Contents

1 Introduction 1

1.1 Digital Image Processing — A New Research Tool 1
1.2 Components of an Image Processing System 2
1.2.1 Image Sensors 2
1.2.2 Image Storage 6
1.2.3 Image Processing Speed 8
1.3 Human and Computer Vision 8
1.4 Examples of Scientific Applications 12
1.5 Hierarchy of Image Processing Operations 15
1.6 Image Processing and Computer Graphics 18

2 Image Formation and Digitization 19

2.1 Interaction between Light and Matter 19
2.1.1 Introduction 19
2.1.2 Opaque Surfaces 20
2.1.3 Volumes 21
2.1.4 Light Sources 22
2.1.5 Reflection 22
2.2 Image formation 22
2.2.1 World and Camera Coordinates 23
2.2.2 Pinhole Camera Model: Perspective Projection 24
2.2.3 Homogeneous Coordinates 26
2.2.4 Geometric Distortion 28
2.2.5 Depth of Focus 29
2.2.6 3-D Point Spread Function 31
2.2.7 Optical Transfer Function 33
2.2.8 Cross Sectional Imaging 37
2.2.9 Stereoscopy 38
2.2.10 Tomography 39
2.3 Digitization 40
2.3.1 Image matrix 40
2.3.2 Moiré-Effect and Aliasing 43
2.3.3 The Sampling Theorem 45
2.3.4 Reconstruction from Samples 50
2.3.5 Standard Sampling 52

3 Space and Wave Number Domain 53
3.1 Introduction . . . 53
3.2 The Discrete Fourier transform (DFT) . . . 54
3.2.1 The one-dimensional DFT . . . 54
3.2.2 The Two-Dimensional DFT . . . 56
3.2.3 Periodicity . . . 57
3.2.4 Symmetry . . . 57
3.2.5 Dynamical Range of the DFT . . . 60
3.2.6 Phase and Amplitude . . . 61
3.3 Discrete Unitary Transforms . . . 63
3.3.1 General Properties . . . 63
3.3.2 Further Examples for Unitary Transforms . . . 65
3.4 Fast Algorithms for Unitary Transforms . . . 67
3.4.1 Importance of Fast Algorithms . . . 67
3.4.2 The 1-D Radix-2 FFT Algorithms . . . 68
3.4.3 Other 1-D FFT Algorithms . . . 72
3.4.4 Multidimensional FFT Algorithms . . . 75

4 Pixels 77
4.1 Introduction . . . 77
4.2 Random Variables . . . 77
4.2.1 Basics . . . 77
4.2.2 Quantization . . . 81
4.2.3 Histograms . . . 83
4.3 Point Operations . . . 86
4.3.1 Homogeneous Point Operations . . . 86
4.3.2 Look-Up Tables . . . 86
4.3.3 Inhomogeneous Point Operations . . . 91
4.4 Dyadic LUT Operations . . . 94
4.5 Correlations and Spectra . . . 95
4.5.1 Random Fields . . . 95
4.5.2 Correlations and Covariances . . . 95
4.5.3 Spectra and Coherence . . . 97

5 Neighborhoods 100
5.1 Combining Pixels . . . 100
5.1.1 Linear Filtering . . . 101
5.1.2 Recursive Filters and Linear Systems . . . 103
5.1.3 Rank Value Filtering . . . 106
5.2 Linear Shift-Invariant Filters . . . 107
5.2.1 Linearity . . . 108
5.2.2 Shift Invariance . . . 109
5.2.3 Impulse Response, Transfer Function, and Eigenfunctions . . . 109
5.2.4 Symmetry . . . 111
5.2.5 General Properties of Linear Shift-Invariant Operators . . . 114

6 Mean and Edges 117
6.1 Smoothing . . . 117
6.1.1 Box Filters . . . 117
6.1.2 Binomial Filters . . . 122
6.1.3 Recursive Smoothing Filters . . . 128
6.1.4 Median Filter . . . 131
6.2 Edge Detection . . . 134
6.2.1 First-Order Derivative Operators . . . 135
6.2.2 Laplace Filter . . . 138
6.3 Filter Design . . . 140
6.3.1 Filter Nets . . . 142
6.3.2 Filter Decomposition . . . 146
6.3.3 Smoothing Operators . . . 147
6.3.4 Bandpass Filters; DoG and LoG Filter . . . 153
6.3.5 Derivative Operators . . . 155

7 Local Orientation 157
7.1 Introduction . . . 157
7.1.1 Vectorial Representation of Local Orientation . . . 159
7.1.2 Color Coding of Vectorial Image Features . . . 159
7.2 The Quadrature Filter Set Method . . . 160
7.2.1 Directional Quadrature Filters . . . 160
7.2.2 Vectorial Filter Response Addition . . . 162
7.3 The Tensor Method . . . 164
7.3.1 Analogy: The Inertia Tensor . . . 166
7.3.2 Eigenvalue Analysis of the 2-D Inertia Tensor . . . 167
7.3.3 Computing the Inertia Tensor in the Space Domain . . . 168
7.3.4 Examples and Applications . . . 170

8 Scales 173
8.1 Multigrid Data Structures . . . 173
8.2 Gauss and Laplace Pyramids . . . 174
8.2.1 Introduction . . . 174
8.2.2 Algorithms for Pyramidal Decomposition . . . 177
8.2.3 Filters for Pyramid Formation . . . 180
8.2.4 Interpolation . . . 180

9 Texture 185
9.1 Introduction . . . 185
9.2 Rotation and Scale Invariant Texture Features . . . 188
9.2.1 Local Variance . . . 188
9.3 Rotation and Scale Variant Texture Features . . . 190
9.3.1 Local Orientation . . . 190
9.3.2 Local Wave Number . . . 190
9.3.3 Pyramidal Texture Analysis . . . 190
9.4 Fractal Description of Texture . . . 192

10 Segmentation 193
10.1 Introduction . . . 193
10.2 Pixel-Based Methods . . . 193
10.3 Region-Based Methods . . . 195
10.4 Edge-Based Methods . . . 198

11 Shape 200
11.1 Introduction . . . 200
11.2 Morphological Operators . . . 200
11.2.1 Neighborhood Operations on Binary Images . . . 200
11.2.2 General Properties of Morphological Operations . . . 202
11.2.3 Further Morphological Operations . . . 204
11.3 Representation of Shape . . . 208
11.3.1 Chain Code . . . 208
11.3.2 Run-length Code . . . 209
11.3.3 Quadtrees . . . 210
11.4 Shape Parameters . . . 212
11.4.1 Simple Geometric Parameters . . . 212
11.4.2 Moment-based Shape Features . . . 214
11.4.3 Fourier Descriptors . . . 216

12 Classification 219
12.1 Introduction . . . 219
12.2 Feature Space; Clusters . . . 221
12.3 Feature Selection; Principal-Axes Transform . . . 223
12.4 Classification Techniques . . . 225
12.5 Application . . . 226

13 Reconstruction from Projections 231
13.1 Introduction . . . 231
13.2 Focus Series . . . 233
13.2.1 Reconstruction of Surfaces in Space . . . 233
13.2.2 Reconstruction by Inverse Filtering . . . 234
13.2.3 Confocal Laser Scanning Microscopy . . . 237
13.3 Reconstruction of Tomographic Images . . . 239
13.3.1 Introduction . . . 239
13.3.2 Radon Transform and Fourier Slice Theorem . . . 240
13.3.3 Filtered Back Projection . . . 241
13.3.4 Algebraic Reconstruction . . . 245

14 Motion 253
14.1 Introduction . . . 253
14.1.1 Gray Value Changes . . . 254
14.1.2 The Aperture Problem . . . 257
14.1.3 The Correspondence Problem . . . 257
14.1.4 Motion Analysis and 3-D Reconstruction . . . 259
14.2 Motion Kinematics . . . 259
14.2.1 Mass points . . . 261
14.2.2 Deformable Objects . . . 263

14.2.3 Kinematics of Projected Motion . . . 266
14.3 Motion Dynamics . . . 268
14.4 Motion Models . . . 269
14.4.1 Motion of Points . . . 270
14.4.2 Motion of Planar Surfaces . . . 272
14.4.3 Motion in Cross-Sectional Images . . . 274

15 Displacement Vectors 275
15.1 Introduction . . . 275
15.2 Differential Methods . . . 276
15.2.1 Optical Flux . . . 276
15.2.2 Least Squares Solution of the Aperture Problem . . . 279
15.2.3 Differential Geometric Modeling . . . 286
15.3 Correlation Methods . . . 289
15.3.1 Principle . . . 290
15.3.2 Fast Implementation . . . 291
15.3.3 Monotony Operator . . . 293
15.3.4 Signum of the Laplace Operator . . . 296

16 Displacement Vector Fields 297
16.1 Introduction . . . 297
16.2 Determination of DVF by Variational Calculus . . . 298
16.2.1 General Approach . . . 298
16.2.2 Differential Method as a Minimal Problem . . . 299
16.3 Smooth Displacement Vector Fields . . . 300
16.3.1 Smoothness Constraints . . . 300
16.3.2 Elasticity Models . . . 302
16.3.3 Network Models . . . 304
16.3.4 Diffusion Models . . . 308
16.4 Controlling Smoothness . . . 309
16.4.1 Smooth Displacement Vector Fields . . . 310
16.4.2 Edge-oriented Smoothness . . . 313
16.4.3 Region-limited Smoothness . . . 315
16.4.4 Oriented Smoothness . . . 315
16.5 Summary . . . 316

17 Space-Time Images 318
17.1 Motion is Orientation . . . 318
17.2 Motion in Fourier Domain . . . 321
17.3 Velocity Filtering . . . 323
17.3.1 Projection Filters . . . 324
17.3.2 Gabor Filters . . . 326
17.4 1-D Motion Determination . . . 327
17.4.1 Conversion of the Differential Method into a Filter Method . . . 327
17.4.2 The Tensor Method . . . 330
17.4.3 The Quadrature Filter Set Method . . . 331
17.4.4 The Phase Method . . . 332
17.4.5 Accuracy of Motion Determination . . . 334
17.5 2-D Motion Determination . . . 336

17.5.1 The Quadrature Filter Set Method . . . 336
17.5.2 The Tensor Method . . . 337

A Mathematical Preliminaries 341
A.1 Matrix Algebra . . . 341
A.1.1 Definitions . . . 341
A.1.2 The Overdetermined Discrete Inverse Problem . . . 342
A.1.3 Suggested Further Readings . . . 344
A.2 Fourier Transformation . . . 344
A.2.1 Definition . . . 344
A.2.2 Properties of the Fourier Transform . . . 345
A.2.3 Important Fourier Transform Pairs . . . 346
A.2.4 Suggested Further Readings . . . 346
A.3 Discrete Fourier transform (DFT) . . . 346
A.3.1 Definition . . . 346
A.3.2 Important Properties . . . 347
A.3.3 Important Transform Pairs . . . 348
A.3.4 Suggested Further Readings . . . 348

B PC-Based Image Processing Systems 349
B.1 Overview . . . 349
B.2 Video Input . . . 350
B.3 Frame Buffer . . . 354
B.4 Video Output . . . 355
B.5 Dedicated Image Processing Hardware . . . 356
B.5.1 Parallel Processing in the Video Pipeline . . . 356
B.5.2 Processing Windows: Area-of-Interest . . . 357
B.5.3 Arithmetic Pipeline Processors . . . 357
B.5.4 Filter processors . . . 358
B.5.5 Histogram and Feature Extractors . . . 358
B.6 Programmable Systems . . . 358
B.6.1 Frame Grabbers with Programmable Processors . . . 359
B.6.2 Frame Grabbers for Fast PC Bus Systems . . . 359
B.6.3 Portable Software Versus Dedicated Hardware . . . 360

Bibliography 370

Index 376