

Contents

List of Contributors XV

Foreword XIX

Part I Fundamentals I

1	Introduction	3
	<i>Gabriel Cristóbal, Laurent U. Perrinet, and Matthias S. Keil</i>	
1.1	Why Should We Be Inspired by Biology?	4
1.2	Organization of Chapters in the Book	6
1.3	Conclusion	9
	Acknowledgments	9
	References	9
2	Bioinspired Vision Sensing	11
	<i>Christoph Posch</i>	
2.1	Introduction	11
2.1.1	Neuromorphic Engineering	12
2.1.2	Implementing Neuromorphic Systems	13
2.2	Fundamentals and Motivation: Bioinspired Artificial Vision	13
2.2.1	Limitations in Vision Engineering	14
2.2.2	The Human Retina from an Engineering Viewpoint	14
2.2.3	Modeling the Retina in Silicon	17
2.3	From Biological Models to Practical Vision Devices	18
2.3.1	The Wiring Problem	18
2.3.2	Where and What	20
2.3.3	Temporal Contrast: The DVS	21
2.3.4	Event-Driven Time-Domain Imaging: The ATIS	22
2.4	Conclusions and Outlook	25
	References	26

3	Retinal Processing: From Biology to Models and Applications	29
	<i>David Alleysson and Nathalie Guyader</i>	
3.1	Introduction	29
3.2	Anatomy and Physiology of the Retina	30
3.2.1	Overview of the Retina	30
3.2.2	Photoreceptors	31
3.2.3	Outer and Inner Plexiform Layers (OPL and IPL)	33
3.2.4	Summary	34
3.3	Models of Vision	34
3.3.1	Overview of the Retina Models	34
3.3.2	Biological Models	35
3.3.2.1	Cellular and Molecular Models	35
3.3.2.2	Network Models	36
3.3.2.3	Parallel and Descriptive Models	38
3.3.3	Information Models	39
3.3.4	Geometry Models	40
3.4	Application to Digital Photography	42
3.4.1	Color Demosaicing	43
3.4.2	Color Constancy – Chromatic Adaptation – White Balance – Tone Mapping	44
3.5	Conclusion	45
	References	46
4	Modeling Natural Image Statistics	53
	<i>Holly E. Gerhard, Lucas Theis, and Matthias Bethge</i>	
4.1	Introduction	53
4.2	Why Model Natural Images?	53
4.3	Natural Image Models	55
4.3.1	Model Evaluation	65
4.4	Computer Vision Applications	69
4.5	Biological Adaptations to Natural Images	71
4.6	Conclusions	75
	References	76
5	Perceptual Psychophysics	81
	<i>C. Alejandro Parraga</i>	
5.1	Introduction	81
5.1.1	What Is Psychophysics and Why Do We Need It?	81
5.2	Laboratory Methods	82
5.2.1	Accuracy and Precision	83
5.2.2	Error Propagation	84
5.3	Psychophysical Threshold Measurement	85
5.3.1	Weber's Law	85
5.3.2	Sensitivity Functions	86
5.4	Classic Psychophysics: Theory and Methods	86

5.4.1	Theory	87
5.4.2	Method of Constant Stimuli	88
5.4.3	Method of Limits	90
5.4.3.1	Forced-Choice Methods	92
5.4.4	Method of Adjustments	93
5.4.5	Estimating Psychometric Function Parameters	94
5.5	Signal Detection Theory	94
5.5.1	Signal and Noise	94
5.5.2	The Receiver Operating Characteristic	96
5.6	Psychophysical Scaling Methods	98
5.6.1	Discrimination Scales	99
5.6.2	Rating Scales	100
5.6.2.1	Equipartition Scales	100
5.6.2.2	Paired Comparison Scales	101
5.7	Conclusions	105
	References	106

Part II Sensing 109

6	Bioinspired Optical Imaging	111
	<i>Mukul Sarkar</i>	
6.1	Visual Perception	111
6.1.1	Natural Single-Aperture and Multiple-Aperture Eyes	112
6.1.1.1	Human Eyes	113
6.1.1.2	Compound Eyes	114
6.1.1.3	Resolution	114
6.1.1.4	Visual Acuity	115
6.1.1.5	Depth Perception	115
6.1.1.6	Color Vision	116
6.1.1.7	Speed of Imaging and Motion Detection	117
6.1.1.8	Polarization Vision	117
6.2	Polarization Vision - Object Differentiation/Recognition	119
6.2.1	Polarization of Light	121
6.2.2	Polarization Imaging	125
6.2.2.1	Detection of Transparent and Opaque Objects	126
6.2.2.2	Shape Detection Using Polarized Light	131
6.3	High-Speed Motion Detection	133
6.3.1	Temporal Differentiation	135
6.4	Conclusion	138
	References	139
7	Biomimetic Vision Systems	143
	<i>Reinhard Voelkel</i>	
7.1	Introduction	143
7.2	Scaling Laws in Optics	144

7.2.1	Optical Properties of Imaging Lens Systems	144
7.2.2	Space Bandwidth Product (SW)	146
7.3	The Evolution of Vision Systems	147
7.3.1	Single-Aperture Eyes	148
7.3.2	Compound Eyes	149
7.3.3	The Array Optics Concept	150
7.3.4	Jumping Spiders: Perfect Eyes for Small Animals	151
7.3.5	Nocturnal Spiders: Night Vision	153
7.4	Manufacturing of Optics for Miniaturized Vision Systems	154
7.4.1	Optics Industry	154
7.4.2	Planar Array Optics for Stereoscopic Vision	155
7.4.3	The Lack of a Suitable Fabrication Technology Hinders Innovation	155
7.4.4	Semiconductor Industry Promotes Wafer-Based Manufacturing	156
7.4.5	Image Sensors	156
7.4.6	Wafer-Based Manufacturing of Optics	158
7.4.7	Manufacturing of Microlens Arrays on Wafer Level	159
7.4.8	Diffraction Optical Elements and Subwavelength Structures for Antireflection Coatings	160
7.4.9	Microlens Imprint and Replication Processes	162
7.4.10	Wafer-Level Stacking or Packaging (WLP)	162
7.4.11	Wafer-Level Camera (WLC)	163
7.5	Examples for Biomimetic Compound Vision Systems	164
7.5.1	Ultraflat Cameras	165
7.5.2	Biologically Inspired Vision Systems for Smartphone Cameras	166
7.5.3	PiCam Cluster Camera	167
7.5.4	Panoramic Motion Camera for Flying Robots	169
7.5.5	Conclusion	170
	References	172
8	Plenoptic Cameras	175
	<i>Fernando Pérez Nava, Alejandro Pérez Nava, Manuel Rodríguez Valido, and Eduardo Magdaleno Castellò</i>	
8.1	Introduction	175
8.2	Light Field Representation of the Plenoptic Function	177
8.2.1	The Plenoptic Function	177
8.2.2	Light Field Parameterizations	178
8.2.3	Light Field Reparameterization	179
8.2.4	Image Formation	180
8.2.5	Light Field Sampling	180
8.2.5.1	Pinhole and Thin Lens Camera	180
8.2.5.2	Multiple Devices	181
8.2.5.3	Temporal Multiplexing	181
8.2.5.4	Frequency Multiplexing	182

8.2.5.5	Spatial Multiplexing	182
8.2.5.6	Simulation	182
8.2.6	Light Field Sampling Analysis	183
8.2.7	Light Field Visualization	183
8.3	The Plenoptic Camera	185
8.4	Applications of the Plenoptic Camera	188
8.4.1	Refocusing	188
8.4.2	Perspective Shift	190
8.4.3	Depth Estimation	190
8.4.4	Extended Depth of Field Images	192
8.4.5	Superresolution	192
8.5	Generalizations of the Plenoptic Camera	193
8.6	High-Performance Computing with Plenoptic Cameras	195
8.7	Conclusions	196
	References	197

Part III Modelling 201

9	Probabilistic Inference and Bayesian Priors in Visual Perception	203
	<i>Grigorios Sotiropoulos and Peggy Seriès</i>	
9.1	Introduction	203
9.2	Perception as Bayesian Inference	204
9.2.1	Deciding on a Single Percept	205
9.3	Perceptual Priors	207
9.3.1	Types of Prior Expectations	207
9.3.2	Impact of Expectations	208
9.3.3	The Slow Speed Prior	210
9.3.4	Expectations and Environmental Statistics	212
9.4	Outstanding Questions	214
9.4.1	Are Long-Term Priors Plastic?	214
9.4.2	How Specific are Priors?	215
9.4.3	Inference in Biological and Computer Vision	215
9.4.4	Conclusions	217
	References	219
10	From Neuronal Models to Neuronal Dynamics and Image Processing	221
	<i>Matthias S. Keil</i>	
10.1	Introduction	221
10.2	The Membrane Equation as a Neuron Model	222
10.2.1	Synaptic Inputs	224
10.2.2	Firing Spikes	227
10.3	Application 1: A Dynamical Retinal Model	230
10.4	Application 2: Texture Segregation	234
10.5	Application 3: Detection of Collision Threats	236

10.6	Conclusions	239
	Acknowledgments	240
	References	240
11	Computational Models of Visual Attention and Applications	245
	<i>Olivier Le Meur and Matei Mancas</i>	
11.1	Introduction	245
11.2	Models of Visual Attention	246
11.2.1	Taxonomy	246
11.3	A Closer Look at Cognitive Models	250
11.3.1	Itti <i>et al.</i> 's Model [3]	250
11.3.2	Le Meur <i>et al.</i> 's Model [8]	251
11.3.2.1	Motivations	251
11.3.2.2	Global Architecture	252
11.3.3	Limitations	255
11.4	Applications	256
11.4.1	Saliency-Based Applications: A Brief Review	256
11.4.2	Predicting Memorability of Pictures	257
11.4.2.1	Memorability Definition	257
11.4.2.2	Memorability and Eye Movement	257
11.4.2.3	Computational Models	259
11.4.3	Quality Metric	260
11.4.3.1	Introduction	260
11.4.3.2	Eye Movement During a Quality Task	260
11.4.3.3	Saliency-Based Quality Metrics	261
11.5	Conclusion	262
	References	262
12	Visual Motion Processing and Human Tracking Behavior	267
	<i>Anna Montagnini, Laurent U. Perrinet, and Guillaume S. Masson</i>	
12.1	Introduction	267
12.2	Pursuit Initiation: Facing Uncertainties	269
12.2.1	Where Is the Noise? Motion-Tracking Precision and Accuracy	269
12.2.2	Where Is the Target Really Going?	270
12.2.3	Human Smooth Pursuit as Dynamic Readout of the Neural Solution to the Aperture Problem	272
12.3	Predicting Future and On-Going Target Motion	273
12.3.1	Anticipatory Smooth Tracking	273
12.3.2	If You Don't See It, You Can Still Predict (and Track) It	274
12.4	Dynamic Integration of Retinal and Extra-Retinal Motion Information: Computational Models	276
12.4.1	A Bayesian Approach for Open-Loop Motion Tracking	276
12.4.2	Bayesian (or Kalman-Filtering) Approach for Smooth Pursuit: Hierarchical Models	278

12.4.3	A Bayesian Approach for Smooth Pursuit: Dealing with Delays	279
12.5	Reacting, Inferring, Predicting: A Neural Workspace	282
12.6	Conclusion	286
12.6.1	Interest for Computer Vision	287
	Acknowledgments	288
	References	288
13	Cortical Networks of Visual Recognition	295
	<i>Christian Thériault, Nicolas Thome, and Matthieu Cord</i>	
13.1	Introduction	295
13.2	Global Organization of the Visual Cortex	296
13.3	Local Operations: Receptive Fields	297
13.4	Local Operations in V1	298
13.5	Multilayer Models	301
13.6	A Basic Introductory Model	302
13.7	Idealized Mathematical Model of V1: Fiber Bundle	307
13.8	Horizontal Connections and the Association Field	311
13.9	Feedback and Attentional Mechanisms	312
13.10	Temporal Considerations, Transformations and Invariance	312
13.11	Conclusion	314
	References	315
14	Sparse Models for Computer Vision	319
	<i>Laurent U. Perrinet</i>	
14.1	Motivation	319
14.1.1	Efficiency and Sparseness in Biological Representations of Natural Images	319
14.1.2	Sparseness Induces Neural Organization	320
14.1.3	Outline: Sparse Models for Computer Vision	322
14.2	What Is Sparseness? Application to Image Patches	323
14.2.1	Definitions of Sparseness	323
14.2.2	Learning to Be Sparse: The SparseNet Algorithm	325
14.2.3	Results: Efficiency of Different Learning Strategies	326
14.3	SparseLets: A Multiscale, Sparse, Biologically Inspired Representation of Natural Images	328
14.3.1	Motivation: Architecture of the Primary Visual Cortex	328
14.3.2	The SparseLets Framework	330
14.3.3	Efficiency of the SparseLets Framework	333
14.4	SparseEdges: Introducing Prior Information	336
14.4.1	Using the Prior in First-Order Statistics of Edges	336
14.4.2	Using the Prior Statistics of Edge Co-Occurrences	338
14.5	Conclusion	341
	Acknowledgments	341
	References	342

15	Biologically Inspired Keypoints	347
	<i>Alexandre Alahi, Georges Goetz, and Emmanuel D'Angelo</i>	
15.1	Introduction	347
15.2	Definitions	349
15.3	What Does the Frond-End of the Visual System Tell Us?	350
15.3.1	The Retina	350
15.3.2	From Photoreceptors to Pixels	350
15.3.3	Visual Compression	351
15.3.4	Retinal Sampling Pattern	351
15.3.5	Scale-Space Representation	352
15.3.6	Difference of Gaussians as a Model for RGC-Receptive Fields	353
15.3.7	A Linear Nonlinear Model	354
15.3.8	Gabor-Like Filters	354
15.4	Bioplausible Keypoint Extraction	355
15.4.1	Scale-Invariant Feature Transform	355
15.4.2	Speeded-Up Robust Features	356
15.4.3	Center Surround Extrema	356
15.4.4	Features from Accelerated Segment Test	357
15.5	Biologically Inspired Keypoint Representation	357
15.5.1	Motivations	357
15.5.2	Dense Gabor-Like Descriptors	358
15.5.2.1	Scale-Invariant Feature Transform Descriptor	358
15.5.2.2	Speeded-Up Robust Features Descriptor	359
15.5.3	Sparse Gaussian Kernels	360
15.5.3.1	Local Binary Descriptors	360
15.5.3.2	Fast Retina Keypoint Descriptor	360
15.5.3.3	Fast Retina Keypoint Saccadic Matching	362
15.5.4	Fast Retina Keypoint versus Other Local Binary Descriptors	363
15.6	Qualitative Analysis: Visualizing Keypoint Information	363
15.6.1	Motivations	363
15.6.2	Binary Feature Reconstruction: From Bits to Image Patches	364
15.6.2.1	Feature Inversion as an Inverse Problem	364
15.6.2.2	Interest of the Retinal Descriptor	367
15.6.3	From Feature Visualization to Crowd-Sourced Object Recognition	368
15.7	Conclusions	370
	References	371

Part IV Applications 375

16	Nightvision Based on a Biological Model	377
	<i>Magnus Oskarsson, Henrik Malm, and Eric Warrant</i>	
16.1	Introduction	377
16.1.1	Related Work	378

16.2	Why Is Vision Difficult in Dim Light?	380
16.3	Why Is Digital Imaging Difficult in Dim Light?	382
16.4	Solving the Problem of Imaging in Dim Light	383
16.4.1	Enhancing the Image	385
16.4.1.1	Visual Image Enhancement in the Retina	385
16.4.1.2	Digital Image Enhancement	387
16.4.2	Filtering the Image	388
16.4.2.1	Spatial and Temporal Summation in Higher Visual Processing	388
16.4.2.2	Structure Tensor Filtering of Digital Images	391
16.5	Implementation and Evaluation of the Night-Vision Algorithm	393
16.5.1	Adaptation of Parameters to Noise Levels	394
16.5.2	Parallelization and Computational Aspects	395
16.5.3	Considerations for Color	396
16.5.4	Experimental Results	397
16.6	Conclusions	399
	Acknowledgment	400
	References	401
17	Bioinspired Motion Detection Based on an FPGA Platform	405
	<i>Tim Köhler</i>	
17.1	Introduction	405
17.2	A Motion Detection Module for Robotics and Biology	406
17.3	Insect Motion Detection Models	407
17.4	Overview of Robotic Implementations of Bioinspired Motion Detection	412
17.4.1	Field-Programmable Gate Arrays (FPGA)	413
17.5	An FPGA-Based Implementation	414
17.5.1	FPGA-Camera-Module	414
17.5.2	A Configurable Array of EMDs	416
17.6	Experimental Results	419
17.7	Discussion	421
17.8	Conclusion	422
	Acknowledgments	423
	References	423
18	Visual Navigation in a Cluttered World	425
	<i>N. Andrew Browning and Florian Raudies</i>	
18.1	Introduction	425
18.2	Cues from Optic Flow: Visually Guided Navigation	426
18.3	Estimation of Self-Motion: Knowing Where You Are Going	429
18.4	Object Detection: Understanding What Is in Your Way	434
18.5	Estimation of TTC: Time Constraints from the Expansion Rate	439
18.6	Steering Control: The Importance of Representation	442

18.7	Conclusions	444
	Acknowledgments	445
	References	445

	Index	447
--	-------	-----