholding 395
5.4.2 Region-oriented segmentation of images 396
5.4.3 Splitting and merging of regions 397
5.4.4 Region growing using an additive tolerance 397
5.4.5 Region growing using a multiplicative tolerance 400
5.4.6 Analysis of region growing in the presence of noise . . 401
5.4.7 Iterative region growing with multiplicative tolerance 402
5.4.8 Region growing based upon the human visual system 405
5.4.9 Application: Detection of calcifications by multitolerance region growing 410
5.4.10 Application: Detection of calcifications by linear prediction error 414
5.5 Fuzzy-set-based Region Growing to Detect Breast Tumors . . 417
5.5.1 Preprocessing based upon fuzzy sets 419
5.5.2 Fuzzy segmentation based upon region growing 421
5.5.3 Fuzzy region growing 429
5.6 Detection of Objects of Known Geometry 434
5.6.1 The Hough transform 435
5.6.2 Detection of straight lines 437
5.6.3 Detection of circles 440
5.7 Methods for the Improvement of Contour or Region Estimates 444
5.8 Application: Detection of the Spinal Canal 449
5.9 Application: Detection of the Breast Boundary in Mammograms 451
5.9.1 Detection using the traditional active deformable contour model 456
5.9.2 Adaptive active deformable contour model 464
5.9.3 Results of application to mammograms 476
5.10 Application: Detection of the Pectoral Muscle in Mammograms 481
5.10.1 Detection using the Hough transform 481
5.10.2 Detection using Gabor wavelets 487
5.10.3 Results of application to mammograms 495
5.11 Application: Improved Segmentation of Breast Masses by Fuzzy-set-based Fusion of Contours and Regions 500
5.12 Remarks 524
5.13 Study Questions and Problems 527
5.14 Laboratory Exercises and Projects 527

6 Analysis of Shape **529**
6.1 Representation of Shapes and Contours 529
6.1.1 Signatures of contours 530
6.1.2 Chain coding 530
6.1.3 Segmentation of contours 534

6.1.4 Polygonal modeling of contours 537
6.1.5 Parabolic modeling of contours 543
6.1.6 Thinning and skeletonization 548
6.2 Shape Factors 549
6.2.1 Compactness 551
6.2.2 Moments 555
6.2.3 Chord-length statistics 560
6.3 Fourier Descriptors 562
6.4 Fractional Concavity 569
6.5 Analysis of Spicularity 570
6.6 Application: Shape Analysis of Calcifications 575
6.7 Application: Shape Analysis of Breast Masses and Tumors . 578
6.8 Remarks 581
6.9 Study Questions and Problems 581
6.10 Laboratory Exercises and Projects 582

7 Analysis of Texture **583**
7.1 Texture in Biomedical Images 584
7.2 Models for the Generation of Texture 584
7.2.1 Random texture 589
7.2.2 Ordered texture 589
7.2.3 Oriented texture 590
7.3 Statistical Analysis of Texture 596
7.3.1 The gray-level co-occurrence matrix 597
7.3.2 Haralick's measures of texture 600
7.4 Laws' Measures of Texture Energy 603
7.5 Fractal Analysis 605
7.5.1 Fractal dimension 608
7.5.2 Fractional Brownian motion model 609
7.5.3 Fractal analysis of texture 609
7.5.4 Applications of fractal analysis 611
7.6 Fourier-domain Analysis of Texture 612
7.7 Segmentation and Structural Analysis of Texture 621
7.7.1 Homomorphic deconvolution of periodic patterns . . . 623
7.8 Audification and Sonification of Texture in Images 625
7.9 Application: Analysis of Breast Masses Using Texture and Gradient Measures 627
7.9.1 Adaptive normals and ribbons around mass margins . 629
7.9.2 Gradient and contrast measures 632
7.9.3 Results of pattern classification 635
7.10 Remarks 637
7.11 Study Questions and Problems 637
7.12 Laboratory Exercises and Projects 638

8 Analysis of Oriented Patterns **639**
8.1 Oriented Patterns in Images 639
8.2 Measures of Directional Distribution 641
8.2.1 The rose diagram 641
8.2.2 The principal axis 641
8.2.3 Angular moments 642
8.2.4 Distance measures 643
8.2.5 Entropy 643
8.3 Directional Filtering 644
8.3.1 Sector filtering in the Fourier domain 646
8.3.2 Thresholding of the component images 649
8.3.3 Design of fan filters 651
8.4 Gabor Filters 657
8.4.1 Multiresolution signal decomposition 660
8.4.2 Formation of the Gabor filter bank 664
8.4.3 Reconstruction of the Gabor filter bank output 665
8.5 Directional Analysis via Multiscale Edge Detection 666
8.6 Hough-Radon Transform Analysis 671
8.6.1 Limitations of the Hough transform 671
8.6.2 The Hough and Radon transforms combined 673
8.6.3 Filtering and integrating the Hough-Radon space . . 676
8.7 Application: Analysis of Ligament Healing 679
8.7.1 Analysis of collagen remodeling 680
8.7.2 Analysis of the microvascular structure 684
8.8 Application: Detection of Breast Tumors 699
8.8.1 Framework for pyramidal decomposition 707
8.8.2 Segmentation based upon density slicing 710
8.8.3 Hierarchical grouping of isointensity contours 712
8.8.4 Results of segmentation of masses 712
8.8.5 Detection of masses in full mammograms 719
8.8.6 Analysis of mammograms using texture flow-field . . . 726
8.8.7 Adaptive computation of features in ribbons 732
8.8.8 Results of mass detection in full mammograms 735
8.9 Application: Bilateral Asymmetry in Mammograms 742
8.9.1 The fibroglandular disc 743
8.9.2 Gaussian mixture model of breast density 744
8.9.3 Delimitation of the fibroglandular disc 747
8.9.4 Motivation for directional analysis of mammograms . 755
8.9.5 Directional analysis of fibroglandular tissue 757
8.9.6 Characterization of bilateral asymmetry 766
8.10 Application: Architectural Distortion in Mammograms . . . 775
8.10.1 Detection of spiculated lesions and distortion 775
8.10.2 Phase portraits 779
8.10.3 Estimating the orientation field 780
8.10.4 Characterizing orientation fields with phase portraits 782

8.10.5 Feature extraction for pattern classification 785
8.10.6 Application to segments of mammograms 785
8.10.7 Detection of sites of architectural distortion 786
8.11 Remarks 791
8.12 Study Questions and Problems 796
8.13 Laboratory Exercises and Projects 796

9 Image Reconstruction from Projections 797
9.1 Projection Geometry 797
9.2 The Fourier Slice Theorem 798
9.3 Backprojection 801
9.3.1 Filtered backprojection 804
9.3.2 Discrete filtered backprojection 806
9.4 Algebraic Reconstruction Techniques 813
9.4.1 Approximations to the Kaczmarz method 820
9.5 Imaging with Diffracting Sources 825
9.6 Display of CT Images 825
9.7 Agricultural and Forestry Applications 829
9.8 Microtomography 831
9.9 Application: Analysis of the Tumor in Neuroblastoma 834
9.9.1 Neuroblastoma 834
9.9.2 Tissue characterization using CT 838
9.9.3 Estimation of tissue composition from CT images . . 839
9.9.4 Results of application to clinical cases 844
9.9.5 Discussion 845
9.10 Remarks 854
9.11 Study Questions and Problems 854
9.12 Laboratory Exercises and Projects 855

10 Deconvolution, Deblurring, and Restoration 857
10.1 Linear Space-invariant Restoration Filters 857
10.1.1 Inverse filtering 858
10.1.2 Power spectrum equalization 860
10.1.3 The Wiener filter 863
10.1.4 Constrained least-squares restoration 872
10.1.5 The Metz filter 874
10.1.6 Information required for image restoration 875
10.1.7 Motion deblurring 875
10.2 Blind Deblurring 877
10.2.1 Iterative blind deblurring 878
10.3 Homomorphic Deconvolution 885
10.3.1 The complex cepstrum 885
10.3.2 Echo removal by Radon-domain cepstral filtering . . . 886
10.4 Space-variant Restoration 891
10.4.1 Sectioned image restoration 893

10.4.2 Adaptive-neighborhood deblurring 894
10.4.3 The Kalman filter 898
10.5 Application: Restoration of Nuclear Medicine Images 919
10.5.1 Quality control 922
10.5.2 Scatter compensation 922
10.5.3 Attenuation correction 923
10.5.4 Resolution recovery 924
10.5.5 Geometric averaging of conjugate projections 926
10.5.6 Examples of restoration of SPECT images 934
10.6 Remarks 949
10.7 Study Questions and Problems 953
10.8 Laboratory Exercises and Projects 954

11 Image Coding and Data Compression 955
11.1 Considerations Based on Information Theory 956
11.1.1 Noiseless coding theorem for binary transmission . . . 957
11.1.2 Lossy versus lossless compression 957
11.1.3 Distortion measures and fidelity criteria 959
11.2 Fundamental Concepts of Coding 960
11.3 Direct Source Coding 961
11.3.1 Huffman coding 961
11.3.2 Run-length coding 969
11.3.3 Arithmetic coding 969
11.3.4 Lempel–Ziv coding 974
11.3.5 Contour coding 977
11.4 Application: Source Coding of Digitized Mammograms . . . 978
11.5 The Need for Decorrelation 980
11.6 Transform Coding 984
11.6.1 The discrete cosine transform 987
11.6.2 The Karhunen–Loève transform 989
11.6.3 Encoding of transform coefficients 992
11.7 Interpolative Coding 1001
11.8 Predictive Coding 1004
11.8.1 Two-dimensional linear prediction 1005
11.8.2 Multichannel linear prediction 1009
11.8.3 Adaptive 2D recursive least-squares prediction 1026
11.9 Image Scanning Using the Peano-Hilbert Curve 1033
11.9.1 Definition of the Peano-scan path 1035
11.9.2 Properties of the Peano-Hilbert curve 1040
11.9.3 Implementation of Peano scanning 1040
11.9.4 Decorrelation of Peano-scanned data 1041
11.10 Image Coding and Compression Standards 1043
11.10.1 The JBIG Standard 1046
11.10.2 The JPEG Standard 1049
11.10.3 The MPEG Standard 1050

11.10.4 The ACR/ NEMA and DICOM Standards 1050
11.11 Segmentation-based Adaptive Scanning 1051
11.11.1 Segmentation-based coding 1051
11.11.2 Region-growing criteria 1052
11.11.3 The SLIC procedure 1055
11.11.4 Results of image data compression with SLIC 1055
11.12 Enhanced JBIG Coding 1062
11.13 Lower-limit Analysis of Lossless Data Compression 1066
11.13.1 Memoryless entropy 1070
11.13.2 Markov entropy 1071
11.13.3 Estimation of the true source entropy 1071
11.14 Application: Teleradiology 1079
11.14.1 Analog teleradiology 1080
11.14.2 Digital teleradiology 1082
11.14.3 High-resolution digital teleradiology 1084
11.15 Remarks 1086
11.16 Study Questions and Problems 1086
11.17 Laboratory Exercises and Projects 1087

12 Pattern Classification and Diagnostic Decision 1089
12.1 Pattern Classification 1091
12.2 Supervised Pattern Classification 1095
12.2.1 Discriminant and decision functions 1095
12.2.2 Distance functions 1097
12.2.3 The nearest-neighbor rule 1104
12.3 Unsupervised Pattern Classification 1104
12.3.1 Cluster-seeking methods 1105
12.4 Probabilistic Models and Statistical Decision 1110
12.4.1 Likelihood functions and statistical decision 1110
12.4.2 Bayes classifier for normal patterns 1118
12.5 Logistic Regression 1120
12.6 The Training and Test Steps 1125
12.6.1 The leave-one-out method 1125
12.7 Neural Networks 1126
12.8 Measures of Diagnostic Accuracy 1132
12.8.1 Receiver operating characteristics 1135
12.8.2 McNemar's test of symmetry 1138
12.9 Reliability of Features, Classifiers, and Decisions 1140
12.9.1 Statistical separability and feature selection 1141
12.10 Application: Image Enhancement for Breast Cancer Screening 1143
12.10.1 Case selection, digitization, and presentation 1145
12.10.2 ROC and statistical analysis 1147
12.10.3 Discussion 1159

12.11 Application: Classification of Breast Masses and Tumors via Shape Analysis 1160
12.12 Application: Content-based Retrieval and Analysis of Breast Masses 1166
12.12.1 Pattern classification of masses 1167
12.12.2 Content-based retrieval 1169
12.12.3 Extension to telemedicine 1177
12.13 Remarks 1182
12.14 Study Questions and Problems 1184
12.15 Laboratory Exercises and Projects 1185

References **1187**

Index **1262**