

Contents

List of Abbreviations	xv
Preface to the Second Edition	xix
Preface to the First Edition	xxi
1 Introduction	1
2 Image Acquisition	5
2.1 Illumination	5
2.1.1 Electromagnetic Radiation	5
2.1.2 Types of Light Sources	7
2.1.3 Interaction of Light and Matter	8
2.1.4 Using the Spectral Composition of the Illumination	10
2.1.5 Using the Directional Properties of the Illumination	12
2.1.5.1 Diffuse Bright-Field Front Light Illumination	13
2.1.5.2 Directed Bright-Field Front Light Illumination	14
2.1.5.3 Directed Dark-Field Front Light Illumination	15
2.1.5.4 Diffuse Bright-Field Back Light Illumination	16
2.1.5.5 Telecentric Bright-Field Back Light Illumination	17
2.2 Lenses	18
2.2.1 Pinhole Cameras	18
2.2.2 Gaussian Optics	19
2.2.2.1 Refraction	19
2.2.2.2 Thick Lens Model	20
2.2.2.3 Aperture Stop and Pupils	22
2.2.2.4 Relation of the Pinhole Model to Gaussian Optics	24
2.2.3 Depth of Field	25
2.2.4 Telecentric Lenses	28
2.2.4.1 Object-Side Telecentric Lenses	28
2.2.4.2 Bilateral Telecentric Lenses	30
2.2.4.3 Image-Side Telecentric Lenses	31
2.2.4.4 Projection Characteristics of Lenses	32

2.2.5	Tilt Lenses and the Scheimpflug Principle	32
2.2.6	Lens Aberrations	36
2.2.6.1	Spherical Aberration	36
2.2.6.2	Coma	36
2.2.6.3	Astigmatism	37
2.2.6.4	Curvature of Field	37
2.2.6.5	Distortion	37
2.2.6.6	Chromatic Aberration	39
2.2.6.7	Edge-Spread Function	39
2.2.6.8	Vignetting	40
2.3	Cameras	41
2.3.1	CCD Sensors	41
2.3.1.1	Line Sensors	41
2.3.1.2	Full Frame Array Sensors	43
2.3.1.3	Frame Transfer Sensors	43
2.3.1.4	Interline Transfer Sensors	44
2.3.1.5	Readout Modes	46
2.3.2	CMOS Sensors	46
2.3.2.1	Sensor Architecture	46
2.3.2.2	Rolling and Global Shutters	47
2.3.3	Color Cameras	48
2.3.3.1	Spectral Response of Monochrome Cameras	48
2.3.3.2	Single-Chip Cameras	49
2.3.3.3	Three-Chip Cameras	50
2.3.3.4	Spectral Response of Color Cameras	50
2.3.4	Sensor Sizes	50
2.3.5	Camera Performance	52
2.3.5.1	Noise	52
2.3.5.2	Signal-to-Noise Ratio	53
2.3.5.3	Dynamic Range	54
2.3.5.4	Nonuniformities	54
2.4	Camera–Computer Interfaces	55
2.4.1	Analog Video Signals	56
2.4.1.1	Analog Video Standards	56
2.4.1.2	Analog Frame Grabbers	58
2.4.2	Digital Video Signals	60
2.4.2.1	Camera Link	61
2.4.2.2	Camera Link HS	62
2.4.2.3	CoaXPress	64
2.4.2.4	IEEE 1394	65
2.4.2.5	USB 2.0	67
2.4.2.6	USB3 Vision	68
2.4.2.7	GigE Vision	69
2.4.3	Generic Interfaces	72
2.4.3.1	GenICam	72

2.4.3.2	GenICam GenTL	77
2.4.4	Image Acquisition Modes	79
2.5	3D Image Acquisition Devices	82
2.5.1	Stereo Sensors	82
2.5.2	Sheet of Light Sensors	84
2.5.3	Structured Light Sensors	86
2.5.3.1	Pattern Projection	87
2.5.3.2	Gray Codes	88
2.5.3.3	Fringe Projection	90
2.5.3.4	Hybrid Systems	91
2.5.4	Time-of-Flight Cameras	91
2.5.4.1	Continuous-Wave-Modulated Time-of-Flight Cameras	92
2.5.4.2	Pulse-Modulated Time-of-Flight Cameras	93

3 Machine Vision Algorithms 97

3.1	Fundamental Data Structures	97
3.1.1	Images	97
3.1.2	Regions	98
3.1.3	Subpixel-Precise Contours	101
3.2	Image Enhancement	101
3.2.1	Gray Value Transformations	102
3.2.1.1	Contrast Enhancement	102
3.2.1.2	Contrast Normalization	102
3.2.1.3	Robust Contrast Normalization	103
3.2.2	Radiometric Calibration	105
3.2.2.1	Chart-Based Radiometric Calibration	105
3.2.2.2	Chartless Radiometric Calibration	106
3.2.3	Image Smoothing	110
3.2.3.1	Temporal Averaging	111
3.2.3.2	Mean Filter	112
3.2.3.3	Border Treatment of Filters	113
3.2.3.4	Runtime Complexity of Filters	114
3.2.3.5	Linear Filters	115
3.2.3.6	Frequency Response of the Mean Filter	116
3.2.3.7	Gaussian Filter	117
3.2.3.8	Noise Suppression by Linear Filters	118
3.2.3.9	Median and Rank Filters	119
3.2.4	Fourier Transform	120
3.2.4.1	Continuous Fourier Transform	120
3.2.4.2	Discrete Fourier Transform	123
3.3	Geometric Transformations	126
3.3.1	Affine Transformations	126
3.3.1.1	Projective Transformations	127

3.3.2	Image Transformations	128
3.3.2.1	Nearest-Neighbor Interpolation	128
3.3.2.2	Bilinear Interpolation	129
3.3.2.3	Bicubic Interpolation	130
3.3.2.4	Smoothing to Avoid Aliasing	132
3.3.3	Projective Image Transformations	133
3.3.4	Polar Transformations	133
3.4	Image Segmentation	135
3.4.1	Thresholding	135
3.4.1.1	Global Thresholding	135
3.4.1.2	Automatic Threshold Selection	136
3.4.1.3	Dynamic Thresholding	138
3.4.1.4	Variation Model	141
3.4.2	Extraction of Connected Components	144
3.4.3	Subpixel-Precise Thresholding	147
3.5	Feature Extraction	149
3.5.1	Region Features	149
3.5.1.1	Area	149
3.5.1.2	Moments	150
3.5.1.3	Ellipse Parameters	151
3.5.1.4	Enclosing Rectangles and Circles	153
3.5.1.5	Contour Length	154
3.5.2	Gray Value Features	154
3.5.2.1	Statistical Features	154
3.5.2.2	Moments	155
3.5.2.3	Ellipse Parameters	155
3.5.2.4	Comparison of Region and Gray Value Moments	155
3.5.3	Contour Features	158
3.5.3.1	Contour Length, Enclosing Rectangles and Circles	158
3.5.3.2	Moments	158
3.6	Morphology	159
3.6.1	Region Morphology	159
3.6.1.1	Set Operations	159
3.6.1.2	Minkowski Addition and Dilation	161
3.6.1.3	Minkowski Subtraction and Erosion	163
3.6.1.4	Region Boundaries	166
3.6.1.5	Hit-or-Miss Transform	167
3.6.1.6	Opening and Closing	168
3.6.1.7	Skeleton	172
3.6.1.8	Distance Transform	173
3.6.2	Gray Value Morphology	175
3.6.2.1	Minkowski Addition and Dilation	175
3.6.2.2	Minkowski Subtraction and Erosion	176
3.6.2.3	Opening and Closing	177
3.6.2.4	Morphological Gradient	179

3.7	Edge Extraction	180
3.7.1	Definition of Edges	180
3.7.1.1	Definition of Edges in 1D	180
3.7.1.2	Definition of Edges in 2D	181
3.7.2	1D Edge Extraction	183
3.7.2.1	Discrete Derivatives	184
3.7.2.2	Smoothing Perpendicular to a Profile	185
3.7.2.3	Optimal Edge Filters	186
3.7.2.4	Pixel-Accurate Edge Extraction	188
3.7.2.5	Subpixel-Accurate Edge Extraction	189
3.7.3	2D Edge Extraction	189
3.7.3.1	Discrete Derivatives	190
3.7.3.2	Optimal Edge Filters	191
3.7.3.3	Non-Maximum Suppression	192
3.7.3.4	Hysteresis Thresholding	194
3.7.3.5	Subpixel-Accurate Edge Extraction	194
3.7.4	Accuracy and Precision of Edges	196
3.7.4.1	Definition of Accuracy and Precision	197
3.7.4.2	Analytical Edge Accuracy and Precision	198
3.7.4.3	Edge Accuracy and Precision on Real Images	199
3.8	Segmentation and Fitting of Geometric Primitives	203
3.8.1	Fitting Lines	204
3.8.1.1	Least-Squares Line Fitting	204
3.8.1.2	Robust Line Fitting	205
3.8.2	Fitting Circles	208
3.8.2.1	Least-Squares Circle Fitting	208
3.8.2.2	Robust Circle Fitting	209
3.8.3	Fitting Ellipses	210
3.8.3.1	Least-Squares Ellipse Fitting	210
3.8.3.2	Robust Ellipse Fitting	210
3.8.4	Segmentation of Contours	211
3.8.4.1	Segmentation of Contours into Lines	211
3.8.4.2	Segmentation of Contours into Lines, Circles, and Ellipses	213
3.9	Camera Calibration	215
3.9.1	Camera Models for Area Scan Cameras with Regular Lenses	216
3.9.1.1	Exterior Orientation	217
3.9.1.2	Projection From 3D to 2D	219
3.9.1.3	Lens Distortions	219
3.9.1.4	Image Coordinates	221
3.9.2	Camera Models for Area Scan Cameras with Tilt Lenses	222
3.9.2.1	Lens Distortions	222
3.9.2.2	Modeling the Pose of the Tilted Image Plane	222
3.9.2.3	Image-Space Telecentric Lenses	223
3.9.2.4	Image-Space Perspective Lenses	224

3.9.3	Camera Model for Line Scan Cameras	225
3.9.3.1	Camera Motion	225
3.9.3.2	Exterior Orientation	226
3.9.3.3	Interior Orientation	227
3.9.3.4	Nonlinearities of the Line Scan Camera Model	229
3.9.4	Calibration Process	230
3.9.4.1	Calibration Target	230
3.9.4.2	Single-Image Camera Calibration	232
3.9.4.3	Degeneracies When Calibrating With a Single Image	233
3.9.4.4	Multi-Image Camera Calibration	234
3.9.4.5	Degeneracies Occurring With Tilt Lenses	234
3.9.4.6	Excluding Parameters From the Optimization	235
3.9.5	World Coordinates from Single Images	235
3.9.5.1	Telecentric Cameras	236
3.9.5.2	Perspective Cameras	236
3.9.5.3	Line-Scan Cameras	238
3.9.5.4	Image Rectification	238
3.9.6	Accuracy of the Camera Parameters	238
3.9.6.1	Influence of the Number of Calibration Images on the Accuracy	239
3.9.6.2	Influence of the Focus Setting on the Camera Parameters	240
3.9.6.3	Influence of the Diaphragm Setting on the Camera Parameters	240
3.10	3D Reconstruction	241
3.10.1	Stereo Reconstruction	241
3.10.1.1	Stereo Geometry	242
3.10.1.2	Stereo Calibration	243
3.10.1.3	Epipolar Geometry	244
3.10.1.4	Image Rectification	247
3.10.1.5	Disparity	249
3.10.1.6	Stereo Matching	250
3.10.1.7	Effect of Window Size	252
3.10.1.8	Robust Stereo Matching	253
3.10.1.9	Spacetime Stereo Matching	254
3.10.2	Sheet of Light Reconstruction	254
3.10.2.1	Extraction of the Laser Line	255
3.10.2.2	Sensor Calibration and 3D Reconstruction	256
3.10.3	Structured Light Reconstruction	257
3.10.3.1	Decoding the Stripes	257
3.10.3.2	Sensor Calibration and 3D Reconstruction	258
3.11	Template Matching	262
3.11.1	Gray-Value-Based Template Matching	263
3.11.1.1	Similarity Measures Based on Gray Value Differences	263

3.11.1.2	Normalized Cross-Correlation	264
3.11.1.3	Efficient Evaluation of the Similarity Measures	266
3.11.2	Matching Using Image Pyramids	267
3.11.2.1	Image Pyramids	268
3.11.2.2	Hierarchical Search	270
3.11.3	Subpixel-Accurate Gray-Value-Based Matching	271
3.11.4	Template Matching with Rotations and Scalings	272
3.11.5	Robust Template Matching	273
3.11.5.1	Mean Squared Edge Distance	274
3.11.5.2	Hausdorff Distance	276
3.11.5.3	Generalized Hough Transform	277
3.11.5.4	Geometric Hashing	281
3.11.5.5	Matching Geometric Primitives	283
3.11.5.6	Shape-Based Matching	286
3.12	3D Object Recognition	292
3.12.1	Deformable Matching	293
3.12.1.1	Principle of Deformable Matching	293
3.12.1.2	Model Generation	295
3.12.1.3	Similarity Measure	295
3.12.1.4	Hierarchical Search	297
3.12.1.5	Least-Squares Pose Refinement	297
3.12.1.6	3D Pose Estimation	297
3.12.1.7	Recognition of Locally Deformed Objects	300
3.12.2	Shape-Based 3D Matching	302
3.12.2.1	View-Based Approach	303
3.12.2.2	Restricting the Pose Range	306
3.12.2.3	Hierarchical Model	307
3.12.2.4	2D Model Generation	308
3.12.2.5	Perspective Correction	310
3.12.2.6	Least-Squares Pose Refinement	311
3.12.2.7	Examples	312
3.12.3	Surface-Based 3D Matching	313
3.12.3.1	Global Model Description	314
3.12.3.2	Local Parameters	316
3.12.3.3	Voting	318
3.12.3.4	Least-Squares Pose Refinement	319
3.12.3.5	Extension for Recognizing Deformed Objects	321
3.12.3.6	Extension for Multimodal Data	321
3.13	Hand–Eye Calibration	323
3.13.1	Introduction	323
3.13.2	Problem Definition	325
3.13.3	Dual Quaternions and Screw Theory	327
3.13.3.1	Quaternions	327
3.13.3.2	Screws	329
3.13.3.3	Dual Numbers	330

3.13.3.4	Dual Quaternions	330
3.13.4	Linear Hand–Eye Calibration	331
3.13.5	Nonlinear Hand–Eye Calibration	334
3.13.6	Hand–Eye Calibration of SCARA Robots	335
3.14	Optical Character Recognition	337
3.14.1	Character Segmentation	338
3.14.2	Feature Extraction	339
3.15	Classification	342
3.15.1	Decision Theory	343
3.15.1.1	Bayes Decision Rule	343
3.15.1.2	Classifier Types	345
3.15.1.3	Training, Test, and Validation Sets	345
3.15.1.4	Novelty Detection	345
3.15.2	Classifiers Based on Estimating Class Probabilities	346
3.15.2.1	k Nearest-Neighbor Classifiers	347
3.15.2.2	Gaussian Mixture Model Classifiers	347
3.15.3	Classifiers Based on Constructing Separating Hypersurfaces	350
3.15.3.1	Single-Layer Perceptrons	350
3.15.3.2	Multilayer Perceptrons	352
3.15.3.3	Support Vector Machines	358
3.15.3.4	Convolutional Neural Networks	365
3.15.4	Example of Using Classifiers for OCR	369

4	Machine Vision Applications	371
4.1	Wafer Dicing	371
4.1.1	Determining the Width and Height of the Dies	372
4.1.2	Determining the Position of the Dies	374
4.1.3	Exercises	376
4.2	Reading of Serial Numbers	377
4.2.1	Rectifying the Image Using a Polar Transformation	377
4.2.2	Segmenting the Characters	380
4.2.3	Reading the Characters	382
4.2.4	Exercises	382
4.3	Inspection of Saw Blades	383
4.3.1	Extracting the Saw Blade Contour	384
4.3.2	Extracting the Teeth of the Saw Blade	385
4.3.3	Measuring the Angles of the Teeth of the Saw Blade	386
4.3.4	Exercise	388
4.4	Print Inspection	388
4.4.1	Creating the Model of the Correct Print on the Relay	389
4.4.2	Creating the Model to Align the Relays	390
4.4.3	Performing the Print Inspection	391
4.4.4	Exercises	392
4.5	Inspection of Ball Grid Arrays	392
4.5.1	Finding Balls with Shape Defects	393

4.5.2	Constructing a Geometric Model of a Correct BGA	395
4.5.3	Finding Missing and Extraneous Balls	397
4.5.4	Finding Displaced Balls	398
4.5.5	Exercises	400
4.6	Surface Inspection	400
4.6.1	Segmenting the Doorknob	401
4.6.2	Finding the Surface to Inspect	402
4.6.3	Detecting Defects	405
4.6.4	Exercises	407
4.7	Measurement of Spark Plugs	408
4.7.1	Calibrating the Camera	409
4.7.2	Determining the Position of the Spark Plug	410
4.7.3	Performing the Measurement	411
4.7.4	Exercises	413
4.8	Molding Flash Detection	414
4.8.1	Molding Flash Detection Using Region Morphology	414
4.8.2	Molding Flash Detection with Subpixel-Precise Contours	418
4.8.3	Exercise	421
4.9	Inspection of Punched Sheets	421
4.9.1	Extracting the Boundaries of the Punched Sheets	422
4.9.2	Performing the Inspection	424
4.9.3	Exercises	425
4.10	3D Plane Reconstruction with Stereo	425
4.10.1	Calibrating the Stereo Setup	426
4.10.2	Performing the 3D Reconstruction and Inspection	428
4.10.3	Exercise	432
4.11	Pose Verification of Resistors	432
4.11.1	Creating Models of the Resistors	433
4.11.2	Verifying the Pose and Type of the Resistors	436
4.11.3	Exercises	438
4.12	Classification of Non-Woven Fabrics	438
4.12.1	Training the Classifier	438
4.12.2	Performing the Texture Classification	440
4.12.3	Exercise	443
4.13	Surface Comparison	443
4.13.1	Creating the Reference Model	443
4.13.2	Reconstructing and Aligning Objects	445
4.13.3	Comparing Objects and Classifying Errors	445
4.13.4	Exercise	450
4.14	3D Pick-and-Place	451
4.14.1	Performing the Hand-Eye Calibration	452
4.14.2	Defining the Grasping Point	455
4.14.3	Picking and Placing Objects	457
4.14.4	Exercises	458

References

461

Index

475