Acquisition and Reproduction of Color Images:

Colorimetric and Multispectral Approaches

by

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Preface

In the last two decades we have seen the field of digital color imaging emerging from specialized scientific applications, into being a part of the daily lives of most people in industrialized countries. Broadcast television, computers, newspapers and magazines, are just a few examples of technologies relying on digital color imaging.

The increased use of color has brought with it new challenges and problems. Digital color imaging is a research field with great prospects, since many problems are still unsolved.

One typical case that illustrates the problems that needs to be solved is that of an e-commerce business. Prospective customers use the World Wide Web to evaluate their products, typically by visualizing them on the computer monitor or by printing the product images on a desktop printer. If the customer decides to buy, and the color of the delivered product is not what she expected, she might decide to return it.

The book you're holding in your hands (or maybe you're reading it on your computer or eBook device) is the second edition of my Ph.D. dissertation. It is my hope that this book may be of service to the academic and industrial color imaging community, in many ways:

- As support for learning and teaching.
- Through the advances in the state-of-the-art represented by the proposed methods for the acquisition and reproduction of high quality digital color images.
- By advocating the multispectral approach to color imaging, that is to

use more than three color channels, in order to overcome the problems of metamerism.

- By giving ideas for further research concerning the technology, science, and art of color imaging.

Finally, I have to apologize that there's no color in the printed edition of this book. I find it amazing that color printing of a book like this is still not found to be cost-effective, even using an on-demand printing model. The only consolation in this is that I don't expect to be out of work for many many years to come!

Redmond, Washington, USA, June 2001

Abstract

The goal of the work reported in this dissertation is to develop methods for the acquisition and reproduction of high quality digital color images. To reach this goal it is necessary to understand and control the way in which the different devices involved in the entire color imaging chain treat colors. Therefore we addressed the problem of *colorimetric characterization* of scanners and printers, providing efficient and colorimetrically accurate means of conversion between a device-independent color space such as the CIELAB space, and the device-dependent color spaces of a scanner and a printer.

First, we propose a new method for the colorimetric characterization of color scanners. It consists of applying a non-linear correction to the scanner RGB values followed by a 3rd order 3D polynomial regression function directly to CIELAB space. This method gives very good results in terms of residual color differences. The method has been successfully applied to several color image acquisition devices, including digital cameras. Together with other proposed algorithms for image quality enhancements it has allowed us to obtain very high quality digital color images of fine art paintings.

An original method for the colorimetric characterization of a printer is then proposed. The method is based on a computational geometry approach. It uses a 3D triangulation technique to build a tetrahedral partition of the printer color gamut volume and it generates a surrounding structure enclosing the definition domain. The characterization provides the inverse

transformation from the device-independent color space CIELAB to the device-dependent color space CMY, taking into account both colorimetric properties of the printer, and color gamut mapping.

To further improve the color precision and color fidelity we have performed another study concerning the acquisition of multispectral images using a monochrome digital camera together with a set of $K > 3$ carefully selected color filters. Several important issues are addressed in this study. A first step is to perform a spectral characterization of the image acquisition system to establish the spectral model. The choice of color chart for this characterization is found to be very important, and a new method for the design of an optimized color chart is proposed. Several methods for an optimized selection of color filters are then proposed, based on the spectral properties of the camera, the illuminant, and a set of color patches representative for the given application. To convert the camera output signals to device-independent data, several approaches are proposed and tested. One consists of applying regression methods to convert to a color space such as CIEXYZ or CIELAB. Another method is based on the spectral model of the acquisition system. By inverting the model, we can estimate the spectral reflectance of each pixel of the imaged surface. Finally we present an application where the acquired multispectral images are used to predict changes in color due to changes in the viewing illuminant. This method of illuminant simulation is found to be very accurate, and it works well on a wide range of illuminants having very different spectral properties. The proposed methods are evaluated by their theoretical properties, by simulations, and by experiments with a multispectral image acquisition system assembled using a CCD camera and a tunable filter in which the spectral transmittance can be controlled electronically.

Key words

Color imaging, colorimetry, colorimetric characterization, multispectral imaging, spectral characterization, filter selection, spectral reconstruction.

Acknowledgements

The work described in this document has been carried out at the Signal and Image Processing Department at the Ecole Nationale Supérieure des

Télécommunications (ENST) in Paris, France. This endeavor would not have been completed without the support and help of many people. You all deserve thanks! Running the risk of forgetting someone important, I will mention some of you in particular.

First of all, I would like to thank my advisors Francis Schmitt and Hans Brettel. Thanks for showing me the way into the wonderful world of color, and for guiding and encouraging me throughout my tenure at the ENST. A big thank you goes then to all my colleagues and friends at the ENST. To the former and present Ph.D. students with whom I have shared moments of work and pleasure: Anne, Bert, Dimitri, Florence, Geneviève, Jean-Pierre, Jorge, Lars, Maria-Elena, Mehdi, Raouf, Selim, Sophie, Sudha, Wirawan, Yann, and many others. You have meant a great deal to me, and I sincerely hope to be able to stay in touch with you! To those of you who have worked with me on colorful projects: Bahman, Brice, Frédéric, Henri, Ingeborg, Jean-Pierre. To our relations in the industry, for showing me that my research could be able to solve some real problems out there.

I thank the members of the jury, Jean-Marc Chassery, Jean-François Le Nest, Khadi Bouatouch, and Roger D. Hersch, for your fruitful questions, comments and suggestions, and for honoring me by your presence at my defence. Furthermore, I would like to thank the organizing committees of the international conferences I have attended, for accepting the papers I submitted. Not only has this allowed me to present my work, and learn about the work of other researchers in the field of color imaging, it has given me the opportunity to meet and discuss with several inspiring individuals. I have seen that the world of color is a small one, after all.

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Finally, I cannot imagine doing anything without you, Kristine. Thank you for giving me a reason to move to Paris, thank you for putting up with me through times of hard pressure, thank you for my two lovely children, Pauline and Samuel, and most of all, thank you for being you.

Kirkland, Washington, USA, November 1999

About the author

Jon Y. Hardeberg received his sivilingeniør (M.Sc.) degree in signal processing from the Norwegian Institute of Technology (Trondheim, Norway) in 1995. He received his Ph.D. from the Ecole Nationale Supérieure des Télécommunications (Paris, France) in February 1999. His Ph.D. research concerned color image acquisition and reproduction, with applications in facsimile, fine-art paintings, and multi-spectral imaging. He is currently employed with Conexant Systems, Inc., where he designs, implements, and evaluates color imaging system solutions for multifunction peripherals and other imaging devices and systems. His professional memberships include IS&T, SPIE, and ISCC.

About this book

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Changes from the first edition include layout, adding of a List of Tables and a List of Figures, correction of miscellaneous typographical errors, translation to American English (you know, *color* instead of *colour*, etc.), modifications to Figures 2.7 on page 21 and 3.11 on page 68, modifications to the numbering of Figures and Equations, and this preface.

Further information

More information about the described research can be found at the following locations:

- At http://color.hardeberg.com/
- By contacting the author by E-mail: jon.hardeberg@conexant.com, jon@hardeberg.com
- By contacting Prof. Francis Schmitt or Dr. Hans Brettel by E-mail: schmitt@tsi.enst.fr, brettel@tsi.enst.fr, or through the following address: Ecole Nationale Supérieure des Télécommunications, Département TSI, 46, rue Barrault, F-75634 Paris Cedex 13, France

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Chapter 1

Introduction

1.1 Motivation

The use of color in imaging continues to grow at an ever-increasing pace. Every day, most people in the industrialized parts of the world are users of color images that come from a wide range of imaging devices; for example color photographs, magazines, and television at home, computers with color displays, and color printers in the office.

As long as the colors are found to be approximately as expected, people are generally happy with their images. However, with the increased use of color images, people's quality requirements also have increased considerably. Just a few years ago, a computer graphics system capable of producing 256 different colors was more than enough for most users, while today, most computers that are sold have *true color* capabilities, being able to produce 16.7 million[1] colors.

Furthermore, several professions have particular needs for high-quality color images. Artists are very concerned about colors in their works, and so are the art historians and curators studying their works. The printing, graphic arts, and photography industries have been concerned about color imaging for a long time. Most of the color imaging standards and equip-

[1] Note that this number represents only the number of different colors that can be specified to the monitor ($2^8 \cdot 2^8 \cdot 2^8 = 16777216$); the actual number of distinguishable resulting colors is much lower, approximately on the order of 1 million (Pointer and Attridge, 1998).

ment used today have their roots in these industries. But the past twenty years have seen the field of digital color imaging emerging from specialized scientific applications into the mainstream of computing. Color is also extremely important in several other fields, such as the textile and clothing industry, automotive industry, decoration and architecture.

Digital color imaging systems process electronic information from various sources: images may come from the Internet, a remote sensing device, a local scanner, etc. After processing, a document is usually compressed and transmitted to several places via a computer network for viewing, editing or printing. To achieve color consistency throughout such a widely distributed system, it is necessary to understand and control the way in which the different devices involved in the entire color imaging chain treat colors. Each scanner, monitor, printer, or other color imaging device, senses or displays color in a different, device-dependent, way. One approach to exchanging images between these devices is to calibrate each color image acquisition and reproduction device to a device-independent color space. The exchange of images can then be done in this color space, which should conform to international standards.

However, colors represent an important but nevertheless limited aspect of the objects that surround us. They correspond to the human perception of its surface under given light conditions. For the needs of, for example, an art curator wanting to control any changes or ageing of the materials in a fine arts painting, or a publisher wanting extra high-fidelity color reproduction, it becomes necessary to provide a more complete spectral analysis of the objects. This requires technology and devices capable of acquiring multispectral images. A multispectral image may also be used to reproduce an image of the object, as it would have appeared under a given illuminant.

In this research, we have investigated several of the aspects mentioned above. We have developed novel algorithms for the colorimetric characterization of scanners and printers providing efficient and colorimetrically accurate means of conversion between a device-independent color space such as CIELAB, and the device-dependent color spaces of a scanner and a printer. Furthermore, we have developed algorithms for multispectral image capture using a CCD camera with carefully selected optical filters. The developed algorithms have been used for several applications, such as fine-arts archiving and color facsimile.

1.2 Dissertation outline

This thesis is organized as follows. Chapter 2 provides an introduction to light, objects, human color vision, and the interaction between them, gives an introduction to important elements of colorimetry, and finally presents the subject of color imaging.

In Chapter 3, a methodology for the colorimetric characterization of color scanners is proposed. It consists of applying a non-linear correction to the scanner RGB values followed by a 3rd order 3D polynomial regression function directly to CIELAB space. This method gives very good results in terms of residual color differences. This is partly due to the fact that the RMS error that is minimized in the regression corresponds to ΔE_{ab}, which is well correlated to visual color differences. The method has been successfully applied to several color image acquisition devices.

In Chapter 4, various techniques for the digital acquisition and processing of high quality and high definition color images using a CCD camera are developed. The techniques have been applied to fine arts paintings on several occasions, *e.g.* for the making of a CDROM on the French painter Jean-Baptiste Camille Corot (1796-1876).

A novel method for the colorimetric characterization of a printer is proposed in Chapter 5. The method is based on a computational geometry approach. It uses a 3D triangulation technique to build a tetrahedral partition of the printer color gamut volume and it generates a surrounding structure enclosing the definition domain. The characterization provides the inverse transformation from the device-independent color space CIELAB to the device-dependent color space CMY, taking into account both colorimetric properties of the printer, and color gamut mapping.

We construct two 3D structures which provide us with a partition of the space into two sets of non-intersecting tetrahedra, an inner structure covering the printer gamut (*i.e.* the full set of the printable colors), and a surrounding structure, the union of these two structures covering the entire definition domain of the CIELAB space. These 3D structures allow us to easily determine if a CIELAB point is inside or outside the printer color gamut, to apply a gamut mapping technique when necessary, and then to compute by irregular tetrahedral interpolation the corresponding CMY values. We establish thus an empirical inverse printer model. This algorithm has been protected by a patent, and is now transferred to industry and used in commercial color management software.

In Chapter 6, we describe a system for the acquisition of multispectral