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Multispectral Color System with an Encoding Format Compatible to the Conventional Tristimulus Model

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Abstract

Based on the discussion of the disadvantages of today's color analysis in an open system architecture, a fundamentally improved reproduction system is proposed. This includes multispectral sampling and multispectral color information transport via the communication net using an encoded multispectral format compatible to conventional tristimulus color values.

Introduction

A main problem of electronic color reproduction is the color equalization between the reproduced and the original colors of a document. Essential errors are caused by the commonly used three-channel color scanning, color transport based on only three color values, different scanning and viewing illuminants and by the static reference to a standard observer only. Acceptable results are only achieved under restricted conditions in a closed system architecture, where the equipments for color analysis and reproduction are well known and mutual color correction is possible.

In this presentation a multispectral color system is proposed, which solves the essential problems of color reproduction and is also well suited for open system architectures. Above all, the proposed system shows a possible document-independent and device-independent color analysis and an effective multispectral data format compatible to a conventional three component data format.

Basic problems of today's electronic color systems with three-channel color analysis are the following:

- Spectral characteristics of the light source of a scanner cannot be separated from the color analysis so that the results are device-dependent.
- Systematic errors result from deviations of the three-channel filters from theoretical spectral matching curves. Error reduction by subsequent electronic signal processing is document-dependent.
- Practical sensitivity curves deviate more or less from each other and from one scanner to another producing unknown errors. Even if the sensitivity curves are correct, the analysis is only true for the standard observer.
- Color interfaces using non-standard color description often lead to additional errors in today's systems. But even interfaces using standard tristimulus values X, Y, Z or CIELAB are illuminant-dependent.

The new system is proposed to solve the essential problems by introducing a multispectral technology by which the complete spectral information of documents is scanned. The complete multispectral information is then transported via communication net to the receiver, where optimal reproduction from spectral information with a common printer or display becomes possible. In the future, it may also become possible to reconstruct the remission curve of the document by multispectral printing. The reproduction would then be correct for all observers under all illuminants.

Proposed Color Reproduction System

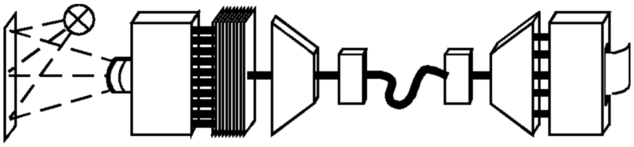

Figure 1. Proposed color reproduction system with multispectral measurement, multispectral encoding and decoding. With the spectral information of each pixel the receiver can optimize the image reproduction.

With the structure of the reproduction system in Figure 1, device-independence, document-independence and observer-independence are achieved, if the measuring system samples the spectral reflection of each pixel in a document. Keusen[1] has shown, that with 12 interference-filters used for sampling, all the sampled and reconstructed reflectance curves of an investigated large data set of spectral curves show reconstruction errors lower than the threshold $\Delta E_{ab} = 1$ (CIE 1976). This was possible by using a special correction method called Modified Discrete Sinus Transformation (MDST), which reduces errors due to finite filter widths. It is not possible to reduce the number of filters further as long as the simple spectral geometry of interference-filters is applied. With this sampling method it is possible to normalize these curves to the illuminant of equal energy white to make the input information completely independent from any special illuminant of an image source.

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The high amount of source data for multispectral color representation can be reduced remarkably by introducing data encoding. Suitable encoding schemes for spectral reflectance curves using the information of the data set have already been published by several authors [e.g. Cohen[2],Vrhel et. al.[3]. These concepts, however, do not consider any aspects of compatibility to existing color description in electronic systems. Introducing a new improved system for color transport, however, requires compatibility with the existing system to allow both conventional color reproduction and improved reproduction with higher effort.

In this presentation, a concept is proposed which provides efficient encoding of spectral reflectance curves on one hand and direct compatibility to tristimulus color values on the other.

The input to the multispectral encoder are the spectral curves of the pixels of images. The encoded result is a set of coefficients. The first three coefficients represent tristimulus values of a standard color space referred to a standard illuminant. For example, the RGB or CIE XYZ space referred to the illuminant D65 could be chosen to allow easy reproduction on standard displays from the first three components. The other coefficients b_i together with a linear transformation of the first three coefficients are called multispectral values. They represent the coefficients of the approximation of the spectral input curve by a set of orthonormal basis functions. The original spectral curve $\beta(\lambda)$ is approximated by the superposition of P basisspectra $p_i(\lambda)$ weighted by the coefficients b_i:

$$\beta(\lambda) \approx \sum_{i=1}^{P} b_i \cdot p_i(\lambda) = \tilde{\beta}(\lambda)$$

$$\text{with} \quad \int_{400nm}^{700nm} p_i(\lambda) \cdot p_k(\lambda)\, d\lambda = \begin{cases} 0, & k \neq i \\ 1, & k = i \end{cases} \qquad (1)$$

In Figure 2, an example is given for possible data encoding assuming the CIE XYZ-values are referred to D65 for the compatible multispectral data format.

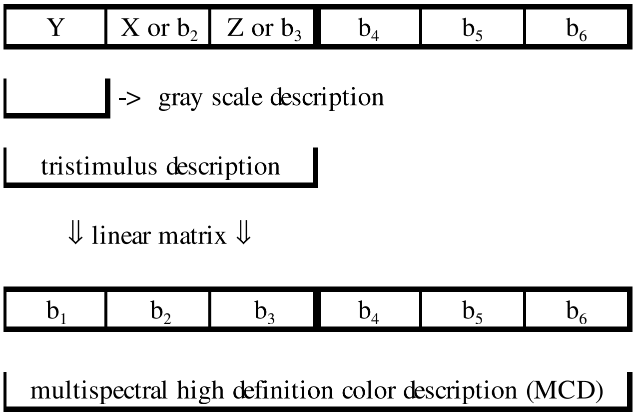

Figure 2. The proposed multispectral data format is compatible to a conventional tristimulus description and performs device- and document-independent high definition color description by encoding the remission curve of each pixel of a document

Because the first three multispectral color values are a linear combination of the three conventional color values, it is possible to use the first three values alone for conventional reproduction in a printer or monitor. Improved reproduction uses all the multispectral color values.

Linear Modeling of Reflectance Spectra

This concept is based on the color object matching function (so called by Worthey[4]) as well as the human visual space first published by Cohen and Kappauf[5]. As a suitable description the typical vector space notation of Trussell 6 is chosen. With this notation, the first three orthonormal basisspectra $\mathbf{P}_v = [\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3]$, that correspond to the first three multispectral values of the data format, are given through orthonormalization of the color object matching functions $\mathbf{A}^* = \mathbf{D}_{D65}\,\mathbf{A}$, where $\mathbf{A}$ is the color matching Matrix and $\mathbf{D}_{D65}$ the diagonal matrix of the illuminant D65, which has been taken as an example. The other coefficients represent orthonormal basisspectra that are calculated for example with the Karhunen-Loéve-Transformation (KLT) based on the given three basisspectra and on the data set $\mathbf{F}$ for encoding. Therefore a modified data set $\mathbf{F}_s$ spanning a vectorsubspace is calculated, which is orthogonal to $\mathbf{P}_v$:

$$\mathbf{F}_s = \mathbf{F} - \mathbf{P}_v\, \mathbf{P}_v^{T}\, \mathbf{F} \qquad (2)$$

With the mean of the modified data set $\bar{\mathbf{f}}_s$ the other orthonormal basisspectra $\mathbf{p}4, \mathbf{p}5, .., \mathbf{p}p$ are the eigenvectors of the covariance matrix $\mathbf{K}fs$:

$$\mathbf{K}_{fs}\ \mathbf{p}_j = \mu_j \cdot \mathbf{p}_j \ \text{with}\ \mathbf{K}_{fs} = \left[\mathbf{F}_s - \bar{\mathbf{f}}_s\right]\left[\mathbf{F}_s - \bar{\mathbf{f}}_s\right]^{T}$$
$$\text{and } j = 4, \ldots, N; \quad \mu_4 \geq \ldots \geq \mu_P \geq \ldots \geq \mu_N \qquad (3)$$

Other optimizing methods are possible as well (e. g. Praefcke and Keusen[7]).

Results

In comparison to an encoding method based on a simple Karhunen-Loéve-Transformation (Table I), Table II shows some extracts of investigations with the proposed multispectral data format. To demonstrate the accuracy, 354 remission curves measured by Vrhel, Gershon and Iwan[3] have been encoded into the compatible format proposed in this paper, reconstructed and transformed back into color values for a number of different illuminants and the resulting errors have been calculated.

Although the square errors are considerably greater than in Table I, the results show that an improved approximation is achieved even if the multispectral data format is made compatible to a conventional three color value format as proposed in this paper. With only 7 components the color difference between all decoded spectra and the original are under the acceptable tolerance[8,9] of $\Delta E_{ab} = 3$ for natural illuminants. For a wider range of illuminants including illuminant F2, up to 10 components must be used. Similar results are achieved with a corresponding multispectral encoding format using D50.

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Table I. CIE 1976 ΔE_{ab} and square errors for the entire data set. The used basis spectra system was calculated with the Karhunen-Loéve-Transformation.

Table II. CIE 1976 ΔE_{ab} and errors for the entire data s used orthonormal basis system was calculated wi proposed method in presentation.

illuminant	number of basis spectra	average ΔE_{ab}	percentage of spectra with $\Delta E_{ab} > 3$	percentage of spectra with $\Delta E_{ab} > 1$	average square error (*10^3)	average ΔE_{ab}	percentage of spectra with $\Delta E_{ab} > 3$	percentage of spectra with $\Delta E_{ab} > 1$
D65	7	0,53	0,8%	14,4%	3,08	0,00	0,0%	0,0%
	6	1,33	9,0%	34,7%	5,15	0,00	0,0%	0,0%
	5	1,52	11,0%	52,3%	8,23	0,00	0,0%	0,0%
	4	1,87	17,2%	60,5%	14,56	0,00	0,0%	0,0%
	3	8,16	73,7%	94,6%	28,07	0,00	0,0%	0,0%
C	7	0,57	1,4%	16,1%	3,23	0,13	0,0%	0,3%
	6	1,41	9,3%	36,2%	5,27	0,14	0,0%	0,6%
	5	1,46	10,5%	51,1%	8,18	0,21	0,0%	0,3%
	4	1,85	17,2%	60,5%	14,92	0,23	0,0%	0,3%
	3	7,93	72,6%	93,8%	28,53	0,95	4,5%	30,5%
D50	7	0,54	0,8%	14,1%	3,11	0,11	0,0%	0,0%
	6	1,30	9,3%	35,6%	4,83	0,21	0,6%	3,7%
	5	1,54	10,7%	53,1%	7,15	0,50	0,3%	12,7%
	4	1,95	17,8%	65,5%	13,12	0,64	0,6%	16,4%
	3	7,43	70,6%	94,4%	26,36	2,91	26,0%	72,3%
E	7	0,53	0,8%	13,8%	3,57	0,14	0,0%	0,0%
	6	1,34	8,8%	36,4%	5,94	0,16	0,0%	4,2%
	5	1,35	9,6%	46,6%	9,41	0,26	0,0%	5,1%
	4	1,91	18,1%	59,9%	16,56	0,38	8,8%	27,7%
	3	7,66	71,8%	93,5%	31,20	3,04	30,2%	74,0%
A	7	0,56	0,3%	13,8%	6,11	0,31	0,0%	4,8%
	6	1,18	8,2%	37,6%	8,71	0,57	2,5%	13,8%
	5	1,40	7,9%	50,6%	12,20	1,49	13,0%	52,3%
	4	2,21	19,5%	69,2%	23,09	2,32	23,7%	67,8%
	3	5,18	53,1%	88,1%	43,39	10,53	78,8%	96,0%
F2	10	0,31	0,0%	5,1%	0,54	0,26	0,0%	3,4%
	9	0,35	0,0%	5,9%	0,92	0,79	3,1%	27,4%
	8	0,91	5,6%	29,9%	1,46	0,77	1,7%	26,0%
	7	0,97	7,3%	29,1%	2,10	0,87	3,1%	28,8%
	6	1,99	15,3%	55,9%	3,49	1,35	11,3%	43,2%
	5	1,72	14,7%	56,8%	4,89	1,54	13,6%	56,5%
	4	2,55	27,1%	68,4%	8,52	2,87	31,6%	83,3%
	3	6,97	65,8%	92,9%	20,31	8,40	65,0%	96,6%

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