

AN INTRODUCTION TO 3D COMPUTER VISION TECHNIQUES AND ALGORITHMS

Bogusław Cyganek

Department of Electronics, AGH University of Science and Technology, Poland

J. Paul Siebert

Department of Computing Science, University of Glasgow, Scotland, UK

 **WILEY**

A John Wiley and Sons, Ltd., Publication

Contents

Preface	xv
Acknowledgements	xvii
Notation and Abbreviations	xix
Part I	1
1 Introduction	3
1.1 Stereo-pair Images and Depth Perception	4
1.2 3D Vision Systems	4
1.3 3D Vision Applications	5
1.4 Contents Overview: The 3D Vision Task in Stages	6
2 Brief History of Research on Vision	9
2.1 Abstract	9
2.2 Retrospective of Vision Research	9
2.3 Closure	14
2.3.1 <i>Further Reading</i>	14
Part II	15
3 2D and 3D Vision Formation	17
3.1 Abstract	17
3.2 Human Visual System	18
3.3 Geometry and Acquisition of a Single Image	23
3.3.1 <i>Projective Transformation</i>	24
3.3.2 <i>Simple Camera System: the Pin-hole Model</i>	24
3.3.2.1 <i>Extrinsic Parameters</i>	26
3.3.2.2 <i>Intrinsic Parameters</i>	27
3.3.3 <i>Projective Transformation of the Pin-hole Camera</i>	28
3.3.4 <i>Special Camera Setups</i>	29
3.3.5 <i>Parameters of Real Camera Systems</i>	30

3.4	Stereoscopic Acquisition Systems	31
3.4.1	<i>Epipolar Geometry</i>	31
3.4.1.1	<i>Fundamental Matrix</i>	34
3.4.1.2	<i>Epipolar Lines and Epipoles</i>	35
3.4.2	<i>Canonical Stereoscopic System</i>	36
3.4.3	<i>Disparity in the General Case</i>	38
3.4.4	<i>Bifocal, Trifocal and Multifocal Tensors</i>	39
3.4.5	<i>Finding the Essential and Fundamental Matrices</i>	41
3.4.5.1	<i>Point Normalization for the Linear Method</i>	44
3.4.5.2	<i>Computing F in Practice</i>	46
3.4.6	<i>Dealing with Outliers</i>	49
3.4.7	<i>Catadioptric Stereo Systems</i>	54
3.4.8	<i>Image Rectification</i>	55
3.4.9	<i>Depth Resolution in Stereo Setups</i>	59
3.4.10	<i>Stereo Images and Reference Data</i>	61
3.5	Stereo Matching Constraints	66
3.6	Calibration of Cameras	70
3.6.1	<i>Standard Calibration Methods</i>	71
3.6.2	<i>Photometric Calibration</i>	73
3.6.3	<i>Self-calibration</i>	73
3.6.4	<i>Calibration of the Stereo Setup</i>	74
3.7	Practical Examples	75
3.7.1	<i>Image Representation and Basic Structures</i>	75
3.7.1.1	<i>Computer Representation of Pixels</i>	76
3.7.1.2	<i>Representation of Images</i>	78
3.7.1.3	<i>Image Operations</i>	87
3.8	Appendix: Derivation of the Pin-hole Camera Transformation	91
3.9	Closure	93
3.9.1	<i>Further Reading</i>	93
3.9.2	<i>Problems and Exercises</i>	94
4	Low-level Image Processing for Image Matching	95
4.1	Abstract	95
4.2	Basic Concepts	95
4.2.1	<i>Convolution and Filtering</i>	95
4.2.2	<i>Filter Separability</i>	97
4.3	Discrete Averaging	99
4.3.1	<i>Gaussian Filter</i>	100
4.3.2	<i>Binomial Filter</i>	101
4.3.2.1	<i>Specification of the Binomial Filter</i>	101
4.3.2.2	<i>Spectral Properties of the Binomial Filter</i>	102
4.4	Discrete Differentiation	105
4.4.1	<i>Optimized Differentiating Filters</i>	105
4.4.2	<i>Savitzky–Golay Filters</i>	108
4.4.2.1	<i>Generation of Savitzky–Golay Filter Coefficients</i>	114

4.5	Edge Detection	115
4.5.1	<i>Edges from Signal Gradient</i>	117
4.5.2	<i>Edges from the Savitzky–Golay Filter</i>	119
4.5.3	<i>Laplacian of Gaussian</i>	120
4.5.4	<i>Difference of Gaussians</i>	126
4.5.5	<i>Morphological Edge Detector</i>	127
4.6	Structural Tensor	127
4.6.1	<i>Locally Oriented Neighbourhoods in Images</i>	128
4.6.1.1	<i>Local Neighbourhood with Orientation</i>	130
4.6.1.2	<i>Definition of a Local Neighbourhood of Pixels</i>	130
4.6.2	<i>Tensor Representation of Local Neighbourhoods</i>	133
4.6.2.1	<i>2D Structural Tensor</i>	136
4.6.2.2	<i>Computation of the Structural Tensor</i>	140
4.6.3	<i>Multichannel Image Processing with Structural Tensor</i>	143
4.7	Corner Detection	144
4.7.1	<i>The Most Common Corner Detectors</i>	144
4.7.2	<i>Corner Detection with the Structural Tensor</i>	149
4.8	Practical Examples	151
4.8.1	<i>C++ Implementations</i>	151
4.8.1.1	<i>Convolution</i>	151
4.8.1.2	<i>Implementing the Structural Tensor</i>	155
4.8.2	<i>Implementation of the Morphological Operators</i>	157
4.8.3	<i>Examples in Matlab: Computation of the SVD</i>	161
4.9	Closure	162
4.9.1	<i>Further Reading</i>	163
4.9.2	<i>Problems and Exercises</i>	163
5	Scale-space Vision	165
5.1	Abstract	165
5.2	Basic Concepts	165
5.2.1	<i>Context</i>	165
5.2.2	<i>Image Scale</i>	166
5.2.3	<i>Image Matching Over Scale</i>	166
5.3	Constructing a Scale-space	168
5.3.1	<i>Gaussian Scale-space</i>	168
5.3.2	<i>Differential Scale-space</i>	170
5.4	Multi-resolution Pyramids	172
5.4.1	<i>Introducing Multi-resolution Pyramids</i>	172
5.4.2	<i>How to Build Pyramids</i>	175
5.4.3	<i>Constructing Regular Gaussian Pyramids</i>	175
5.4.4	<i>Laplacian of Gaussian Pyramids</i>	177
5.4.5	<i>Expanding Pyramid Levels</i>	178
5.4.6	<i>Semi-pyramids</i>	179
5.5	Practical Examples	181
5.5.1	<i>C++ Examples</i>	181
5.5.1.1	<i>Building the Laplacian and Gaussian Pyramids in C++</i>	181

5.5.2	<i>Matlab Examples</i>	186
5.5.2.1	<i>Building the Gaussian Pyramid in Matlab</i>	190
5.5.2.2	<i>Building the Laplacian of Gaussians Pyramid in Matlab</i>	190
5.6	Closure	191
5.6.1	<i>Chapter Summary</i>	191
5.6.2	<i>Further Reading</i>	191
5.6.3	<i>Problems and Exercises</i>	192
6	Image Matching Algorithms	193
6.1	Abstract	193
6.2	Basic Concepts	193
6.3	Match Measures	194
6.3.1	<i>Distances of Image Regions</i>	194
6.3.2	<i>Matching Distances for Bit Strings</i>	198
6.3.3	<i>Matching Distances for Multichannel Images</i>	199
6.3.3.1	<i>Statistical Distances</i>	201
6.3.4	<i>Measures Based on Theory of Information</i>	202
6.3.5	<i>Histogram Matching</i>	205
6.3.6	<i>Efficient Computations of Distances</i>	206
6.3.7	<i>Nonparametric Image Transformations</i>	209
6.3.7.1	<i>Reduced Census Coding</i>	212
6.3.7.2	<i>Sparse Census Relations</i>	214
6.3.7.3	<i>Fuzzy Relationships Among Pixels</i>	215
6.3.7.4	<i>Implementation of Nonparametric Image Transformations</i>	216
6.3.8	<i>Log-polar Transformation for Image Matching</i>	218
6.4	Computational Aspects of Matching	222
6.4.1	<i>Occlusions</i>	222
6.4.2	<i>Disparity Estimation with Subpixel Accuracy</i>	224
6.4.3	<i>Evaluation Methods for Stereo Algorithms</i>	226
6.5	Diversity of Stereo Matching Methods	229
6.5.1	<i>Structure of Stereo Matching Algorithms</i>	233
6.5.1.1	<i>Aggregation of the Cost Values</i>	234
6.5.1.2	<i>Computation of the Disparity Map</i>	235
6.5.1.3	<i>Disparity Map Postprocessing</i>	237
6.6	Area-based Matching	238
6.6.1	<i>Basic Search Approach</i>	239
6.6.2	<i>Interpreting Match Cost</i>	241
6.6.3	<i>Point-oriented Implementation</i>	245
6.6.4	<i>Disparity-oriented Implementation</i>	250
6.6.5	<i>Complexity of Area-based Matching</i>	256
6.6.6	<i>Disparity Map Cross-checking</i>	257
6.6.7	<i>Area-based Matching in Practice</i>	259
6.6.7.1	<i>Intensity Matching</i>	260
6.6.7.2	<i>Area-based Matching in Nonparametric Image Space</i>	260
6.6.7.3	<i>Area-based Matching with the Structural Tensor</i>	262

6.7	Area-based Elastic Matching	273
6.7.1	Elastic Matching at a Single Scale	273
6.7.1.1	Disparity Match Range	274
6.7.1.2	Search and Subpixel Disparity Estimation	275
6.7.2	Elastic Matching Concept	278
6.7.3	Scale-based Search	280
6.7.4	Coarse-to-fine Matching Over Scale	283
6.7.5	Scale Subdivision	284
6.7.6	Confidence Over Scale	285
6.7.7	Final Multi-resolution Matcher	286
6.8	Feature-based Image Matching	288
6.8.1	Zero-crossing Matching	289
6.8.2	Corner-based Matching	292
6.8.3	Edge-based Matching: The Shirai Method	295
6.9	Gradient-based Matching	296
6.10	Method of Dynamic Programming	298
6.10.1	Dynamic Programming Formulation of the Stereo Problem	301
6.11	Graph Cut Approach	306
6.11.1	Graph Cut Algorithm	306
6.11.1.1	Graphs in Computer Vision	309
6.11.1.2	Optimization on Graphs	310
6.11.2	Stereo as a Voxel Labelling Problem	311
6.11.3	Stereo as a Pixel Labelling Problem	312
6.12	Optical Flow	314
6.13	Practical Examples	318
6.13.1	Stereo Matching Hierarchy in C++	318
6.13.2	Log-polar Transformation	319
6.14	Closure	321
6.14.1	Further Reading	321
6.14.2	Problems and Exercises	322
7	Space Reconstruction and Multiview Integration	323
7.1	Abstract	323
7.2	General 3D Reconstruction	323
7.2.1	Triangulation	324
7.2.2	Reconstruction up to a Scale	325
7.2.3	Reconstruction up to a Projective Transformation	327
7.3	Multiview Integration	329
7.3.1	Implicit Surfaces and Marching Cubes	330
7.3.1.1	Range Map Pre-segmentation	331
7.3.1.2	Volumetric Integration Algorithm Overview	332
7.3.1.3	Hole Filling	332
7.3.1.4	Marching Cubes	333
7.3.1.5	Implementation Considerations	338
7.3.2	Direct Mesh Integration	338

7.4 Closure	342
7.4.1 <i>Further Reading</i>	342
8 Case Examples	343
8.1 Abstract	343
8.2 3D System for Vision-Impaired Persons	343
8.3 Face and Body Modelling	345
8.3.1 <i>Development of Face and Body Capture Systems</i>	345
8.3.2 <i>Imaging Resolution, 3D Resolution and Implications for Applications</i>	346
8.3.3 <i>3D Capture and Analysis Pipeline for Constructing Virtual Humans</i>	350
8.4 Clinical and Veterinary Applications	352
8.4.1 <i>Development of 3D Clinical Photography</i>	352
8.4.2 <i>Clinical Requirements for 3D Imaging</i>	353
8.4.3 <i>Clinical Assessment Based on 3D Surface Anatomy</i>	353
8.4.4 <i>Extraction of Basic 3D Anatomic Measurements</i>	354
8.4.5 <i>Vector Field Surface Analysis by Means of Dense Correspondences</i>	357
8.4.6 <i>Eigenspace Methods</i>	359
8.4.7 <i>Clinical and Veterinary Examples</i>	362
8.4.8 <i>Multimodal 3D Imaging</i>	367
8.5 Movie Restoration	370
8.6 Closure	374
8.6.1 <i>Further Reading</i>	374
Part III	375
9 Basics of the Projective Geometry	377
9.1 Abstract	377
9.2 Homogeneous Coordinates	377
9.3 Point, Line and the Rule of Duality	379
9.4 Point and Line at Infinity	380
9.5 Basics on Conics	382
9.5.1 <i>Conics in \wp^2</i>	382
9.5.1.1 <i>The Dual Conic</i>	383
9.5.1.2 <i>Circular Points</i>	383
9.5.2 <i>Conics in \wp^2</i>	384
9.5.2.1 <i>The Absolute Conic</i>	384
9.5.2.2 <i>The Dual Absolute Conic</i>	385
9.6 Group of Projective Transformations	385
9.6.1 <i>Projective Base</i>	385
9.6.2 <i>Hyperplanes</i>	386
9.6.3 <i>Projective Homographies</i>	386
9.7 Projective Invariants	387
9.8 Closure	388
9.8.1 <i>Further Reading</i>	389

10	Basics of Tensor Calculus for Image Processing	391
10.1	Abstract	391
10.2	Basic Concepts	391
	10.2.1 <i>Linear Operators</i>	392
	10.2.2 <i>Change of Coordinate Systems: Jacobians</i>	393
10.3	Change of a Base	394
10.4	Laws of Tensor Transformations	396
10.5	The Metric Tensor	397
	10.5.1 <i>Covariant and Contravariant Components in a Curvilinear Coordinate System</i>	397
	10.5.2 <i>The First Fundamental Form</i>	399
10.6	Simple Tensor Algebra	399
	10.6.1 <i>Tensor Summation</i>	399
	10.6.2 <i>Tensor Product</i>	400
	10.6.3 <i>Contraction and Tensor Inner Product</i>	400
	10.6.4 <i>Reduction to Principal Axes</i>	400
	10.6.5 <i>Tensor Invariants</i>	401
10.7	Closure	401
	10.7.1 <i>Further Reading</i>	401
11	Distortions and Noise in Images	403
11.1	Abstract	403
11.2	Types and Models of Noise	403
11.3	Generating Noisy Test Images	405
11.4	Generating Random Numbers with Normal Distributions	407
11.5	Closure	408
	11.5.1 <i>Further Reading</i>	408
12	Image Warping Procedures	409
12.1	Abstract	409
12.2	Architecture of the Warping System	409
12.3	Coordinate Transformation Module	410
	12.3.1 <i>Projective and Affine Transformations of a Plane</i>	410
	12.3.2 <i>Polynomial Transformations</i>	411
	12.3.3 <i>Generic Coordinates Mapping</i>	412
12.4	Interpolation of Pixel Values	412
	12.4.1 <i>Bilinear Interpolation</i>	412
	12.4.2 <i>Interpolation of Nonscalar-Valued Pixels</i>	414
12.5	The Warp Engine	414
12.6	Software Model of the Warping Schemes	415
	12.6.1 <i>Coordinate Transformation Hierarchy</i>	415
	12.6.2 <i>Interpolation Hierarchy</i>	416
	12.6.3 <i>Image Warp Hierarchy</i>	416
12.7	Warp Examples	419
12.8	Finding the Linear Transformation from Point Correspondences	420
	12.8.1 <i>Linear Algebra on Images</i>	424

12.9 Closure	427
12.9.1 <i>Further Reading</i>	428
13 Programming Techniques for Image Processing and Computer Vision	429
13.1 Abstract	429
13.2 Useful Techniques and Methodology	430
13.2.1 <i>Design and Implementation</i>	430
13.2.1.1 <i>Comments and Descriptions of 'Ideas'</i>	430
13.2.1.2 <i>Naming Conventions</i>	431
13.2.1.3 <i>Unified Modelling Language (UML)</i>	431
13.2.2 <i>Template Classes</i>	436
13.2.2.1 <i>Expression Templates</i>	437
13.2.3 <i>Asserting Code Correctness</i>	438
13.2.3.1 <i>Programming by Contract</i>	438
13.2.4 <i>Debugging Issues</i>	440
13.3 Design Patterns	441
13.3.1 <i>Template Function Objects</i>	441
13.3.2 <i>Handle-body or Bridge</i>	442
13.3.3 <i>Composite</i>	445
13.3.4 <i>Strategy</i>	447
13.3.5 <i>Class Policies and Traits</i>	448
13.3.6 <i>Singleton</i>	450
13.3.7 <i>Proxy</i>	450
13.3.8 <i>Factory Method</i>	451
13.3.9 <i>Prototype</i>	452
13.4 Object Lifetime and Memory Management	453
13.5 Image Processing Platforms	455
13.5.1 <i>Image Processing Libraries</i>	455
13.5.2 <i>Writing Software for Different Platforms</i>	455
13.6 Closure	456
13.6.1 <i>Further Reading</i>	456
14 Image Processing Library	457
References	459
Index	475