# Color Image Processing with Biomedical Applications

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# Color Image Processing with Biomedical Applications

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# *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*

## 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 significant 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 information 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*

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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.

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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 |
| $A$ | 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 |
| $Av$ | camera aperture setting |
| $A_z$ | area under the ROC curve |
| b | bit |
| $B, b$ | blue component |
| B | byte |
| BMP | bitmap |
| cd | candela |
| cm | centimeter |
| $C$ | 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 |
| $CMYK$ | [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-$\alpha$TM | GVDF - double window - $\alpha$-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 |
| $j$ | $\sqrt{-1}$ |
| 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 |
| $MVD$ | minimum vector dispersion |
| $MVDED$ | minimum vector dispersion edge detector |
| $MVR$ | 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 |

| | |
|---|---|
| $\gamma$ | gamma (slope) of an imaging system or process |
| $\delta$ | Dirac delta (impulse) function |
| $\eta$ | noise process |
| $\kappa$ | a kernel function |
| $\lambda$ | wavelength |
| $\mu$ | the mean of a random variable |
| $\mu$m | micrometer = $10^{-6}$ m |
| $\Pi$ | product |
| $\rho_{RG}$ | correlation between the $R$ and $G$ components |
| $\rho(\lambda)$ | reflectance of a surface |
| $\sigma$ | the standard deviation of a random variable |
| $\sigma^2$ | the variance of a random variable |
| $\Sigma$ | sum |
| $\Phi$ | radiant flux |
| $\Phi_v$ | luminous flux |
| $\omega$ | solid angle (steradian) |
| $\nabla$ | 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 |
| $\bar{}$ | average or normalized version of the variable under the bar |
| $\hat{}$ | 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 |
| $\bigcap$ | intersection |
| $\bigcup$ | union |
| $\backslash$ | set-theoretic difference between sets, except for |
| $\equiv$ | equivalent to |
| $\vert$ | given, conditional upon |
| $\rightarrow$ | maps to |
| $\leftarrow$, $\Leftarrow$ | 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 $\leq x$ |