

Contents

Preface	XXI
1 Introduction	1
1.1 Organization of the Book	1
2 Fundamentals of Light	7
2.1 Introduction	7
2.2 Electromagnetic Radiation	9
2.3 Principles of Light Generation	10
2.3.1 Thermal Radiation	13
Radiation, Absorption and Efficiency	14
2.3.2 Applications of Thermal Radiation Laws	20
2.3.3 Open Systems and the Greenhouse Effect	22
2.3.4 Color Temperature	24
2.3.5 Bremsstrahlung	26
2.3.6 Photon Energies	28
2.3.7 Electron Excitation	29

Contents

2.3.8	Gas Discharge	31
	Plasma Lamps	32
	Arc Lamps	32
	Phosphors	33
	Fluorescent lamps	35
	Other Forms of Luminescence	35
2.3.9	Electro Luminescence	36
	LED	36
	OLED	37
2.4	Measuring Light	38
2.4.1	Radiometry	38
	Angular Range	39
	Lambert Emitters	39
	Solid Angle and Angular Density	39
	The Ulbricht Sphere	41
2.4.2	Photometry	44
2.4.3	Luminous Efficiency of Light Sources	46
2.4.4	Durability of Light Sources	48
2.5	Physics of Light	49
2.5.1	Interference	49
2.5.2	Quantum Effects	50
2.5.3	The Double Slit Experiment	55
	The Uncertainty Relation	62

Contents

2.5.4	Fourier Spectrum	65
2.5.5	Radiation Processes Revisited	67
2.5.6	Tunneling	68
2.5.7	Quantum Dots	70
2.5.8	Polarization	71
	Polarizer Filters	73
	Polarization and Quantum Physics	73
	Turning Polarization	76
2.5.9	Circular Polarization	77
	Producing Circular Polarized Light	78
2.6	Summary	80
3	Principles of Optics	81
3.1	Introduction	81
3.2	Wave Optics	83
3.3	Lasers	89
	3.3.1 Stimulated Emission	89
	3.3.2 Laser Beam Divergence	95
3.4	Geometric Optics	99
	3.4.1 Light Modulation	100
	Scattering	100
	Refraction	102
	3.4.2 Homogeneous vs. Inhomogeneous Media	106
	3.4.3 Snell's Law Vectorized	108

Contents

3.5	Formation of Point Images	111
3.5.1	Reflective Optics	113
	Planar Mirrors	113
	Spherical Mirrors	114
	Concave Parabolic Mirrors	116
	Convex Parabolic Mirrors	117
	Varifocal Mirrors	117
3.5.2	Refractive Optics	118
	Lenses	119
	Converging Lenses	121
	Diverging Lenses	123
	Plane Parallel and Curved Parallel Lenses	123
	Apertures	124
	Vignetting	127
	Varifocal Lenses	127
	Fresnel Lenses	129
	Lens Resolution	130
	Depth of Field	132
3.5.3	The Plenoptic Function	133
3.6	Summary	137
4	Basics of Visual Perception	139
4.1	Introduction	139
4.2	The Human Visual System	141

Contents

4.2.1	The Eye as an Optical System	141
4.2.2	Saccades	142
4.2.3	Temporal Response	143
4.2.4	Contrast and Dynamic Range	144
4.2.5	Resolution	148
4.3	Colorimetry	150
4.3.1	CIE Color Matching Functions	154
4.3.2	The CIE Chromaticity Diagram	156
4.3.3	Color Separation of the Eye	158
4.3.4	Color Recording	160
4.3.5	Neuro-Physiological Results	163
	Retinal Image Processing	165
4.4	Depth Perception	167
4.4.1	The Human Visual Field	169
4.4.2	Depth Cues	170
	Convergence	172
	Retinal Disparity	172
	Accommodation	174
	Focus Effects	177
	Haze	178
	Color	178
	Motion Parallax and Motion Dynamics	179
4.4.3	Stereo Picture Recording	183

Contents

4.5	Motion Pictures	184
4.5.1	Pitfalls	185
4.5.2	Film Projection	186
4.6	Summary	187
5	Holographic Principles	189
5.1	Introduction	189
5.2	Holography: An Executive Summary	192
5.2.1	Holographic Object Recognition	194
5.2.2	A Basic Hologram Setup	195
5.3	Interference and Diffraction	198
5.3.1	The Grating Equation	201
5.3.2	Holographic Point Formation in Detail	203
5.3.3	Phase Holograms	206
5.3.4	Embossed Holograms	208
5.3.5	Color Dispersion	209
5.3.6	Volume Gratings	210
	Volume Grating Construction	210
	Volume Grating Reconstruction	212
	Resolution Requirements	216
	Bragg's Law	217
	Color Dependency	218
5.3.7	Hologram Efficiency	219
5.3.8	Holograms and Displays - Basic Considerations	220

Contents

5.3.9	Temporal Coherence	222
5.3.10	Spatial Coherence	225
5.3.11	Laser Speckle	227
5.4	Holographic Optical Elements (HOE)	228
5.4.1	Headup Displays	229
5.4.2	Construction of an HOE	231
	A Detailed Construction Setup	232
5.4.3	HOE Angular and Frequency Response	234
5.4.4	HOE's vs. Conventional Optics	236
5.4.5	Camera Lenses with HOE's	240
5.4.6	Virtual HOE's	240
5.4.7	Spatial Light Modulators	240
5.4.8	Beam Splitters and Diverters	241
	Switched HOE's	242
5.4.9	Holographic Projection Screens	242
5.4.10	Visual Perception of Holograms	249
5.4.11	'Keyhole' Holograms	252
5.5	Optical Holography	253
5.5.1	Optical Distortion	257
5.5.2	Transmission Holograms	260
5.5.3	Reflection Holograms	261
5.5.4	Rainbow Holograms	264
5.5.5	Color Holograms	268

Contents

5.5.6	Multi-Channel Holograms	273
5.5.7	Holographic Stereograms	275
5.5.8	Digital Volumetric Holograms	280
5.6	Summary	281
6	Display Basics	283
6.1	Introduction	283
6.2	Fundamental Measures	284
6.2.1	Resolution	285
6.2.2	Interlacing	291
6.2.3	TV Standards	294
	Eye Resolution and Displays	297
6.2.4	Brightness	301
6.2.5	Contrast and Dynamic Range	301
6.2.6	Gamma	303
6.2.7	Angular Range	305
	Viewing Cone	306
6.2.8	Speed	309
6.3	Color and Intensity Production	310
6.3.1	Color Gamut	311
6.3.2	Wide Color Gamut Displays	312
6.3.3	Multi Color Displays	313
6.3.4	Additive and Subtractive Color Mixing	315
	Subtractive Color Mixing	316

Contents

6.3.5	YUV-Formats	317
6.3.6	Dyes and Filters	320
6.3.7	Light Sources	322
6.3.8	Luminescent vs. Light Valve Displays	323
6.3.9	Test Pictures	324
6.4	Electronics	326
6.4.1	Signal Transmission	326
6.4.2	Signal Processing	328
6.4.3	Anti-Aliasing	330
6.4.4	Moiré	331
6.4.5	Image Processing	332
	Resizing	333
	Noise Reduction	333
6.4.6	Image Compression	334
6.4.7	De-Interlacing	337
6.4.8	Semiconductors	342
6.4.9	Passive Matrix Displays	347
6.4.10	Multiplexing and Connection	348
	Connection	350
6.4.11	Active Matrix Displays	352
6.5	Assembly	358
6.5.1	Panel Construction	358
6.5.2	Backlighting	359

Contents

6.5.3	Anti-Reflective Coatings	361
	Sol-Gel Coating	363
6.5.4	Touch Screens	364
	Force Sensors	365
	Surface Wave Detection	366
	Light Grid and Optical Imaging	367
	Bi-Directional Display Touch Detection	368
	Resistive Panels	368
	Percolation	370
	Quantum Tunneling Composite (QTC)	371
	Surface Capacitance	371
	Projected Capacitance (PCT)	371
	Inductive Touch Panels	373
6.5.5	Flexible Electronics	373
6.5.6	Transparent Circuits	375
	Inorganic Transparent Conductors and Semiconductors	376
	Carbon Nanotubes	377
6.5.7	Printed Displays	381
6.6	Summary	383
7	Spatial Light Modulation	384
7.1	Introduction	384
7.2	Transmissive Displays	386
7.2.1	LCD	386

Contents

	Driving LC Displays	390
	Driver Structures	390
	LCD and Motion	391
7.2.2	FLC	393
7.2.3	TMOS	393
7.2.4	Dyed Guest Host Displays	394
7.2.5	Other	395
7.3	Reflective Displays	396
7.3.1	LCOS	396
	F-LCOS	397
	Phase Shifting LCD	399
7.3.2	Bi-Stable LC displays	399
7.3.3	DMD	403
	Driving DMDs	406
7.3.4	Advanced Driving Techniques	408
7.3.5	PISTON Type Micro Mirror Displays	410
7.3.6	MLM	412
7.3.7	GLV	412
7.3.8	Polymer Displays	414
	Electrochromic Polymers	414
7.3.9	E-Ink	414
7.3.10	Electrowetting Displays	417
7.3.11	Electrofluidic Displays	417

Contents

7.3.12	iMOD Displays	418
7.3.13	Refractive Index Modulation	419
7.3.14	Electronic Paper	420
7.4	Transflective Displays	422
7.5	Emissive Displays	425
7.5.1	CRT	425
	Deflection	432
7.5.2	FED and SED	433
7.5.3	Plasma Displays	435
	ALIS	436
7.5.4	Electroluminescence Displays	438
7.5.5	LED	439
7.5.6	OLED	440
	Transparent OLED	443
	OLED on CMOS	443
7.5.7	Vacuum Fluorescence Displays	444
7.5.8	Cold Cathode Tubes	444
7.6	High Dynamic Range Displays	445
7.6.1	Rendering for HDR LCD Displays	449
7.7	Bi-Directional Displays	451
7.8	Projection Displays	452
7.8.1	Projector Optics Overview	454
7.8.2	Projection Lenses	460

Contents

Offset Projection	461
7.8.3 Projector Lamps	462
7.8.4 CRT and OLED Projectors	465
7.8.5 LCD Projectors	468
7.8.6 DLP and GLV Projectors	470
7.8.7 Eidophor Projector	471
7.8.8 Dichroic Combiners	472
7.8.9 Fourier Holographic Projector	473
7.8.10 Projection Screens	475
7.8.11 Rear Projection	477
7.8.12 Wedge Displays	479
7.8.13 Collimated Displays	481
7.8.14 'Quantum' Displays	482
7.8.15 Laser Projectors	485
Far-Field Laser Projectors	487
MEMS Scanners	488
7.8.16 Beam Deflection Modes	491
7.9 Summary	493
8 Projector-Camera Systems	495
8.1 Introduction	495
8.2 Challenges of Non-Optimized Surfaces	498
8.3 Geometric Registration	500
8.3.1 Uniformly Colored Surfaces of Known Geometry	500

Contents

8.3.2	Textured Surfaces and Surfaces of Unknown Geometry . .	505
8.3.3	Embedded Structured Light	507
8.4	Radiometric Compensation	512
8.4.1	Static Techniques	513
8.4.2	Dynamic Surfaces and Configurations	521
8.4.3	Dynamic Image Adaptation	525
8.4.4	Enhancing Contrast	530
8.5	Correcting Complex Light Modulations	531
8.5.1	Interreflections	532
8.5.2	Specular Reflections	536
8.5.3	Radiometric Compensation through Inverse Light Trans- port	537
8.6	Overcoming Technical Limitations	542
8.6.1	Increasing Depth of Field	543
8.6.2	Super-Resolution	549
8.6.3	High Dynamic Range	555
8.6.4	High Speed	561
8.7	Summary	567
9	Three-Dimensional Displays	569
9.1	Introduction	569
9.2	Three-Dimensional Displays: Basic Considerations	574
9.2.1	Orientation	574
9.2.2	Distance and Depth	575

Contents

9.2.3	Perspective	580
9.2.4	3D TV vs. 3D Cinema	582
9.2.5	Toward Light Field Displays	585
9.3	Spatial Stereoscopic Displays	587
9.3.1	Stereo-Channel Separation	588
9.3.2	Projection Screens	599
9.3.3	Screen Configurations and Rendering	601
9.3.4	Stereoscopic Multi-Viewer Techniques	605
9.4	Autostereoscopic Displays	609
9.4.1	Parallax Displays	610
	Barrier Displays	610
	Lenticular Displays	613
	Time-Multiplexed Displays	617
	Multi-Viewer Techniques	619
	Basic Categories	622
9.4.2	Volumetric Displays	623
	Swept Volume Displays	624
	Static Volume Displays	626
9.5	Light Field Displays	628
9.5.1	Parameterization	631
9.5.2	Light Fields vs. Holograms	633
9.5.3	Light Field Display Implementations	636
9.5.4	An Adaptive Approach to Light Field Displays	638

Contents

Electrowetting Prisms and other approaches	644
9.5.5 Light Field Focus Synthesis	645
9.5.6 Depth Of Field and Light field Recording	647
9.6 Computer-Generated Holograms	648
9.6.1 Displaying Computed Fringe Patterns	649
9.6.2 Computing a Hologram	649
9.6.3 Fourier Hologram Synthesis	653
9.6.4 Adaptive Holographic Displays	656
Discussion	665
9.7 3D Media Encoding	666
9.7.1 Light Field Encoding	667
9.7.2 Camera Array (Multi-View) Encoding	668
9.7.3 Holographic 'Millimeter Wave' Encoding	671
9.8 Summary	674
10 Near-Eye Displays	680
10.1 Introduction	680
10.2 Examples of Near-Eye Displays	682
10.2.1 View-Covering Head-Attached Displays for Virtual Real- ity and Personal Video Viewing	683
10.2.2 Semi-Covering Head-Attached Displays for Personal In- formation Presentation	684
10.2.3 Optical See-Through Displays	686
10.3 Eye Physiological Aspects	688

Contents

10.4 Economy and Ecology	692
10.4.1 Brightness of Virtual Displays	692
10.5 Micro Display Technologies	694
10.6 An Optical Design Study	697
10.6.1 Exit Pupil	702
10.6.2 Self-Adaptation	703
10.7 Laser Displays	707
10.7.1 A Classical Laser Scanner Design	708
10.7.2 A More Versatile Laser Display Design	709
10.7.3 Exit Pupil	712
10.8 Advanced Laser Scanning	713
10.8.1 Holographic Scanners	718
10.9 Holographic Near-Eye Displays	722
10.10 Beam Combiners	724
10.10.1 Dichroic Combiners	725
10.10.2 Holographic Combiners	728
10.10.3 Advanced HOE Designs	730
10.10.4 Contact Lens Displays	731
10.11 Geometry Adaptive Displays and Eye Tracking	737
10.11.1 Adaptation Requirements	738
10.11.2 Eye Tracking	740
Optical Constructions with Eye Trackers	743
Combining Eye Tracking with SLMs	744

Contents

10.11.3 Retina Tracking	746
10.11.4 Dynamic Image Linearization	753
10.11.5 Micro Motors	754
10.12 Image Integration	757
10.12.1 Optical Compensation	757
10.12.2 Eyetaps and Video-See-Trough	758
10.12.3 Mask Displays	760
Technologies for Mask Displays	768
10.13 Summary	770
11 Discussion and Outlook	772
Appendix: Image Processing for Displays	773
A The Fixed Function Graphics Pipeline	774
A.1 Transformations	776
A.2 Rasterization	778
A.3 Framebuffer Operations	779
B The Programmable Graphics Pipeline	780
C Graphics Hardware	782
D GPU Programming Languages	784
D.1 High Level Shading Languages	785
GLSL	785
Cg	786
Other Languages:	786

Contents

D.2	General Purpose Computation on the GPU	787
	Nvidia CUDA	787
	ATI Stream	788
	DirectX Compute Shaders	788
	OpenCL	788
E	An Introduction to GPU Programming by Example	789
F	The Swiss Army Knife of GPU Image Processing	793
F.1	Basics Shaders	794
F.2	Homography Warping via Vertex Shading	800
F.3	Compensation of Interreflection via Dependent Texture Lookups	802
F.4	Histogram Calculations with Geometry Shading	804
F.5	Anaglyph Rendering via Fragment Shading	806
F.6	Color Space Conversion via Fragment Shading	809
F.7	Image Undistortion via Fragment Shading	813
F.8	Convolution via Fragment Shading	815
F.9	Fast Fourier Transformations via CUDA	817