Physics of Digital Photography (Second Edition)

Series Editor

R Barry Johnson a Senior Research Professor at Alabama A&M University, has been involved for over 50 years in lens design, optical systems design, electro-optical systems engineering, and photonics. He has been a faculty member at three academic institutions engaged in optics education and research, employed by a number of companies, and provided consulting services.

Dr Johnson is an IOP Fellow, SPIE Fellow and Life Member, OSA Fellow, and was the 1987 President of SPIE. He serves on the editorial board of Infrared Physics & Technology and Advances in Optical Technologies. Dr Johnson has been awarded many patents, has published numerous papers and several books and book chapters, and was awarded the 2012 OSA/SPIE Joseph W Goodman Book Writing Award for Lens Design Fundamentals, Second Edition. He is a perennial co-chair of the annual SPIE Current Developments in Lens Design and Optical Engineering Conference.

Foreword

Until the 1960s, the field of optics was primarily concentrated in the classical areas of photography, cameras, binoculars, telescopes, spectrometers, colorimeters, radiometers, etc. In the late 1960s, optics began to blossom with the advent of new types of infrared detectors, liquid crystal displays (LCD), light emitting diodes (LED), charge coupled devices (CCD), lasers, holography, fiber optics, new optical materials, advances in optical and mechanical fabrication, new optical design programs, and many more technologies. With the development of the LED, LCD, CCD and other electo-optical devices, the term 'photonics' came into vogue in the 1980s to describe the science of using light in development of new technologies and the performance of a myriad of applications. Today, optics and photonics are truly pervasive throughout society and new technologies are continuing to emerge. The objective of this series is to provide students, researchers, and those who enjoy self-teaching with a wide-ranging collection of books that each focus on a relevant topic in technologies and application of optics and photonics. These books will provide knowledge to prepare the reader to be better able to participate in these exciting areas now and in the future. The title of this series is Emerging Technologies in Optics and Photonics where 'emerging' is taken to mean 'coming into existence,' 'coming into maturity,' and 'coming into prominence.' IOP Publishing and I hope that you find this Series of significant value to you and your career.

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For my parents, Ann and Gareth

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Preface

The aim of this book is to provide a theoretical overview of the photographic imaging chain. It is intended for use by both graduate students and established researchers as a link between imaging science and photographic practice. It should also be useful for photographers who have a graduate-level technical background.

Chapter 1 titled 'Photographic Optics' describes the formation of an optical image by a compound photographic lens. Topics discussed include focusing, framing, perspective and depth of field. The final section derives the photometric exposure distribution formed at the sensor plane of the camera.

Chapter 2 titled 'Digital Output and Exposure Strategy' discusses the strategy for generating useful digital output in response to the photometric exposure distribution at the sensor plane derived in chapter 1. In modern digital photography, the standard exposure strategy defined by the CIPA DC-004 and ISO 12232 standards is based upon the output JPEG image obtained from the camera. Consequently, this chapter begins by discussing the nature of the digital output levels of a digital image. The theory of the standard exposure strategy is subsequently developed in detail. For a typical scene, the aim is to produce a JPEG image that has the correct mid-tone lightness. The later sections discuss practical exposure strategy and cover topics such as photographic lighting, exposure modes and advanced metering, photographic filters and high dynamic range imaging.

Chapter 3 titled 'Raw Data Model' uses linear systems theory to develop a model of the raw data produced by a camera. The aim is to illustrate how the nature and quality of the raw data is affected by phenomena such as aliasing and noise, along with various blurring phenomena such as diffraction. A derivation of the charge signal is included, along with a model of the analog-to-digital conversion process.

Chapter 4 titled 'Raw Conversion' describes the main steps involved in converting the raw data into a viewable output colour image. The majority of the chapter is devoted to colour conversion of the raw data. Unlike conventional academic treatments, this chapter describes colour conversion and white-balancing strategies that are used by digital cameras in practice.

Chapter 5 titled 'Camera Image Quality' discusses the theory behind camera and lens image quality metrics. Unlike conventional treatments, this chapter demonstrates how such metrics should be applied and interpreted when comparing camera systems that have different sensor pixel counts or are based on different sensor formats. Practical strategies for maximising the full image quality potential of a camera system are also discussed.

In this second edition, the chapter structure of the first edition has been preserved but the material has been reorganised and extensively rewritten. New material has been added, typographical errors have been corrected, the figures have been improved and a detailed index has been included.

I would like to thank Prof. R Barry Johnson for useful discussions.

Andy Rowlands, June 2020

Author biography

D A Rowlands

Andy Rowlands gained a first-class degree in Mathematics and Physics and a PhD in Theoretical Condensed Matter Physics from the University of Warwick, UK.

He was subsequently awarded a Fellowship in Theoretical Physics from the Engineering and Physical Sciences Research Council (EPSRC), which he held at the University of Bristol, UK, and this was followed by research positions at Lawrence Livermore National Laboratory, USA, Tongji University in Shanghai, China, and the University of Cambridge, UK.

Andy's combined interests in physics and photography inspired the writing of this book. His photographic work, much of which features China, can be viewed at http://www.andyrowlands.com.

Abbreviations

1D	one dimension
2D	two dimensions
ADC	analog-to-digital converter
ADU	analog-to-digital unit
AF	autofocus
AFoV	angular field of view
AHD	Adaptive Homogeneity-Directed
APEX	Additive System of Photographic Exposure
APS-C	Advanced Photo System Type-C
AS	aperture stop
ATF	aberration transfer function
Av	aperture value
AW	adopted white
BSI	backside illumination
Bv	brightness value
CAT	chromatic adaptation transform
CCD	charge-coupled device
CCE	charge collection efficiency
CCT	correlated colour temperature
CDS	correlated double sampling
CFA	colour filter array
CIE	Commission Internationale de l'Eclairage
CIPA	Camera and Imaging Products Association
CMM	colour-matching module
CMOS	complimentary metal-oxide semiconductor
CoC	circle of confusion
CRT	cathode ray tube
CSF	contrast sensitivity function
CTF	contrast transfer function
DCNU	dark current non-uniformity
DN	data number
DNG	digital negative
DoF	depth of field
DOL	digital output level
DR	dynamic range
DSC/SMI	digital still camera sensitivity metameric index
D-SLR	digital single-lens reflex
DSNU	dark signal non-uniformity
EC	exposure compensation
EP	entrance pupil
ESF	edge spread function
ETTR	expose to the right
Ev	exposure value
EW	entrance window
EXIF	Exchangeable Image File
FF	fill factor
FFP	front focal plane

FoV	field of view
FP	focal plane
FPN	fixed pattern noise
FS	field stop
FT	Fourier transform
FWC	full-well capacity
GND	graduated neutral density
HDR	high dynamic range
HVS	human visual system
ICC	International Color Consortium
IP	image plane
IQ	image quality
ISO	International Organization for Standardization
Iv	incident light value
JPEG	Joint Photographic Experts Group
LCD	liquid crystal display
LDR	low dynamic range
LENR	long-exposure noise reduction
LRS	least resolvable separation
LSI	linear shift-invariant
LUT	look-up table
MOS	metal oxide semiconductor
MTF	modulation transfer function
NA	numerical aperture
ND	neutral density
OA	optical axis
OECF	opto-electronic conversion function
OLPF	optical low-pass filter
OP	object plane
OPD	optical path difference
OTF	optical transfer function
PCS	profile connection space
PDAF	phase-detect autofocus
PDR	photographic dynamic range
PGA	programmable gain amplifier
PPG	Patterned Pixel Grouping
PRNU	pixel response non-uniformity
PSF	point spread function
PTF	phase transfer function
REI	recommended exposure index
RMS	root mean square
QE	quantum efficiency
RA	relative aperture
REI	recommended exposure index
RFP	rear focal plane
RI	relative illumination
RP	resolving power
SA	spherical aberration
SQF	subjective quality factor
SLR	single-lens reflex

SNR	signal-to-noise ratio
SOS	standard output sensitivity
SP	sensor plane
SPD	spectral power distribution
SQF	subjective quality factor
Sv	speed value
TIFF	Tagged Image File Format
TMO	tone-mapping operator
TTL	through-the-lens
Tv	time value
UCS	uniform chromaticity scale
USM	unsharp mask
VNG	Variable Number of Gradients
WB	white balance
XP	exit pupil
XW	exit window