

Color Image Processing with Biomedical Applications

Library of Congress Cataloging-in-Publication Data

Rangayyan, Rangaraj M.

Color image processing with biomedical applications / Rangaraj M. Rangayyan, Begona Acha, Carmen Serrano.

p. ; cm. -- (Press monograph 206)

Includes bibliographical references and index.

ISBN 978-0-8194-8564-9

1. Imaging systems in medicine--Data processing. 2. Diagnostic imaging--Digital techniques. 3. Color photography. 4. Image processing. I. Acha, Begona. II. Serrano, Carmen, Ph. D. III. Title. IV. Series: SPIE monograph ; 206.

[DNLM: 1. Image Processing, Computer-Assisted--methods. 2. Staining and Labeling--methods. W 26.55.C7]

R857.O6R36 2011

616.07'54--dc23

2011021979

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: Books@spie.org

Web: <http://spie.org>

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Printed in the United States of America.

First Printing



Color Image Processing with Biomedical Applications

Rangaraj M. Rangayyan
Begoña Acha
Carmen Serrano

SPIE
PRESS

Bellingham, Washington USA

Dedication

To Mayura, my wife,
for adding color to my life
Raj

To my father
Bego

To my big and colorful family
Carmen

Todo es de color (*Lole y Manuel*)

Contents

Preface	xi
Acknowledgments	xvii
Symbols and Abbreviations	xxi
1 The Nature and Representation of Color Images	1
1.1 Color Perception by the Human Visual System	3
1.1.1 The radiant spectrum	4
1.1.2 Spectral luminous efficiency	7
1.1.3 Photometric quantities	7
1.1.4 Effects of light sources and illumination	10
1.1.5 Color perception and trichromacy	12
1.1.6 Color attributes	12
1.1.7 Color-matching functions	14
1.1.8 Factors affecting color perception	17
1.2 Representation of Color	30
1.2.1 Device-independent color spaces and CIE standards	31
1.2.2 Device-dependent color spaces	38
1.2.3 Color order systems and the Munsell color system	52
1.2.4 Color-difference formulas	53
1.3 Illustrations of Color Images and Their Characteristics	60
1.3.1 <i>RGB</i> components and their characteristics	60
1.3.2 <i>HSI</i> components and their characteristics	62
1.3.3 Chromatic and achromatic pixels	65
1.3.4 Histograms of <i>HSI</i> components	73
1.3.5 <i>CMYK</i> components and their characteristics	76
1.4 Natural Color, Pseudocolor, Stained, Color-Coded, and Multi- spectral Images	81
1.4.1 Pseudocolor images of weather maps	84
1.4.2 Staining	84
1.4.3 Color coding	88
1.4.4 Multispectral imaging	91
1.5 Biomedical Application: Images of the Retina	97
1.6 Biomedical Application: Images of Dermatological Lesions	99
1.7 Remarks	101

2	Acquisition, Creation, and Quality Control of Color Images	103
2.1	Basics of Color Image Acquisition	103
2.1.1	Color image sensors	103
2.1.2	Dark current correction	106
2.1.3	Demosaicking	106
2.1.4	White balance	109
2.1.5	Color transformation to unrendered color spaces	110
2.1.6	Color transformation to rendered color spaces	115
2.2	Quality and Information Content of Color Images	117
2.2.1	Measures of fidelity	118
2.2.2	Factors affecting perceived image quality: contrast, sharpness, and colorfulness	121
2.3	Calibration and Characterization of Color Images	124
2.3.1	Calibration of a digital still camera	125
2.3.2	Characterization of a digital still camera	127
2.3.3	International Color Consortium profiles	128
2.4	Natural and Artificial Color in Biomedical Imaging	129
2.4.1	Staining in histopathology and cytology	131
2.4.2	Use of fluorescent dyes in confocal microscopy	143
2.4.3	Color in fusion of multimodality images	146
2.4.4	Color coding in Doppler ultrasonography	150
2.4.5	Use of color in white-matter tractography	155
2.5	Biomedical Application: Endoscopy of the Digestive Tract	162
2.6	Biomedical Application: Imaging of Burn Wounds	163
2.6.1	Influence of different illumination conditions	166
2.6.2	Colorimetric characterization of the camera	168
2.7	Remarks	170
3	Removal of Noise and Artifacts	173
3.1	Space-Domain Filters Based on Local Statistics	174
3.1.1	The mean filter	175
3.1.2	The median filter	177
3.1.3	Filters based on order statistics	181
3.2	Ordering Procedures for Multivariate or Vectorial Data	184
3.2.1	Marginal ordering	185
3.2.2	Conditional ordering	185
3.2.3	Reduced ordering	187
3.3	The Vector Median and Vector Directional Filters	188
3.3.1	Extensions to the VMF and VDF	190
3.3.2	The double-window modified trimmed mean filter	190
3.3.3	The generalized VDF–double-window– α -trimmed mean filter	191
3.4	Adaptive Filters	191
3.4.1	The adaptive nonparametric filter with a Gaussian kernel	192

3.4.2	The adaptive hybrid multivariate filter	194
3.5	The Adaptive-Neighborhood Filter	196
3.5.1	Design of the ANF for color images	196
3.5.2	Region-growing techniques	197
3.5.3	Estimation of the noise-free seed pixel	201
3.5.4	Illustrations of application	203
3.6	Biomedical Application: Removal of Noise Due to Dust in Fundus Images of the Retina	210
3.7	Remarks	213
4	Enhancement of Color Images	215
4.1	Componentwise Enhancement of Color Images	216
4.1.1	Image enhancement in the <i>RGB</i> versus <i>HSI</i> domains	216
4.1.2	Hue-preserving contrast enhancement	217
4.1.3	Enhancement of saturation	219
4.1.4	Selective reduction of saturation	220
4.1.5	Alteration of hue	221
4.2	Correction of Tone and Color Balance	223
4.3	Filters for Image Sharpening	229
4.3.1	Unsharp masking	229
4.3.2	Subtracting Laplacian	234
4.4	Contrast Enhancement	235
4.5	Color Histogram Equalization and Modification	239
4.5.1	Componentwise histogram equalization	244
4.5.2	3D histogram equalization	246
4.5.3	Histogram explosion	250
4.5.4	Histogram decimation	251
4.5.5	Adaptive-neighborhood histogram equalization	251
4.5.6	Comparative analysis of methods for color histogram equalization	257
4.6	Pseudocolor Transforms for Enhanced Display of Medical Im- ages	265
4.7	The Gamut Problem in the Enhancement and Display of Color Images	268
4.8	Biomedical Application: Correction of Nonuniform Illumina- tion in Fundus Images of the Retina	269
4.9	Remarks	272
5	Segmentation of Color Images	275
5.1	Histogram-based Thresholding	275
5.1.1	Thresholding of grayscale images	276
5.1.2	Thresholding of color images	279
5.2	Color Clustering	283
5.2.1	Color feature spaces and distance measures	285
5.2.2	Algorithms to partition a feature space	286

5.3	Detection of Edges	297
5.3.1	Edge detectors extended from grayscale to color	298
5.3.2	Vectorial approaches	302
5.4	Region Growing in Color Images	311
5.4.1	Seed selection	312
5.4.2	Belonging conditions	316
5.4.3	Stopping condition	317
5.5	Morphological Operators for Segmentation of Color Images	319
5.5.1	The watershed algorithm for grayscale images	322
5.5.2	The watershed algorithm applied to color images	324
5.6	Biomedical Application: Segmentation of Burn Images	325
5.7	Biomedical Application: Analysis of the Tissue Composition of Skin Lesions	330
5.8	Biomedical Application: Segmentation of Blood Vessels in the Retina	333
5.8.1	Gabor filters	337
5.8.2	Detection of retinal blood vessels	339
5.8.3	Dataset of retinal images and preprocessing	339
5.8.4	Single-scale filtering and analysis	341
5.8.5	Multiscale filtering and analysis	341
5.8.6	Use of multiple color components for improved detec- tion of retinal blood vessels	343
5.8.7	Distinguishing between retinal arteries and veins	344
5.9	Biomedical Application: Segmentation of Histopathology Im- ages	345
5.9.1	Color separation in histopathology images	346
5.9.2	Segmentation of lumen in histopathology images	349
5.9.3	Detection of tubules in histopathology images	350
5.10	Remarks	353
6	Afterword	355
	References	357
	Index	395
	About the Authors	403

Preface

The Importance of Color

Color plays an important role in our visual world: we are attracted more by tones of color than by shades of gray. The human visual system (HVS) can sense, analyze, and appreciate more tones of color than shades of gray at a given time and under a given set of viewing conditions. The colors and skin tones of our bodies, the colors and texture of the clothes we wear, and the colors of the natural scenery that surrounds us are all innate aspects of our lives. Who would not be thrilled to view a meadow filled with a splash of colorful flowers? Who would not be mesmerized by the extravagant colors of corals and tropical fishes in a reef? Who would not be excited with a surprise gift of a bouquet of flowers with a burst of colors?

Color permeates our world and life. We are so accustomed to color that we use related words, for example, “colorful,” to describe nonvisual entities such as personalities. Indeed, a world without color would be very dull — and gray!

The Growing Popularity of Color Imaging

With the increasing popularity of computers and digital cameras as personal devices for education, research, communication, professional work, as well as entertainment, the use of images in day-to-day life is growing by leaps and bounds. Personal computers (PCs) have standard features and accessories for the acquisition of images via scanners, still cameras, and video cameras, as well as easy downloading of images from the Internet, the Web, or storage devices such as compact discs (CDs) and digital versatile (or video) discs (DVDs). The acquisition, manipulation, and printing of personal or family photos have now become an easy (and even pleasant!) task for an individual who is not necessarily at ease with computers. Needless to say, color is a significant aspect of all of the above.

From Grayscale to Color Image Processing

Digital image processing (DIP) — the manipulation of images in digital format by computers — has been an important field of research and development since the 1960s [1–12]. Much of the initial work in DIP dealt exclusively with monochromatic or grayscale images. (See the special issues of the *Proceedings of the IEEE*, July 1972 and May 1979, for historically significant papers on DIP.) In fact, the processing of images in just black and white (binary images) has been an important area with applications in facsimile transmission (fax) and document analysis.

As the knowledge and understanding of techniques for DIP developed, so did the recognition of the need to include color. With remote sensing of the Earth and its environment using satellites [13], the need also grew to consider more general representations of images than the traditional tristimulus or three-channel characterization of natural color images. Multispectral or hyperspectral imaging with tens of channels or several hundred bands of spectral sensitivity spanning a broad range of the electromagnetic spectrum well beyond the range of visible light is now common, with real-life applications including land-use mapping, analysis of forest cover and deforestation, detection of lightning strikes and forest fires, analysis of agricultural plantations and prediction of crop yield, and extreme weather or flood warning.

Nowadays, medical diagnosis depends heavily upon imaging of the human body. Most medical images, such as those obtained using X rays and ultrasound, are scalar-valued, lack inherent color, and are represented as monochromatic or grayscale images. However, (pseudo-)color is used for enhanced visualization in the registration of multimodality images. Limited colors are used to encode the velocity and direction of blood flow in Doppler imaging. Staining in pathology and cytology leads to vividly colored images of various tissues [14–17]. Even in the case of analysis of external signs and symptoms, such as skin rashes and burns, color imaging can play important roles in enhanced visualization using polarized lighting, transmission, and archival. The application of DIP techniques to images as above calls for the development of specialized techniques for the representation, characterization, and analysis of color.

Initial work on color image processing (CIP) was based on the direct (and simplistic) application of grayscale DIP techniques to the individual channels of color or multispectral images. Although some useful results could be obtained in this manner, it was soon realized that it is important to develop specialized techniques for CIP, taking into consideration the correlation and dependencies that exist between the channels [1–5, 12, 18–20]. (See the January 2005 special issue of the *IEEE Signal Processing Magazine* on color image processing.) Whereas several books are available on the science of color perception, imaging, and display [12, 21–28], very few books on DIP have sig-

nificant examples, sections, or chapters on CIP [1–5, 11, 12, 20, 24], and fewer still are dedicated to CIP [18, 19, 29, 30]. In this book, we shall mainly consider techniques that are specifically designed for CIP.

The Plan of the Book

We begin with a detailed study of the nature of color images. In addition to natural color images, we take into consideration multispectral and pseudocolor images in specialized areas such as photogrammetric and biomedical imaging. Chapter 1 provides descriptions of the HVS, color perception, color-matching functions, and systems for the representation of color images. A pertinent selection of biomedical applications is provided at the end of each chapter, including diagnostic imaging of the retina and imaging of skin lesions.

In Chapter 2, we present details regarding the acquisition, creation, and quality control of color images. Despite the simple appearance and usage of digital cameras, the chain of systems and techniques involved in the acquisition of color images is complex; regardless, the science of imaging is now a well-developed and established subject area [12, 24, 31]. Several operations are required to ensure faithful reproduction of the colors in the scene or object being imaged, or to assure a visually pleasing and acceptable rendition of the complex tonal characteristics in a portrait; the latter hints at the need to include personal preferences and subjective aspects, whereas the former implies rigid technical requirements and the satisfaction of quantitative measures of image characteristics. In addition to processes involving natural color images, we describe techniques related to staining in pathology and the use of fluorescent dyes in confocal microscopy for imaging of biomedical specimens. We present biomedical applications including the acquisition of images of burn wounds and endoscopy.

In Chapter 3, we study the issue of noise and artifacts in color images as well as methods to remove them. The need to consider the interrelationships that exist between the components or channels of color images is emphasized, leading to the formulation of vector filters.

In spite of the high level of sophistication (and cost) of cameras and image-acquisition systems, it is common to acquire or encounter images of poor quality. Image quality is affected by several factors, including the lighting conditions, the environment, and the nature of the scene or object being imaged, in addition to the skills and competence of the individual capturing the image. The topic of image enhancement is considered in Chapter 4, including methods for hue-preserving enhancement, contrast enhancement, sharpening, and histogram-based operations.

Segmentation for the detection of regions of interest or objects is a critical step in the analysis of images. Although a large body of literature exists on this topic, it is recognized that no single technique can directly serve a new purpose: every application or problem demands the development of a specific technique that takes into account the particular characteristics of the images and objects involved. The problem is rendered more complex by the multichannel nature of color images. In Chapter 5, we explore several methods for the detection of edges and objects in color images. Several biomedical applications are presented, including the segmentation and analysis of skin lesions and retinal vasculature.

Chapter 6 provides a few closing remarks on the subjects described in the book and also on advanced topics to be presented in a companion book to follow.

The Intended Audience and Learning Plans

The methods presented in the book are at a fairly high level of technical and mathematical sophistication. A good background in one-dimensional signal and system analysis [32–34] is required in order to follow the procedures and analyses. Familiarity with the theory of linear systems, signals, and transforms, in both continuous and discrete versions, is assumed. Furthermore, familiarity with the basics of DIP [1–9] is assumed and required.

We only briefly study a few representative imaging or image-data acquisition techniques. We study in more detail the problems present with images after they have been acquired, and concentrate on how to solve the problems. Some preparatory reading on imaging systems, equipment, and techniques [12,24,31] would be useful, but is not essential.

The book is primarily directed at engineering students in their (post-)graduate studies. Students of electrical and computer engineering with a good background in signals and systems [32–34] are expected to be well prepared for the material in the book. Students in other engineering disciplines or in computer science, physics, mathematics, or geophysics should also be able to appreciate the material in this book. A course on digital signal processing or digital filters [35] would form a useful link, but a capable student without familiarity of this topic may not face much difficulty. Additional study of a book on DIP [1–9] can assist in developing a good understanding of general image-processing methods.

Practicing engineers, researchers, computer scientists, information technologists, medical physicists, and data-processing specialists working in diverse areas such as DIP, computer vision, pattern recognition, telecommunications, seismic and geophysical applications, biomedical applications, hospital infor-

mation systems, remote sensing, mapping, and geomatics may find this book useful in their quest to learn advanced techniques for the analysis of color or multichannel images.

Practical experience with real-life images is a key element in understanding and appreciating image analysis. We strongly recommend hands-on experiments with intriguing real-life images and technically challenging image-processing algorithms. This aspect can be difficult and frustrating at times, but provides professional satisfaction and educational fun!

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July 2011

Acknowledgments

Writing this book on the exciting subject of color image processing has been difficult, challenging, and stimulating. Simultaneously, it has also yielded more knowledge and deeper understanding of the related subject matter, and satisfaction as each part was brought to a certain stage of completion.

Our understanding and appreciation of related material have been helped by the collaborative research and studies performed with several graduate students, postdoctoral fellows, research associates, and colleagues. We thank the following for their contributions to this book:

- Dr. Mihai Ciuc, Universitatea Politehnica București, Bucharest, Romania, for his contributions to earlier research work and publications on color image processing as well as for providing several examples of filtered or enhanced images and related data.
- Dr. Fábio José Ayres and Shantanu Banik, University of Calgary, for help with image-processing algorithms and MATLAB[®] programming.
- Dr. Hallgrimur Benediktsson, Dr. Serdar Yilmaz, and Sansira Semnowich, University of Calgary, for providing images and information related to color imaging in histology and pathology.
- Dr. Paulo Mazzoncini de Azevedo Marques and Dr. Marco A.C. Frade, Universidade de São Paulo, Ribeirão Preto, São Paulo, Brasil, for providing color images of skin ulcers and for their collaboration on related projects.
- Dr. Philippe Pibarot, Québec Heart and Lung Institute, Québec City, Province of Québec, Canada, for providing color Doppler echocardiographic images.
- Hanford Deglint, ITRES Research Limited, Calgary, Alberta, Canada, for providing CASI images of the campus of the University of Calgary and related notes.
- Dr. Enrico Grisan and Dr. Alfredo Ruggeri, Università degli Studi di Padova, Padova, Italy, for providing illustrations of their results of processing fundus images of the retina.
- Dr. Maitreyi Raman, University of Calgary, for providing images and notes on endoscopy.

- Dr. Myriam Oger, GRECAN — François Baclesse Cancer Centre, Caen, France, for providing histology images and related data.
- Dr. Karl Baum, Rochester Institute of Technology, Rochester, NY, for providing images, advice, and comments on multimodality image fusion.
- Patrick Weeden, Weather Central LLC, Madison, WI, for providing temperature prediction maps and related notes.
- Aurora Sáez Manzano, Departamento de Teoría de la Señal y Comunicaciones, University of Seville, Spain, for her invaluable assistance in implementing several algorithms described in this book and providing the resulting images.
- Irene Fondón García, José Antonio Pérez Carrasco, Carlos Sánchez Mendoza, Francisco Núñez Benjumea, and Antonio Foncubierta Rodríguez, Departamento de Teoría de la Señal y Comunicaciones, University of Seville, Spain, for their assistance.
- Dr. Juan Luis Nieves Gómez, Departamento de Óptica, Facultad de Ciencias, University of Granada, Spain, for providing the measurements of the sensitivity values for the Retiga 1300 camera by QImaging.
- Dr. Tomás Gómez Cía from Servicio de Cirugía Plástica y Grandes Quemados (Hospitales Universitarios Virgen del Rocío, Sevilla) for taking the burn images.
- Shantanu Banik, Faraz Oloumi (University of Calgary), Hanford Deglint, Dr. Paulo Mazzoncini de Azevedo Marques, Dr. Denise Guliato (Universidade Federal de Uberlândia, Uberlândia, Minas Gerais, Brasil), Dr. José I. Acha (University of Seville), and Dr. Mihai Ciuc for reviewing parts of the book.
- Garwin Hancock and Steven Leikeim, Department of Electrical and Computer Engineering, University of Calgary, for help with color-coded electrical and communications circuits.
- Enrique de la Cerda Cisneros (Seville, Spain) for taking our pictures.
- The anonymous reviewers for their careful reading and suggestions for improvement of the book.

The book has benefited significantly from illustrations and text provided by a number of researchers worldwide, as identified in the references and permissions cited. We thank them all for enriching the book with their gifts of knowledge and kindness. Some of the test images used in the book were obtained from the Center for Image Processing Research, Rensselaer Polytechnic Institute, Troy, NY, www.ipl.rpi.edu; the Digital Retinal Images for Vessel

Extraction (DRIVE) database, www.isi.uu.nl/Research/Databases/DRIVE; and the Structured Analysis of the Retina (STARE) database, www.ces.clemson.edu/~ahoover/stare; we thank them for the resources provided.

Several research projects provided us with the background, material, examples, and experience that have gone into the writing of this book. We thank the Natural Sciences and Engineering Research Council of Canada, the University of Calgary, the Comisión Interministerial para Investigaciones Científicas of Ministerio de Ciencia y Tecnología of Spain, and Universidad de Sevilla for supporting our research projects.

We thank the Killam Trusts for awarding (Raj Rangayyan) a Killam Resident Fellowship and the University of Calgary for awarding the “University Professor” position to facilitate work on this book.

We thank CRC Press for permission to use material from previous publications and the LaTeX stylefile for the book, and Shashi Kumar, LaTeX Help Desk, Glyph International, Noida, India, for assistance with the LaTeX stylefile.

We thank SPIE Press for inviting us to write this book and for completing the publication process in a friendly and efficient manner.

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July 2011

Symbols and Abbreviations

Bold-faced letters represent vectors or matrices. Variables or symbols used within limited contexts are not listed here; they are described within their context. The mathematical symbols listed may stand for other entities or variables in different applications; only the common associations used in this book are listed for ready reference.

arctan	inverse tangent, \tan^{-1}
arg	argument of
au	arbitrary units
<i>A</i>	area
AC	alternating current
ADC	analog-to-digital converter
AHMF	adaptive hybrid multivariate filter
AMNFG2	adaptive multichannel nonparametric filter with Gaussian kernel
ANCE	adaptive-neighborhood contrast enhancement
ANF	adaptive-neighborhood filter
ANHE	adaptive-neighborhood histogram equalization
ANN	artificial neural network
ANNS	adaptive-neighborhood noise subtraction
ATMF	alpha-trimmed mean filter
AUC	area under the ROC curve
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
<i>A_v</i>	camera aperture setting
<i>A_z</i>	area under the ROC curve
<i>b</i>	bit
<i>B, b</i>	blue component
<i>B</i>	byte
BMP	bitmap
cd	candela
cm	centimeter
<i>C</i>	cyan component
CAD	computer-aided diagnosis
CASI	Compact Airborne Spectrographic Imager
CBIR	content-based image retrieval
CCD	charge-coupled device

CCITT	Comité Consultatif International Téléphonique et Télégraphique
CD	compact disc
CDF	cumulative (probability) distribution function
CDR	chroma dynamic range
CFA	color filter array
CFM	color filter mosaic
CIE	Commission Internationale de l'Eclairage
CIECAM	CIE color appearance model
CIE $L^*a^*b^*$	the CIE $L^*a^*b^*$ color space
CIE $L^*u^*v^*$	the CIE $L^*u^*v^*$ color space
CIP	color image processing
CMC	British Colour-Measurement Committee of the Society of Dyers and Colourists
CMOS	complementary metal-oxide semiconductor
<i>CMYK</i>	[cyan, magenta, yellow, black] representation of color
CRT	cathode-ray tube
CT	computed tomography
CYGM	cyan, yellow, green, and magenta
d	derivative or differentiation operator
dpi	dots per inch
DAB	diaminobenzidine
DAC	digital-to-analog converter
DC	direct current
DDF	distance-directional filter
DICOM	Digital Imaging and Communications in Medicine
DIP	digital image processing
DNA	deoxyribonucleic acid
DRIVE	Digital Retinal Images for Vessel Extraction
DSC	digital still camera
DT-MRI	diffusion tensor MRI
DVD	digital versatile (or video) disc
DW-MTMF	double-window modified trimmed mean filter
$\exp(x)$	exponential function, e^x
E	irradiance
$E[\]$	statistical expectation operator
E_v	illuminance
$E(\lambda)$	spectral irradiance
EBU	European Broadcasting Union
ECG	electrocardiogram
EHz	exahertz = 10^{18} Hz
EM	electromagnetic
Erf	error function (integral of a Gaussian)
$f(m, n)$	a digital scalar or grayscale image, typically original or undistorted

$f(x, y)$	a scalar or grayscale image, typically original or undistorted
$\mathbf{f}(m, n), \mathbf{f}_n$	an image where each pixel is a vector, a color image
\mathbf{f}	matrix or vector representation of an entire image
$F_f(l)$	CDF of image f
FN	false negative
FNF	false-negative fraction
FOV	field of view
FP	false positive
FPF	false-positive fraction
$g(m, n)$	a digital scalar or grayscale image, typically processed or distorted
$g(x, y)$	a scalar or grayscale image, typically processed or distorted
$\mathbf{g}(m, n), \mathbf{g}_n$	an image where each pixel is a vector, a color image
\mathbf{g}	matrix or vector representation of an entire image
G, g	green component
GB	gigabyte
GHz	gigahertz = 10^9 Hz
GI	gastrointestinal
GVDF	generalized vector directional filter
GVDF-DW- α TM	GVDF - double window - α -trimmed mean filter
h	hour
h_l	data-dependent smoothing term
$h(m, n)$	impulse response of a discrete-space system
$h(x, y)$	impulse response of a continuous-space system
H	entropy
H	hue component
H	as a superscript, Hermitian (complex-conjugate)
	transposition of a matrix
H&E	hematoxylin and eosin
HCI	[hue, chroma, intensity] representation of color
HDTV	high-definition television
HLS	[hue, lightness, saturation] representation of color
HSI	[hue, saturation, intensity] representation of color
HSV	[hue, saturation, value] representation of color
HVS	human visual system
i	index of a series
\mathbf{I}	the identity matrix
I	radiant intensity
I	intensity component
I_v	luminous intensity

ICC	International Color Consortium
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IESNA	Illuminating Engineering Society of North America
ISO	International Organization for Standardization
ITU	International Telecommunication Union
j	index of a series
\bar{j}	$\sqrt{-1}$
JBIG	Joint Bi-level Image (experts) Group
JPEG	Joint Photographic Experts Group
k	kilo (1,000)
kHz	kilohertz = 10^3 Hz
km	kilometer = 10^3 m
K	black component
K	kilo ($2^{10} = 1,024$)
K	Kelvin (unit of absolute temperature)
K	covariance matrix
K_m	maximum spectral luminous efficacy
$K(\lambda)$	spectral luminous efficacy
lm	lumen
ln	natural logarithm (base e)
lx	lux, unit of illuminance
L	radiance
L_v	luminance
$L(\lambda)$	spectral radiance
LCD	liquid crystal display
LDR	luminance dynamic range
LIDAR	light detection and ranging
LLMMSE	local linear minimum mean-squared error
LMMSE	linear minimum mean-squared error
LMS	long, medium, and short (wavelength)
LMS	least mean squares
LSB	least significant bit
LSI	linear shift-invariant
LUT	look-up table
m	meter
max	maximum
min	minimum
mm	millimeter = 10^{-3} m
(m, n)	indices in the discrete space (image) domain
mod	modulus or modulo
M	radiant exitance
M	magenta component
M_v	luminous exitance

MA	moving average
MB	megabyte
MHz	megahertz = 10^6 Hz
MLP	multilayer perceptron
MMF	marginal median filter
MMSE	minimum mean-squared error
MOS	metal-oxide semiconductor
MP	megapixels
MPEG	Moving Picture Experts Group
MR	magnetic resonance
MRI	magnetic resonance imaging
MRS	magnetic resonance spectroscopy
MS	mean squared
MSE	mean-squared error
<i>MVD</i>	minimum vector dispersion
<i>MVDED</i>	minimum vector dispersion edge detector
<i>MVR</i>	minimum vector range
n	an index
nit	unit of luminance
nm	nanometer = 10^{-9} m
NCD	normalized color difference
NE	normalized error
NMSE	normalized mean-squared error
NTSC	National Television System Committee (of the US)
OD	optical density
OECF	optoelectronic conversion function
$p_f(l)$	normalized histogram or PDF of image f
pixel	picture cell or element
pm	picometer = 10^{-12} m
$p(x)$	probability density function of the random variable x
P	dimension or number of elements in a multivariate pixel
$Pr(x)$	probability of the event x
$P_f(l)$	histogram of image f
PACS	picture archival and communication system
PAL	phase alternate line
PAS	periodic acid Schiff
PASM	periodic acid silver methenamine
PC	personal computer
PCA	principal component analysis
PCS	profile connection space
PDF	probability density function
PDF	portable document format
PET	positron emission tomography
PHz	petahertz = 10^{15} Hz
PMT	photomultiplier tube

PPV	positive predictive value
PSF	point spread function
PSNR	peak signal-to-noise ratio
\mathcal{R}	the set of real numbers
\mathcal{R}^+	the set of nonnegative real numbers
\mathcal{R}^P	set of P -dimensional real numbers
$[r, g, b]$	the [red, green, blue] vector of a pixel; a variable in the RGB space
R, r	red component
RADAR	radio detection and ranging
RAM	random access memory
RBF	radial basis functions
RDM	reduced ordering using distance to the mean
RF	radio frequency
RGB	[red, green, blue] color representation
RIMM	reference input medium metric
RMS	root mean-squared
RMSE	root mean-squared error
ROC	receiver operating characteristics
ROI	region of interest
ROMM	reference output medium metric
ROS	region of support
RYK	red-yellow-black model for dermatological lesions
s	second
sr	steradian (unit of solid angle)
$sRGB$	standard RGB color space
S	saturation component
SD	standard deviation
SECAM	Séquentiel Couleur à Mémoire
SI	Système Internationale de Unités (International System of Units)
SMPTE	Society of Motion Picture and Television Engineers
SNR	signal-to-noise ratio
SONAR	sound navigation and ranging
SPD	spectral power distribution
SPECT	single-photon emission computed tomography
SSIM	structural similarity (index)
STARE	Structured Analysis of the Retina
STIR	short-tau inversion recovery (sequence in MRI)
t	time variable
T	a threshold
T	as a superscript, vector or matrix transposition
Th	threshold
THz	terahertz = 10^{12} Hz

TIFF	tagged image file format
TN	true negative
TNF	true-negative fraction
TP	true positive
TPF	true-positive fraction
Tr	trace of a matrix
Tv	camera exposure time setting
TV	television
T1-W	T1-weighted (MRI)
UCS	uniform color space
UHF	ultrahigh frequency
US	United States (of America)
voxel	volume cell or element
v	volt
V	value component
$V(\lambda)$	spectral luminous efficiency or luminosity function
$V'(\lambda)$	spectral luminous efficiency for scotopic vision
VD	vector dispersion
$VDED$	vector dispersion edge detector
VDF	vector directional filter
VIBGYOR	violet, indigo, blue, green, yellow, orange, red
VMF	vector median filter
VOS	vector order statistics
VR	vector range
w	filter tap weight; weighting function
\mathbf{w}	filter or weight vector
W	watt
\mathbf{x}_i	a sample pixel (vector) of a color image
(x, y)	image coordinates in the continuous space domain
\mathbf{X}	a set of sample pixels (vector) from a color image
XYZ	color representation with the CIE coordinates
\mathbf{y}_i	a sample pixel (vector) of a color image
Y	yellow component
Y	intensity or luminance component
\mathbf{Y}	a set of sample pixels (vector) from a color image
YIQ	[luminance, in-phase, quadrature] color representation
\mathbf{z}_i	a sample pixel (vector) of a color image
\mathbf{Z}	a set of sample pixels (vector) from a color image
\mathcal{Z}	the set of all integers
ZHz	zettahertz = 10^{21} Hz
\emptyset	null set
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
4D	four-dimensional

γ	gamma (slope) of an imaging system or process
δ	Dirac delta (impulse) function
η	noise process
κ	a kernel function
λ	wavelength
μ	the mean of a random variable
μm	micrometer = 10^{-6} m
Π	product
ρ_{RG}	correlation between the R and G components
$\rho(\lambda)$	reflectance of a surface
σ	the standard deviation of a random variable
σ^2	the variance of a random variable
Σ	sum
Φ	radiant flux
Φ_v	luminous flux
ω	solid angle (steradian)
∇	gradient operator
$\cdot, \bullet, \langle, \rangle$	dot product
'	modified or transformed version of a variable
' , ''	first and second derivatives of a variable
''	inch
!	factorial
*	when in-line, convolution
*	as a superscript, complex conjugation
#	number of
—	average or normalized version of the variable
	under the bar
^	estimate of the variable under the symbol
\times	cross product when the related entities are vectors
\forall	for all
\in	belongs to or is in (the set)
{ }	a set
\subset	subset
\supset	superset
\cap	intersection
\cup	union
\setminus	set-theoretic difference between sets, except for
\equiv	equivalent to
	given, conditional upon
\rightarrow	maps to
$\leftarrow, \leftleftarrows$	obtains (updated as)
\Rightarrow	leads to
\Leftrightarrow	transform pair
[]	closed interval, including the limits
()	open interval, not including the limits

$ $	absolute value or magnitude
$ $	determinant of a matrix
$\ \ $	norm of a vector or matrix
$\lceil x \rceil$	ceiling operator; the smallest integer $\geq x$
$\lfloor x \rfloor$	floor operator; the largest integer $\leq x$