Handbook of DIGITAL IMAGING
VOL 1: IMAGE CAPTURE AND STORAGE

Editor-in-Chief

Michael Kriss
Adjunct Professor of Physics at the Portland State University, Oregon, USA
Previously with Eastman Kodak; University of Rochester, NY;
and Sharp Laboratories, USA

WILEY
Contents

Volume 1: Image Capture and Storage

List of Contributors xxxv
Preface xxxix
Abbreviations and Acronyms xli

Part I IMAGE CAPTURE AND STORAGE 1

1 Digital Versus Analog Imaging 3
   Michael Kriss
   Introduction 3
   The Continuous Image 4
   Analog Image Values to Sampled Digital Values 5
   Color Digital Images 8
   Color Images Produced from Color Filter Arrays 10
   Noise 15
   Exposure Latitude and Bit Depth 17
   Radiometry and Photometry 19
   References 29

2 Optics for Digital Imaging 31
   Peter B. Catrysse
   The Optical System in Digital Imaging 32
       Imaging Optics 32
       Pixel Optics 34
   Optics Fundamentals for Digital Imaging 37
       Geometrical Optics 38
       Radiometry 43
       Physical Optics (Wave or Fourier Optics) 45
       Electromagnetic Optics 48
Optical System Design and Analysis 50
   Imaging Optics: Create Beautiful Images 50
   Pixel Optics: Waste No Photon 54
Optical System Simulation and Prediction 59
   Generalized Imaging Optics Model 59
   Generalized Pixel Optics Model 61
Design Considerations for Optical Systems 61
   Photons per Pixel 62
   Flux-Invariant Scaling 63
   Microlens Performance Limits 66
   Optical Confinement Methods 68
   Backside Illumination (BSI) 72
Emerging Trends in Optical Systems 72
   Nanophotonics for Digital Imaging 72
   Computational Imaging 76
Summary 78
Acknowledgments 79
References 79

3 Solid-State Image Sensors 85
Boyd Fowler 85
Introduction 85
Image Sensor Parameters and Definitions 86
Silicon Photodetectors 90
   Photoelectric Effect 90
   Photodiode 92
   Photogate 98
   Pinned Photodiode 99
Pixel Optics 100
   Transmission 100
   Shadowing 102
   Color Filters 102
   Microlenses 102
Quantum Efficiency and Modulation Transfer Function 103
   QE and MTF Model 103
   QE and MTF Simulations 107
Noise Sources in Solid-State Image Sensors 108
   Fixed Pattern Noise 110
   Uncorrelated Temporal Noise Sources 111
   Correlated Temporal Noise Sources 116
Readout Architectures 116
   Charge-Coupled Devices (CCDs) 117
   CMOS Image Sensors (CISs) 124
Analog-to-Digital Conversion 133
   Chip Level ADC 134
   Column-Level ADC 135
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel-Level ADC</td>
<td>141</td>
</tr>
<tr>
<td>Scaling</td>
<td>142</td>
</tr>
<tr>
<td>Extended Dynamic Range Image Sensors</td>
<td>143</td>
</tr>
<tr>
<td>Dual-Column Level Amplifier and ADC Architecture</td>
<td>144</td>
</tr>
<tr>
<td>Dynamic Well Capacity Adjustment</td>
<td>146</td>
</tr>
<tr>
<td>Multiply Sampled Pixel-Level ADC</td>
<td>147</td>
</tr>
<tr>
<td>Pixel-Level Sigma-Delta ADC with Residue Readout</td>
<td>150</td>
</tr>
<tr>
<td>Time to Saturation Pixel with Residue Readout</td>
<td>152</td>
</tr>
<tr>
<td>Pixel Scaling</td>
<td>153</td>
</tr>
<tr>
<td>Technologies</td>
<td>155</td>
</tr>
<tr>
<td>Limits</td>
<td>155</td>
</tr>
<tr>
<td>Conclusion</td>
<td>157</td>
</tr>
<tr>
<td>Related Articles</td>
<td>158</td>
</tr>
<tr>
<td>References</td>
<td>158</td>
</tr>
</tbody>
</table>

### 4 Digital Imaging: An Introduction to Image Processing

*Michael Kriss*

- Sampled Images and Aliasing                                             161
- Image Sharpness and Enhancement                                         161
- Optimizing Sharpness While Minimizing Aliasing Artifacts                177
- Noise                                                                  189
- Noise Removal                                                          187
- Exposure Latitude                                                      202
- ISO Speed                                                              205
- Automatic Exposure                                                     205
- Automatic Focus Control                                                211
- References                                                             217

### 5 Color Reproduction for Digital Cameras

*Michael Kriss*

- Introduction                                                           219
- CIE Color Matching System                                              222
- The Spectral Sensitivity of a Digital Camera                           235
- White Balance                                                          243
- Color Reproduction                                                     258
- Color Spaces Used in Digital Imaging                                   267
- Color Filter Arrays                                                    271
- References                                                             284

### 6 Image Compression and File Formats

*Michael Kriss*

- Introduction                                                           287
- Compression Fundamentals                                               289
- JPEG Compression                                                       293
- JPEG 2000                                                              312
7 Image Quality Concepts
Peter D. Burns

Introduction 325
Design 327
Performance Variation and Measurement 329
Imaging Performance Evaluation 330
Tone Reproduction 331
Color Reproduction 334
Image Detail, Resolution, and Sampling 339
Image Noise 351
Human Vision Approach and Distortion Maps 362
Modeling of Human Vision 364
Image Structure 365
Saliency and Sharpness Estimation 365
Rationale and Challenges 366
Conclusions 368
References 368

8 Image Systems Simulation
Joyce E. Farrell and Brian A. Wandell

Introduction 373
Image Systems Simulation Software 374
Scene 375
Efficient Scene Representations 379
Optics and Sensor Irradiance 380
Conversion of Units 380
Geometric Distortion 380
Spatial Blur 381
Optics Operation 382
Extended Optical Designs 383
Sensor 383
Signal Transduction 385
Pixel Geometry 385
Sensor Noise 385
Global Wavelength Management: Lens and Infrared (IR) 387
Cut Filters 387
Local Wavelength Management: Color Filter Array 387
Pixel Spatial Sampling 388
Sensor Operation 388
Novel Sensor Designs 389
Image Processing 389
Interpolation 390
9 Multispectral Imaging
Yoichi Miyake and Vladimir A. Bochko

Introduction
401
Color Reproduction of Conventional Imaging Systems
402
Principal Component Analysis of Spectral Reflectance
404
Wiener Estimation of Spectral Reflectance
406
Development of Spectral Imaging Systems
Spectral Endoscopes
416
Multiband Camera for Digital Archives
Multispectral Scanner
424
Other Multiband Cameras
424
Spectral Display
425
Goniospectral Imaging
426
Summary
429
References
430

10 Understanding Glare and How it Limits Scene Reproduction
Alessandro Rizzi and John J. McCann

Introduction
433
Physics of Scene Capture
Dynamic Range of Scenes
435
Dynamic Range of Light Sensors
435
Dynamic Range of Display Devices
436
Bits per Pixel
436
Summary of Technology Capture Display and Storage
437
Components from Capture to Reproduction to Perception
437
Camera Acquisition Limits
HDR Test Targets
439
Camera Veiling Glare Limits
440
Glare Limits of the Retinal Image
The von Honthorst's Painting and the 4-scale Black HDR Target
446
HDR Displays and Black and White Mondrian
447
HDR and Tone Scale Maps
448
Summary of Limits of Human Vision
449
Two Opposing Spatial Mechanisms
Glare and Neural Contrast
449
Neural Contrast
450
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration of Camera Responses</td>
<td>451</td>
</tr>
<tr>
<td>Converting Camera Digits to Radiometric Values</td>
<td>452</td>
</tr>
<tr>
<td>Reflection Calibration Targets in Uniform Illumination</td>
<td>452</td>
</tr>
<tr>
<td>RAW and HDR Rendering</td>
<td>453</td>
</tr>
<tr>
<td>Spatial Image Processing</td>
<td>453</td>
</tr>
<tr>
<td>Retinex Algorithms</td>
<td>454</td>
</tr>
<tr>
<td>Summary</td>
<td>456</td>
</tr>
<tr>
<td>References</td>
<td>456</td>
</tr>
</tbody>
</table>