

Wilhelm Burger · Mark J. Burge

Digital Image Processing

An algorithmic introduction using Java

With 271 figures and 17 tables

2007

Springer

Berlin Heidelberg New York

Hongkong London

Mailand Paris Tokio

Contents

Preface	V
1 Crunching Pixels	1
1.1 Programming with Images	2
1.2 Image Analysis and Computer Vision	3
2 Digital Images	5
2.1 Types of Digital Images	5
2.2 Image Acquisition	5
2.2.1 The Pinhole Camera Model	7
2.2.2 The “Thin” Lens	8
2.2.3 Going Digital	8
2.2.4 Image Size and Resolution	10
2.2.5 Image Coordinate System	11
2.2.6 Pixel Values	11
2.3 Image File Formats	13
2.3.1 Raster versus Vector Data	14
2.3.2 Tagged Image File Format (TIFF)	15
2.3.3 Graphics Interchange Format (GIF)	15
2.3.4 Portable Network Graphics (PNG)	16
2.3.5 JPEG	17
2.3.6 Windows Bitmap (BMP)	20
2.3.7 Portable Bitmap Format (PBM)	21
2.3.8 Additional File Formats	21
2.3.9 Bits and Bytes	22
2.4 Exercises	24
3 ImageJ	27
3.1 Image Manipulation and Processing	28
3.2 ImageJ Overview	28
3.2.1 Key Features	29
3.2.2 Interactive Tools	30
3.2.3 ImageJ Plugins	31
3.2.4 A First Example: Inverting an Image	32
3.3 Additional Information on ImageJ and Java	35
3.3.1 Resources for ImageJ	35
3.3.2 Programming with Java	35

3.4	Exercises	36
4	Histograms	37
4.1	What Is a Histogram?	38
4.2	Interpreting Histograms	39
4.2.1	Image Acquisition	40
4.2.2	Image Defects	42
4.3	Computing Histograms	44
4.4	Histograms of Images with More than 8 Bits	46
4.4.1	Binning	46
4.4.2	Example	46
4.4.3	Implementation	47
4.5	Color Image Histograms	47
4.5.1	Intensity Histograms	48
4.5.2	Individual Color Channel Histograms	48
4.5.3	Combined Color Histogram	49
4.6	Cumulative Histogram	50
4.7	Exercises	51
5	Point Operations	53
5.1	Modifying Image Intensity	54
5.1.1	Contrast and Brightness	54
5.1.2	Limiting the Results by Clamping	54
5.1.3	Inverting Images	55
5.1.4	Threshold Operation	55
5.2	Point Operations and Histograms	55
5.3	Automatic Contrast Adjustment	57
5.4	Modified Auto-Contrast	58
5.5	Histogram Equalization	59
5.6	Histogram Specification	62
5.6.1	Frequencies and Probabilities	63
5.6.2	Principle of Histogram Specification	65
5.6.3	Adjusting to a Piecewise Linear Distribution	65
5.6.4	Adjusting to a Given Histogram (Histogram Matching)	67
5.6.5	Examples	68
5.7	Gamma Correction	72
5.7.1	Why Gamma?	73
5.7.2	The Gamma Function	74
5.7.3	Real Gamma Values	74
5.7.4	Applications of Gamma Correction	75
5.7.5	Implementation	76
5.7.6	Modified Gamma Correction	76
5.8	Point Operations in ImageJ	80
5.8.1	Point Operations with Lookup Tables	80
5.8.2	Arithmetic Operations	81
5.8.3	Point Operations Involving Multiple Images	81

5.8.4	Methods for Point Operations on Two Images	82
5.8.5	ImageJ Plugins for Multiple Images	82
5.9	Exercises	83
6	Filters	87
6.1	What Is a Filter?	87
6.2	Linear Filters	89
6.2.1	The Filter Matrix	89
6.2.2	Applying the Filter	90
6.2.3	Computing the Filter Operation	91
6.2.4	Filter Plugin Examples	92
6.2.5	Integer Coefficients	93
6.2.6	Filters of Arbitrary Size	94
6.2.7	Types of Linear Filters	95
6.3	Formal Properties of Linear Filters	98
6.3.1	Linear Convolution	99
6.3.2	Properties of Linear Convolution	100
6.3.3	Separability of Linear Filters	101
6.3.4	Impulse Response of a Filter	103
6.4	Nonlinear Filters	104
6.4.1	Minimum and Maximum Filters	105
6.4.2	Median Filter	106
6.4.3	Weighted Median Filter	107
6.4.4	Other Nonlinear Filters	110
6.5	Implementing Filters	111
6.5.1	Efficiency of Filter Programs	111
6.5.2	Handling Image Borders	111
6.5.3	Debugging Filter Programs	112
6.6	Filter Operations in ImageJ	113
6.6.1	Linear Filters	113
6.6.2	Gaussian Filters	114
6.6.3	Nonlinear Filters	115
6.7	Exercises	115
8	Corner Detection	139
8.1	Points of Interest	139
8.2	Harris Corner Detector	140
8.2.1	Local Structure Matrix	140
8.2.2	Corner Response Function (CRF)	141
8.2.3	Determining Corner Points	142
8.2.4	Example	142
8.3	Implementation	142
8.3.1	Step 1: Computing the Corner Response Function	144
8.3.2	Step 2: Selecting “Good” Corner Points	148
8.3.3	Displaying the Corner Points	152
8.3.4	Summary	152
8.4	Exercises	153

9	Detecting Simple Curves	155
9.1	Salient Structures	155
9.2	Hough Transform	156
9.2.1	Parameter Space	157
9.2.2	Accumulator Array	159
9.2.3	A Better Line Representation	159
9.3	Implementing the Hough Transform	160
9.3.1	Filling the Accumulator Array	161
9.3.2	Analyzing the Accumulator Array	163
9.3.3	Hough Transform Extensions	165
9.4	Hough Transform for Circles and Ellipses	167
9.4.1	Circles and Arcs	167
9.4.2	Ellipses	170
9.5	Exercises	170
10	Morphological Filters	173
10.1	Shrink and Let Grow	174
10.1.1	Neighborhood of Pixels	175
10.2	Basic Morphological Operations	175
10.2.1	The Structuring Element	175
10.2.2	Point Sets	176
10.2.3	Dilation	177
10.2.4	Erosion	178
10.2.5	Properties of Dilation and Erosion	178
10.2.6	Designing Morphological Filters	180
10.2.7	Application Example: Outline	181
10.3	Composite Operations	183
10.3.1	Opening	185
10.3.2	Closing	185
10.3.3	Properties of Opening and Closing	186
10.4	Grayscale Morphology	187
10.4.1	Structuring Elements	187
10.4.2	Dilation and Erosion	187
10.4.3	Grayscale Opening and Closing	188
10.5	Implementing Morphological Filters	189
10.5.1	Binary Images in ImageJ	189
10.5.2	Dilation and Erosion	191
10.5.3	Opening and Closing	193
10.5.4	Outline	194
10.5.5	Morphological Operations in ImageJ	194
10.6	Exercises	196
11	Regions in Binary Images	199
11.1	Finding Image Regions	200
11.1.1	Region Labeling with Flood Filling	200
11.1.2	Sequential Region Labeling	204
11.1.3	Region Labeling—Summary	209

11.2	Region Contours	209
11.2.1	External and Internal Contours	209
11.2.2	Combining Region Labeling and Contour Finding	212
11.2.3	Implementation	213
11.2.4	Example	216
11.3	Representing Image Regions	216
11.3.1	Matrix Representation	216
11.3.2	Run Length Encoding	218
11.3.3	Chain Codes	219
11.4	Properties of Binary Regions	222
11.4.1	Shape Features	222
11.4.2	Geometric Features	223
11.4.3	Statistical Shape Properties	226
11.4.4	Moment-Based Geometrical Properties	228
11.4.5	Projections	233
11.4.6	Topological Properties	234
11.5	Exercises	235
12	Color Images	239
12.1	RGB Color Images	239
12.1.1	Organization of Color Images	241
12.1.2	Color Images in ImageJ	244
12.2	Color Spaces and Color Conversion	253
12.2.1	Conversion to Grayscale	256
12.2.2	Desaturating Color Images	257
12.2.3	HSV/HSB and HLS Color Space	258
12.2.4	TV Color Spaces—YUV, YIQ, and YC_bC_r	267
12.2.5	Color Spaces for Printing—CMY and CMYK	271
12.3	Colorimetric Color Spaces	275
12.3.1	CIE Color Spaces	276
12.3.2	CIE $L^*a^*b^*$	281
12.3.3	sRGB	283
12.3.4	Adobe RGB	288
12.3.5	Chromatic Adaptation	288
12.3.6	Colorimetric Support in Java	292
12.4	Statistics of Color Images	299
12.4.1	How Many Colors Are in an Image?	299
12.4.2	Color Histograms	299
12.5	Color Quantization	301
12.5.1	Scalar Color Quantization	303
12.5.2	Vector Quantization	305
12.6	Exercises	311

13	Introduction to Spectral Techniques	313
13.1	The Fourier Transform	314
13.1.1	Sine and Cosine Functions	314
13.1.2	Fourier Series of Periodic Functions	317
13.1.3	Fourier Integral	318
13.1.4	Fourier Spectrum and Transformation	319
13.1.5	Fourier Transform Pairs	320
13.1.6	Important Properties of the Fourier Transform	321
13.2	Working with Discrete Signals	325
13.2.1	Sampling	325
13.2.2	Discrete and Periodic Functions	330
13.3	The Discrete Fourier Transform (DFT)	332
13.3.1	Definition of the DFT	332
13.3.2	Discrete Basis Functions	334
13.3.3	Aliasing Again!	334
13.3.4	Units in Signal and Frequency Space	338
13.3.5	Power Spectrum	339
13.4	Implementing the DFT	340
13.4.1	Direct Implementation	340
13.4.2	Fast Fourier Transform (FFT)	342
13.5	Exercises	342
14	The Discrete Fourier Transform in 2D	343
14.1	Definition of the 2D DFT	343
14.1.1	2D Basis Functions	344
14.1.2	Implementing the Two-Dimensional DFT	344
14.2	Visualizing the 2D Fourier Transform	345
14.2.1	Range of Spectral Values	348
14.2.2	Centered Representation	348
14.3	Frequencies and Orientation in 2D	348
14.3.1	Effective Frequency	349
14.3.2	Frequency Limits and Aliasing in 2D	350
14.3.3	Orientation	350
14.3.4	Correcting the Geometry of a 2D Spectrum	351
14.3.5	Effects of Periodicity	352
14.3.6	Windowing	352
14.3.7	Windowing Functions	354
14.4	2D Fourier Transform Examples	359
14.5	Applications of the DFT	359
14.5.1	Linear Filter Operations in Frequency Space	363
14.5.2	Linear Convolution versus Correlation	364
14.5.3	Inverse Filters	364
14.6	Exercises	366

15	The Discrete Cosine Transform (DCT)	367
15.1	One-Dimensional DCT	367
15.1.1	DCT Basis Functions	368
15.1.2	Implementing the One-Dimensional DCT	368
15.2	Two-Dimensional DCT	370
15.2.1	Separability	371
15.2.2	Examples	371
15.3	Other Spectral Transforms	371
15.4	Exercises	373
16	Geometric Operations	375
16.1	2D Mapping Function	376
16.1.1	Simple Mappings	377
16.1.2	Homogeneous Coordinates	377
16.1.3	Affine (Three-Point) Mapping	378
16.1.4	Projective (Four-Point) Mapping	380
16.1.5	Bilinear Mapping	385
16.1.6	Other Nonlinear Image Transformations	386
16.1.7	Local Image Transformations	389
16.2	Resampling the Image	390
16.2.1	Source-to-Target Mapping	390
16.2.2	Target-to-Source Mapping	391
16.3	Interpolation	392
16.3.1	Simple Interpolation Methods	392
16.3.2	Ideal Interpolation	393
16.3.3	Interpolation by Convolution	397
16.3.4	Cubic Interpolation	397
16.3.5	Spline Interpolation	399
16.3.6	Lanczos Interpolation	402
16.3.7	Interpolation in 2D	404
16.3.8	Aliasing	410
16.4	Java Implementation	413
16.4.1	Geometric Transformations	413
16.4.2	Pixel Interpolation	423
16.4.3	Sample Applications	426
16.5	Exercises	427
17	Comparing Images	429
17.1	Template Matching in Intensity Images	430
17.1.1	Distance between Image Patterns	431
17.1.2	Implementation	438
17.1.3	Matching under Rotation and Scaling	439
17.2	Matching Binary Images	441
17.2.1	Direct Comparison	441
17.2.2	The Distance Transform	442
17.2.3	Chamfer Matching	446
17.3	Exercises	447

A	Mathematical Notation	451
A.1	Symbols	451
A.2	Set Operators	453
A.3	Complex Numbers	453
A.4	Algorithmic Complexity and \mathcal{O} Notation	454
B	Java Notes	457
B.1	Arithmetic	457
B.1.1	Integer Division	457
B.1.2	Modulus Operator	459
B.1.3	Unsigned Bytes	459
B.1.4	Mathematical Functions (Class <code>Math</code>)	460
B.1.5	Rounding	461
B.1.6	Inverse Tangent Function	462
B.1.7	<code>Float</code> and <code>Double</code> (Classes)	462
B.2	Arrays and Collections	462
B.2.1	Creating Arrays	462
B.2.2	Array Size	463
B.2.3	Accessing Array Elements	463
B.2.4	Two-Dimensional Arrays	464
B.2.5	Cloning Arrays	465
B.2.6	Arrays of Objects, Sorting	466
B.2.7	Collections	467
C	ImageJ Short Reference	469
C.1	Installation and Setup	469
C.2	ImageJ API	471
C.2.1	Images and Processors	471
C.2.2	Images (Package <code>ij</code>)	471
C.2.3	Image Processors (Package <code>ij.process</code>)	472
C.2.4	Plugins (Packages <code>ij.plugin</code> , <code>ij.plugin.filter</code>)	473
C.2.5	GUI Classes (Package <code>ij.gui</code>)	474
C.2.6	Window Management (Package <code>ij</code>)	475
C.2.7	Utility Classes (Package <code>ij</code>)	475
C.2.8	Input-Output (Package <code>ij.io</code>)	475
C.3	Creating Images and Image Stacks	476
C.3.1	<code>ImagePlus</code> (Class)	476
C.3.2	<code>ImageStack</code> (Class)	476
C.3.3	<code>IJ</code> (Class)	477
C.3.4	<code>NewImage</code> (Class)	477
C.3.5	<code>ImageProcessor</code> (Class)	478
C.4	Creating Image Processors	478
C.4.1	<code>ImagePlus</code> (Class)	478
C.4.2	<code>ImageProcessor</code> (Class)	478
C.4.3	<code>ByteProcessor</code> (Class)	479
C.4.4	<code>ColorProcessor</code> (Class)	479
C.4.5	<code>FloatProcessor</code> (Class)	479

C.4.6	ShortProcessor (Class)	480
C.5	Loading and Storing Images	480
C.5.1	IJ (Class)	480
C.5.2	Opener (Class)	481
C.5.3	FileSaver (Class)	482
C.5.4	FileOpener (Class)	484
C.6	Image Parameters	485
C.6.1	ImageProcessor (Class)	485
C.6.2	ColorProcessor (Class)	485
C.7	Accessing Pixels	485
C.7.1	Accessing Pixels by 2D Image Coordinates	485
C.7.2	Accessing Pixels by 1D Indices	487
C.7.3	Accessing Multiple Pixels	488
C.7.4	Accessing All Pixels at Once	489
C.7.5	Specific Access Methods for Color Images	490
C.7.6	Direct Access to Pixel Arrays	490
C.8	Converting Images	492
C.8.1	ImageProcessor (Class)	492
C.8.2	ImagePlus , ImageConverter (Classes)	492
C.9	Histograms and Image Statistics	494
C.9.1	ImageProcessor (Class)	494
C.10	Point Operations	494
C.10.1	ImageProcessor (Class)	495
C.11	Filters	497
C.11.1	ImageProcessor (Class)	497
C.12	Geometric Operations	497
C.12.1	ImageProcessor (Class)	497
C.13	Graphic Operations	499
C.13.1	ImageProcessor (Class)	499
C.14	Displaying Images and Image Stacks	500
C.14.1	ImagePlus (Class)	500
C.14.2	ImageProcessor (Class)	502
C.15	Operations on Image Stacks	504
C.15.1	ImagePlus (Class)	504
C.15.2	ImageStack (Class)	505
C.15.3	Stack Example	506
C.16	Regions of Interest	506
C.16.1	ImagePlus (Class)	509
C.16.2	Roi , Line , OvalRoi , PointRoi , PolygonRoi (Classes)	510
C.16.3	ImageProcessor (Class)	511
C.16.4	ImageStack (Class)	512
C.16.5	IJ (Class)	512
C.17	Image Properties	513
C.17.1	ImagePlus (Class)	514
C.18	User Interaction	515
C.18.1	IJ (Class)	515

CONTENTS

C.18.2	GenericDialog (Class)	517
C.19	Plugins	518
C.19.1	PlugIn (Interface)	518
C.19.2	PlugInFilter (Interface)	519
C.19.3	Executing Plugins: IJ (Class)	520
C.20	Window Management	521
C.20.1	WindowManager (Class)	521
C.21	Additional Functions	522
C.21.1	ImagePlus (Class)	522
C.21.2	IJ (Class)	523
D	Source Code	525
D.1	Harris Corner Detector	525
D.1.1	Harris_Corner_Plugin (Class)	525
D.1.2	File Corner (Class)	527
D.1.3	File HarrisCornerDetector (Class)	527
D.2	Combined Region Labeling and Contour Tracing	532
D.2.1	Contour_Tracing_Plugin (Class)	532
D.2.2	Contour (Class)	533
D.2.3	BinaryRegion (Class)	535
D.2.4	ContourTracer (Class)	536
D.2.5	ContourOverlay (Class)	541
	References	543
	Index	549