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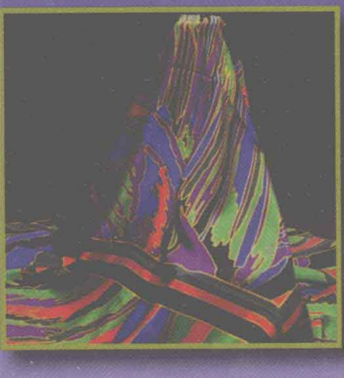
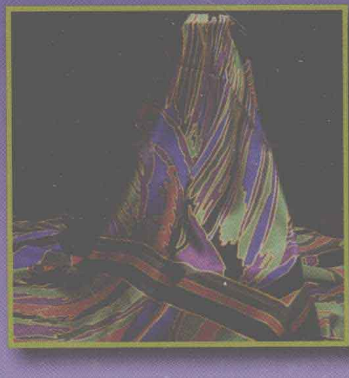
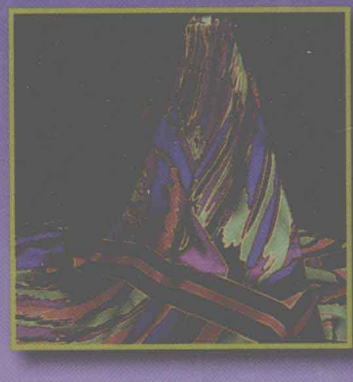
DIGITAL COLOR IMAGE PROCESSING

ANDREAS KOSCHAN
MONGI ABIDI

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Andreas Koschan
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PREFACE

Color information is gaining an ever-greater importance in digital image processing. Nevertheless, the leap to be mastered by the transition from scalar to vector-valued image functions is not yet generally addressed in most textbooks on digital image processing. The main goal of this book is to clarify the significance of vector-valued color image processing and to introduce the reader to new technologies. The present state of the art in several areas of digital color image processing is presented in regard to a systematic division into monochromatic-based and newer vector-valued techniques. The potentials and the requirements in vector-valued color image processing are shown.

This text is organized in regard to advanced techniques for three-dimensional scene analysis in color images. It is structured into four parts. The first four chapters illustrate the fundamentals and requirements for color image processing. In the next four chapters, techniques for preprocessing color images are discussed. In subsequent chapters, the areas of three-dimensional scene analysis using color information and of color-based tracking with PTZ cameras are viewed. In the final two chapters, the new area of multispectral imaging and a case study on applications of color image processing are presented. For selected areas of digital color image processing such as edge detection, color segmentation, interreflection analysis, and stereo analysis, techniques are discussed in detail in order to clarify the respective complexity of the algorithms.

Chapter 12 on multispectral imaging addresses an emerging area in the field of image processing that is not yet covered in detail in textbooks. It is further augmented by a subsection on face recognition using multispectral imaging. The three case studies presented in the final three chapters summarize the results and experience gained by the authors in luggage inspection, video surveillance, and biometrics in research projects that have been funded by the National Safe Sky Alliance, the National Science Foundation, and the U.S. Department of Energy over multiple years. Several algorithms have been tested and evaluated under real conditions in a local airport.

This text is written at a level that can be easily understood by first and second year graduate students in Electrical and Computer Engineering or Computer Science as well as by researchers with basic knowledge in image processing who want to extend their understanding in the area of color image processing. The book instructs the reader beyond the standard of image processing and is a complement to existing textbooks in its field. Furthermore, the three application chapters on assisting screeners in luggage inspection in airports, video surveillance of high security facilities, and multispectral face recognition for authentication address recent problems of high importance to current safety and security issues. These chapters significantly augment the book's content.

This material is based on lectures and courses that have been taught by the authors at (1) the University of Tennessee, Department of Electrical and Computer Engineering, Knoxville, Tennessee and (2) the Technical University of Berlin, Department of Computer Science, Berlin, Germany between 1991 and 2007. Currently, Andreas Koschan is a Research Associate Professor, and Mongi Abidi is a Professor and Associate Department Head. Both are with the Department of Electrical and Computer Engineering, University of Tennessee. The techniques and algorithms have been tested by Masters students and Ph.D. students in Berlin, Germany and Knoxville, Tennessee and the figures illustrate the obtained results.

Andreas Koschan
Mongi Abidi

Knoxville, April 2008

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1 INTRODUCTION

In our daily life, our vision and actions are influenced by an abundance of geometry and color information. When crossing a street, we identify a technical apparatus by its geometry as a traffic light. However, only by analyzing color information do we subsequently decide whether we are to continue, if the light is green, or stop, if the light is red. A camera-assisted driving information system should be able to evaluate similar information and either pass the information on to the driver of a vehicle or directly influence the behavior of the vehicle. The latter is of importance, for example, for the guidance of an autonomous vehicle on a public road. Something similar to this applies to traffic signs, which can be classified as prohibitive, regulatory, or informative signs based on color and geometry.

The assessment of color information also plays an important role in our individual object identification. We usually do not search in a bookcase for a book known to us solely by its title. We try to remember the color of the cover (e.g., blue) and then search among all of the books with a blue cover for the one with the correct title. The same applies to recognizing an automobile in a parking lot. In general, we do not search for model X of company Y, but rather we look for a red car, for example. Only when we see a red vehicle do we decide, according to its geometry, whether that vehicle is the one for which we are looking. The search strategy is driven by a hierarchical combination of color and form. Such hierarchical strategies are also implemented in automatic object recognition systems.

While in the past color image processing was limited essentially to satellite imagery, it has gained importance in recent years on account of new possibilities. This is due, among other things, to the high information level that color images contain in relation to gray-level images. This information allows color image processing to succeed in areas where "classical gray-level image processing" currently dominates. The decision confidence level for various techniques can be greatly improved by the additional classification markers color can provide. The applied procedures are thereby made simpler, more robust, or even applicable in the first place.

The fundamental difference between color images and gray-level images is that in a color space, a color vector (which generally consists of three components) is assigned to a pixel of a color image, while a scalar gray value is assigned to a pixel of a gray-level image. Thus, in color image processing, vector-valued image functions are treated instead of the scalar image functions used in gray-level image processing. Color image processing techniques can be subdivided on the basis of their principal procedures into two classes:

1. *Monochromatic-based techniques* first treat information from the individual color channels or color vector components separately and then combine the individual results.
2. *Vector-valued techniques* treat the color information as color vectors in a vector space provided with a vector norm.

The techniques from the first class can also be designated as *rental schemes* [Zhe et al. 93], since they frequently borrow methods from gray-level image processing and implement them separately on each color component. Thereby the dependencies between the individual color components (or vector components) are usually ignored. The monochromatic-based techniques make it clear that the transition from scalar to vector-valued functions, which can be mastered with color image analysis, is not yet generally known.

Color attributes such as hue or saturation are also used in monochromatic-based techniques. However, the analysis or processing of color information occurs separately for each component, for example, only the hue component or only the saturation component is treated (as in a gray-level image). In contrast, vector-valued techniques treat the color information in its entirety and not separately for each vector component.

While monochromatic-based techniques were predominantly regarded in the early days of color image processing, in recent times vector-valued techniques are being more frequently discussed. The difference between the two techniques serves as a systematization of the procedure in order to point out the respective conditions of developments from monochromatic-based techniques to vector-valued techniques. Better or more robust results are often attained with monochromatic-based techniques for color image processing than with techniques for gray-level processing. The monochromatic-based techniques, however, do not define a new way of image processing but rather demonstrate only transference of known techniques to color images. In contrast, the analysis and processing of vector-valued image information establishes a new step in image processing that simultaneously presents a challenge and a new possibility for analyzing image information. One difficulty with vector-valued techniques has been that the signal-theoretical basics for vector-valued color signals have not yet been presented.

In the past, the application of techniques for color image processing was restricted by additional factors. One factor was limited data memory and the "slow" processors: a three-channel color image of 1024×1024 pixels occupies, for example, 3 MB. For a geometric stereo analysis technique at least two images (6 MB) are needed, and for a photometric stereo analysis technique generally three images (9 MB) are necessary. These must be treated at a processing speed appropriate for the requirements of the application. Using more modern computers, the limitations on memory space and processing speed are not totally eliminated; however, the importance of this problem continues to decrease. Thus, the processor requirements for implementing digital color image processing today are satisfied.

Another factor that limited the applicability of color image processing in the past was color camera technology. In recent years, the availability of robust and low-cost color CCD cameras has made the acquisition of high-quality color images feasible under many varying acquisition conditions. However, in spite of enormous advances in camera technology there is a lack, as already mentioned, of extensive signal-theory investigations of vector-valued color signals. Here an urgent need for basic research exists.

In areas such as photogrammetry and remote sensing, images with more than three "color" channels are frequently analyzed. Newer areas of application analyze color images that represent three-channel spectral transmissions of visible light. Knowledge of the processing occurring in the human eye and brain of the signals that come from the three sensitive (with regard to different wavelengths) receptors in the retina can be used for the development and evaluation of techniques for color image processing.

The three different receptor types in the human retina are also the reason that commercial CCD-color cameras likewise implement measurements in three different wavelength areas of visible light. These cameras deliver a three-channel signal and the three channels are represented separately on a monitor or screen for the observer. Furthermore, the color attributes hue and saturation are defined only within the spectral area of visible light. In this book, techniques for the analysis of three-channel color images are presented whose spectral transmissions lie within the visible area of light.

As an example, correspondence analysis in stereo images shows that red pixels do not correspond with blue pixels, even when their intensity values are similar. The segmentation of color images based on classification of color values is generally substantially more differentiated than segmentation based exclusively on intensity values.

The evaluation of color information in the image creates additional new possibilities for solving problems in computer vision. Many image processing techniques still assume that only matte (Lambertian) surfaces in the scene are analyzed. This assumption does not hold for real scenes with several reflecting (non-Lambertian) surfaces. However, this limitation can be overcome under certain conditions by highlight elimination in color images. Furthermore, physically determined phenomena, such as shadows or interreflections, can be analyzed more easily in color images than in gray-level images. For this, predominantly vector-valued image processing techniques are used that employ reflection models derived from physical optics for modeling image functions. These techniques are denoted as *physics-based vision techniques*. The invariant extraction of color information in relation to varying lighting conditions and description of image characteristics represents another problem in computer vision. Here promising vector-valued techniques for so-called color constancy can make an important contribution.

1.1 GOAL AND CONTENT OF THIS BOOK

Color information is gaining an ever-greater meaning in digital image processing. Nevertheless, the leap to be mastered by the transition from scalar to vector-valued image functions is not yet generally known. One goal of this book is to clarify the significance of vector-valued color image processing. The present state of the art in several areas of digital color image processing is represented in regard to a systematic division into monochromatic-based and newer vector-valued techniques. The more recent potentials and the requirements in vector-valued color image processing are shown. Here references will be made to the fundamentals lacking in many areas of digital color image processing.

While a terminology for gray-level image processing has been established for the most part, corresponding terms do not yet exist for vector-valued color images. Fundamental ideas in color image processing are specified within the context of this work. Monochromatic-based techniques still dominate in many practical applications of digital color image processing, such as in medicine, agriculture, and forestry, as well as industrial manufacturing. A few examples of monochromatic-based and vector-valued techniques of color image analysis in practical usage are presented in Section 1.3.

This book is organized in regard to advanced techniques for three-dimensional scene analysis in color images. In the first four chapters, the fundamentals and requirements for color image processing are illustrated. In the next four chapters, techniques for preprocessing color images are discussed. In subsequent chapters, the area of three-dimensional scene analysis using color information is viewed. In the final three chapters, case studies on application of color image processing are presented. For some selected areas of digital color image processing, such as edge detection, color segmentation, interreflection analysis, and stereo analysis, techniques are discussed in detail in order to clarify the respective complexities of the solution for the problem.

Knowledge of the human visual system is frequently utilized for designing procedures in digital image processing (see, e.g., [Mar82], [Ove92], and [Wat88]). This also applies for digital color image processing. In Chapter 2, an introduction to human color vision is presented whereby color blindness of a section of the population and the phenomenon of color constancy are given special attention. For the representation and treatment of color images, a suitable form of representation for the data must be selected. Different color spaces used in color image processing are presented in Chapter 3. Chapter 4 contains the technical requirements for color image processing (color camera, color filter, standard illuminants, color charts, etc.) as well as techniques of photometric and colorimetric calibration that are necessary for the further treatment of color images.

Techniques for noise suppression and contrast enhancement in color images are the subject of Chapter 5. An important task in preprocessing color images is the extraction of edges in the image. Various procedures for color edge detection are discussed in Chapter 6. A comparison of the results of one monochromatic-based and two vector-valued color edge operators are also given. An overview of different techniques for color image segmentation is presented in Chapter 7. There, a robust technique for the segmentation of color images based on the watershed transformation is presented.

An interesting challenge and at the same time a new possibility of color image processing is the analysis of physical phenomena, such as the analysis of highlights and interreflections. In Chapter 8, an overview of the techniques for highlight analysis and a new method for minimizing interreflections in real color images is presented. In addition, different procedures for achieving color constancy are discussed.

A detailed description of the use of color information for static stereo analysis is given in Chapter 9. There, investigations for edge-based as well as area-based color stereo techniques can be found. Also shown is how stereo matching results can be significantly improved by projecting color-coded light patterns onto the object. The inclusion of color information into dynamic and photometric stereo analysis is the subject of Chapter 10.

Chapter 11 addresses case studies of color use in an automated video tracking and location system that is under development at the University of Tennessee's Imaging, Robotics and Intelligent Systems (IRIS) Laboratory in Knoxville, Tennessee. Chapter 12 discusses the acquisition and analysis of multispectral images. Their use in face recognition is outlined as an example of multispectral image processing. The application of color coding in x-ray imaging is the subject of Chapter 13.

1.2 TERMINOLOGY IN COLOR IMAGE PROCESSING

There is agreement concerning the terminology used in the processing of gray-level images [HarSha91]. In contrast, a corresponding transference onto vector-valued color images does not yet exist. For example, it has not yet been established what a color edge is, what the derivative of a color image is, or what should be understood as the contrast of a color image. In color image processing, the terms are used very differently and also somewhat imprecisely. In the following section, terminology used in color image processing is established.