

Spectrum Recovery from Colorimetric Data for Color Reproductions

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ABSTRACT

Colorimetric data can be readily computed from measured spectral data, however, as illustrated by metameric pairs, the mapping from spectral data to colorimetric values is many-to-one and therefore typically not invertible. In this paper, we investigate inversions of the spectrum-to-colorimetry mapping when the input is constrained to a single color reproduction medium. Under this constraint, accurate recovery of spectral data from colorimetric data is demonstrated for a number of different color reproduction processes. Applications of the spectrum reconstruction process are discussed and demonstrated through examples.

Keywords: spectral imaging, spectrum estimation, spectrum recovery, multi-spectral imaging.

1. INTRODUCTION

Human color vision is trichromatic. Under fixed viewing conditions, a color can be described by three numbers. The CIE system of colorimetry^{1,2} provides a mechanism for the standardized measurement and description of color. Given the spectral reflectance of an object and the spectral radiance of the illuminant it is viewed under, CIE colorimetry allows the color of the object to be specified as a set of *tristimulus* values. The tristimulus values can then be transformed to alternate three-dimensional color descriptions.

The three-dimensional nature of color implies that the human visual system and colorimetry systems do not resolve all differences in spectral reflectances of objects. This limitation of colorimetry is manifested in the occurrence of metameric object pairs that match under one viewing illuminant and differ under another viewing illuminant. It is commonly accepted that the transformation from spectral reflectance to colorimetry is many-to-one and therefore not invertible. Thus, while spectral reflectance data can be transformed into a three-dimensional colorimetric representation, colorimetric data for objects cannot be unambiguously transformed back to the corresponding object spectral reflectance.

While the premise that the mapping from spectral reflectance to colorimetry is many-to-one is true in general, it does not necessarily hold if the domain of spectral reflectances is restricted. Such restrictions arise naturally in image capture applications where the input is itself a reproduction. Under these situations, the mapping from spectral reflectance to colorimetry is often one-to-one and can therefore be inverted to obtain the spectral reflectance from measured colorimetry. This paper investigates several such situations that are of interest in the capture of color hardcopy images.

2. THEORETICAL BASIS FOR SPECTRUM RECOVERY

The colorimetry of a document region can be expressed in terms of its spectral reflectance and the power spectral distribution of the illuminant it is viewed under as

$$t_i = \int_{\lambda_{min}}^{\lambda_{max}} a_i(\lambda) l(\lambda) r(\lambda) d\lambda \quad i = 1, 2, 3; \quad (1)$$

where λ denotes wavelength, $\{a_1(\lambda), a_2(\lambda), a_3(\lambda)\}$ are the CIE XYZ color matching functions (CMFs),¹ $r(\lambda)$ represents the spectral reflectance of the document region, $l(\lambda)$ represents the spectral power distribution for the *viewing illuminant*, and $[\lambda_{min}, \lambda_{max}]$, represents the interval of wavelengths outside of which all the

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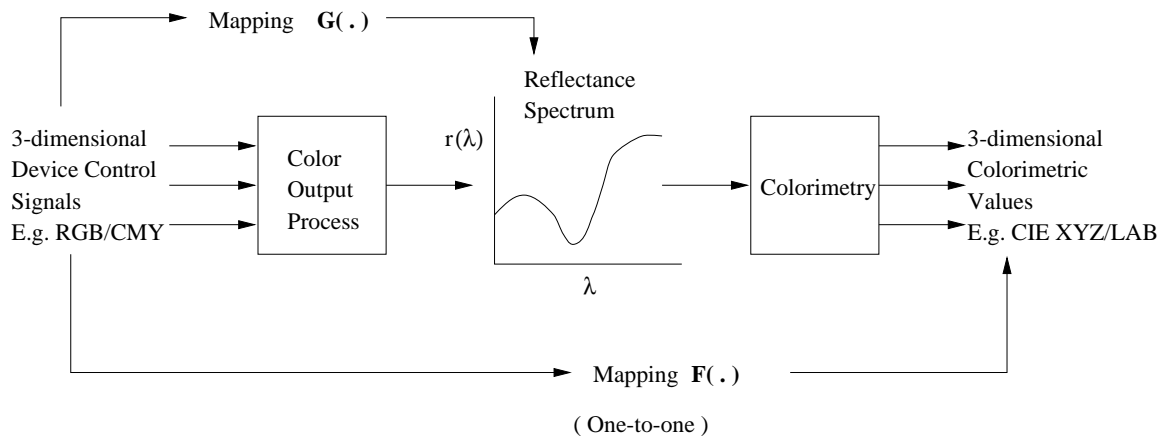


Figure 1: Illustration of relation between color control signals, spectrum, and colorimetry.

CMFs are zero. The three values $[t_1, t_2, t_3]$ represent the colorimetry of the document region in consideration and are referred to as the CIE XYZ tristimulus values. The space of CIE XYZ values represents a color space and the three values may be transformed into alternate representations or color spaces for various purposes. One commonly used color space is the CIELAB¹ color space which is an approximately *uniform color space* in that equal Euclidean distances in CIELAB correspond roughly to equal perceived differences in color.

From (1), it is clear that the colorimetric representation can provide a three-dimensional projection of the object reflectance $r(\lambda)$ onto the human visual (viewing) illuminant space (HVISS) determined by the functions $\{l(\lambda)a_1(\lambda), l(\lambda)a_2(\lambda), l(\lambda)a_3(\lambda)\}$.³ In the absence of additional information, the three dimensional color information is clearly insufficient for accurately reconstructing the object spectral reflectance $r(\lambda)$. In several color imaging applications, however, the “original” input image that is to be electronically captured is often a reproduction. This is the case, for instance, when a photographic print is to be scanned or a Xerographically produced color document is to be copied. Since these reproductions are produced by exploiting the trichromacy of human vision, they are often produced by using only three *independent color controls*. In the specific case of photographic prints, the image is produced using cyan, magenta, and yellow (CMY) dyes, the three of which are individually controlled. Even if more than three colorants are employed often they are controlled by only three independent variables. An example of the latter situation is CMYK printing and Hi-fi printing which are often driven by RGB/CMY signals and a fixed transformation is employed for obtaining the (more than three) colorant values from these 3-dimensional signal values.⁴ For typical color printing applications, four colorants, cyan, magenta, yellow, and black (CMYK), are commonly employed, however, the amounts of these colorants are normally not completely independent but determined from pseudo-CMY colorant amounts through under-color-removal(UCR) and gray-component-replacement(GCR) implying that there are only three inherent independent variables even for CMYK printing.⁵

The reflectance spectrum produced by the color output system in response to a specific set of three-dimensional color control values can be converted to colorimetry using (1). The entire chain consisting of a 3-D device control signal driving a color output device, the resulting spectrum, and conversion to colorimetry is schematically illustrated in Fig. 1.

One key aspect of the chain illustrated in Fig. 1 is that under normal viewing illuminants, the mapping $\mathbf{F}(\cdot)$ from the 3-D device control signals to the resultant colorimetry is typically one-to-one (ignoring quantization and noise artifacts). This one-to-one nature arises because the color production systems are designed to produce different colors in response to different input control signals. The one-to-one nature of the mapping assures its invertibility and therefore there exists a mapping $\mathbf{F}^{-1}(\cdot)$ that can map the colorimetric values back to the 3-D device control signals that were used to produce the corresponding output. Fig. 1 also illustrates the forward device response function $\mathbf{G}(\cdot)$, which represents the mapping from 3-D device control values to the reflectance

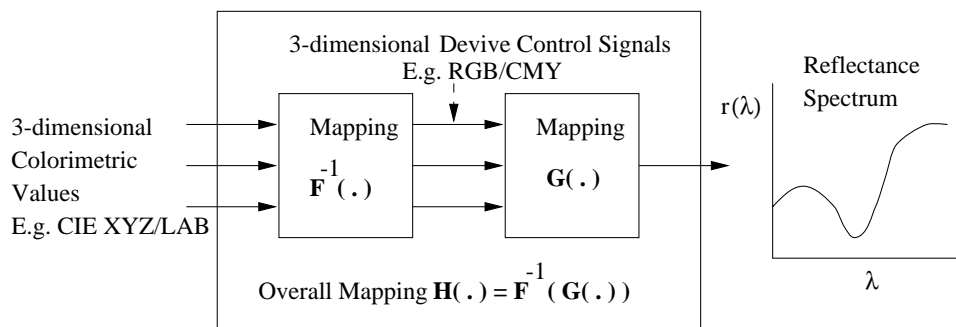


Figure 2: The functional mapping from colorimetry to reflectance spectrum.

spectrum produced on the output device in response to those control values. A concatenation of the mappings $\mathbf{F}^{-1}(\cdot)$ and $\mathbf{G}(\cdot)$ therefore allows colorimetric values to be mapped to the corresponding spectral reflectance values for the given color production system. This is illustrated in Fig. 2. Therefore, conceptually at least, it is feasible to extract spectral reflectance data from colorimetry for a given reproduction process. In the subsequent sections, empirical procedures for realizing this mapping from colorimetry to spectral reflectance, given a specific reproduction process are described.

Note that the formulation above may be generalized to the recovery of spectral data from data other than colorimetry. Any three channel representation obtained from the output spectral reflectance suffices, provided the mapping from 3-D device control signals to the three channel representation is one-to-one. In particular, scanner responses to a scanned reflectance can also be modeled by a relation very similar to (1). Typically, in document capture applications the scanners are three channel devices whose channel spectral sensitivities peak in the long (red), medium (green), and short (blue) wavelength regions of the visible spectrum, which also correspond to the peak absorption bands of CMY colorants used in the reproduction. This ensures that the mapping from device control values to the three channel responses is one-to-one. The formulation could therefore be applied to the spectral calibration of color scanners for inputs from a specific color reproduction process. For the specific case of photographic reflection prints and scanned transparencies alternate model-based calibration schemes have been presented elsewhere.⁶⁻⁹

It is worth mentioning that a situation similar to that described above and illustrated in Figs. 1 and 2 is encountered in the case of measurement of cathode-ray-tube (CRT) displays, where the set of irradiance spectra produced are a linear combination of the spectra of three primaries. In that situation, it can be shown that the output from any three sensors can be used to accurately reconstruct the complete spectrum, provided the sensor response vectors for the three primaries are linearly independent.¹⁰ The latter requirement is the analog of the requirement in the above case that the different color control values result in different colorimetry.

3. NEURAL NETWORK BASED SPECTRUM RECOVERY

The conceptual framework presented in the previous section indicated that for common color reproduction processes, it is possible to recover complete spectral reflectance from colorimetry. The framework described in the last section could potentially be used directly by experimentally determining the functions $\mathbf{F}(\cdot)$ and $\mathbf{G}(\cdot)$. This however requires that one have access to the color reproduction system and the ability to produce output corresponding to desired control values. In typical situations of interest, however, only samples produced on the color reproduction system are available and one does not have the ability to control the system by providing control signals. In this paper, therefore, an alternative empirical scheme will be considered, which utilizes neural networks for empirically determining the overall transformation from colorimetry to spectral data. Note that feed-forward neural networks have been shown to “universal approximators” for continuous functions under suitable conditions^{11,12} and the discussion of the previous section indicates that there is indeed

a continuous function mapping from colorimetry to spectral reflectance. Feed-forward neural networks are therefore appropriate for the purpose of spectral recovery from colorimetry.

Data for training the neural-network is generated using a target produced with the imaging system for which the colorimetry-to-spectral-reflectance mapping is to be generated. The target consists of a number of uniform patches that span the gamut of the reproduction process. The reflectance spectrum of each patch is measured using a spectrophotometer. The colorimetry for the patch is computed using (1). The neural-network is then trained to “learn” the correspondence between colorimetry and reflectance spectra using the target data. The trained neural-network coefficients are recorded. The network with the stored coefficients can subsequently be used to map any colorimetrically specified image to the corresponding spectral representation for the specific imaging system used for the training process.

4. EXPERIMENTAL RESULTS

Neural networks for recovering spectral reflectance from CIELAB colorimetry were trained for several color imaging systems. The systems included one photographic process, a xerographic CMYK printer, a lithographic press, and a CMYK inkjet printer. In each case, a target similar to the IT8.7¹³ scanner calibration target was used for generating the training data. Each target had between 264 and 288 patches. The patches on the target were measured using a Gretag Spectrolino spectrophotometer, which reports 36 samples of spectral data corresponding to samples 10nm apart at wavelengths from 380 to 730 nm. A 3-layer feed-forward neural-network with 7 hidden neurons and 36 output neurons was used for mapping from CIELAB colorimetry to spectral reflectance. The network was trained using a method that combines simulated annealing and conjugate gradient optimization.¹⁴ The optimization of the network weights in the training phase utilized an error metric based on weighted spectral mean squared error where the spectral-weighting was determined as the sum of the CIEXYZ CMFs. While the objective is to recover spectral reflectance, the spectral weighting provides the benefit of shaping the spectral errors so as to reduce visibility. Alternate (reasonable) spectral weighting functions were also experimentally evaluated and the accuracy of spectral recovery was not found to be strongly dependent on the exact weighting function used.

Representative results for spectrum recovery obtained with the trained neural networks are illustrated in Fig. 3. Fig. 3 (a) depicts the spectra reconstructed that are metameric* under CIE illumination D50, and correspond to a “gray” color with a CIELAB value of 75,0,0. Fig. 3 (b) depicts the spectra reconstructed that are metameric† under CIE illumination D50, and correspond to a “skin” color with a CIELAB value of 74,14,9. In both cases one can see that even though the colorimetry matches the spectra for these “colors” are quite different for the different reproduction processes.

The accuracy of spectrum recovery was assessed for each of the reproduction systems for which a neural network was trained for recovering spectrum from colorimetry. In each case, CIELAB values under CIED50 for the training patches were used with the trained network to estimate corresponding spectral reflectances. The spectral reflectance estimates from the neural network based recovery method were then compared to the original spectral measurements using two metrics: a) spectral mean-squared error, and b) the color difference under a set of viewing illuminants. The spectral mean-squared error (MSE) was computed as

$$SMSE = \frac{1}{N_S N_\lambda} \left(\sum_{r(\lambda) \in T_S} \sum_{\lambda_{min}}^{\lambda_{max}} (r(\lambda) - \hat{r}(\lambda))^2 \right) \quad (2)$$

where $r(\lambda)$ represents the actual measured reflectance corresponding to a patch in the target, $\hat{r}(\lambda)$ represents the spectrum recovered from the CIELAB values using the trained neural network, T_S represents the set of reflectances over which the spectral MSE is being computed, N_S is the number of samples in T_S , and N_λ is

Within the accuracy achieved by the reconstruction scheme. The colorimetry of the reconstructions under D50 illumination deviated from the target value with mean and maximum ΔE_{ab}^ color differences of 0.16 and 0.27, respectively.

†In this case, the average and maximum ΔE_{ab}^* from the target values were 0.23 and 0.25, respectively.

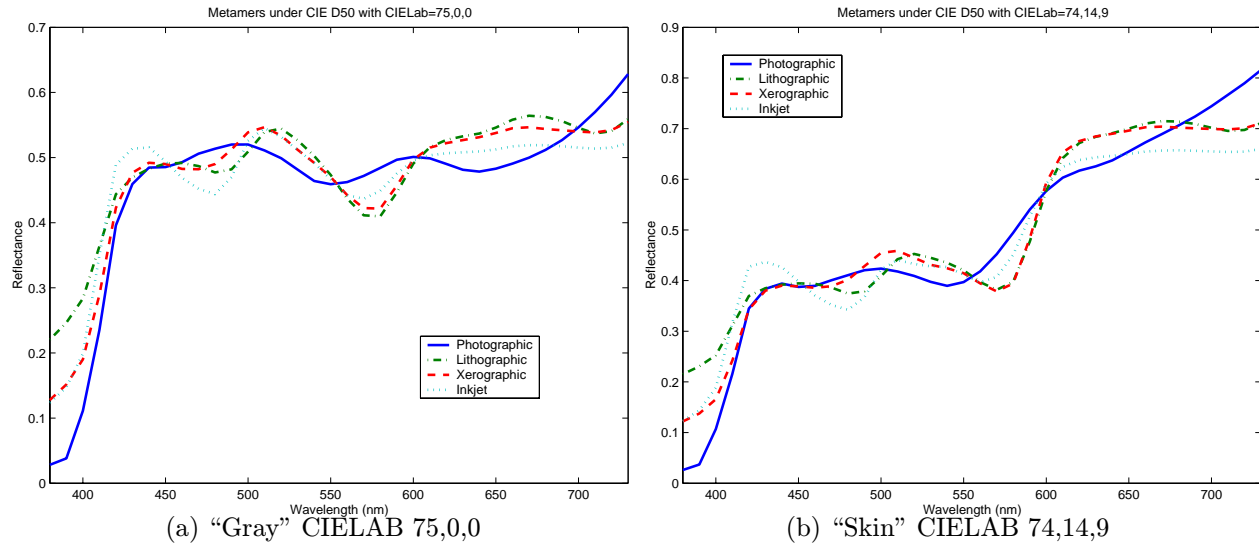


Figure 3: Metameric Spectra for under CIE D50 illumination from different image production processes.

Table 1: Spectral mean-squared-error (MSE) for the neural network based spectrum recovery.

Process	Photographic	Lithographic	Xerographic	Inkjet
SMSE	0.00010	0.00006	0.00002	0.00004
SMSE (dB)	-31.28	-35.28	-38.12	-36.04

the number of spectral samples from λ_{min} to λ_{max} . A normalized version of the SMSE was also computed in decibels as

$$SMSE(dB) = 10 \log_{10} \left(\frac{\sum_{r(\lambda) \in T_S} \sum_{\lambda_{min}}^{\lambda_{max}} (r(\lambda) - \hat{r}(\lambda))^2}{\sum_{r(\lambda) \in T_S} \sum_{\lambda_{min}}^{\lambda_{max}} (r(\lambda))^2} \right) \quad (3)$$

Table 1 lists the SMSEs for the different cases. From the table it is clear that the neural network based spectrum recovery method works quite well, producing very accurate estimates of the spectra for each of the cases. Due to the unavailability of independent test targets from most of these image production systems, the SMSE could not be evaluated for targets independent of those used in the generation of the neural network training data in all cases. For the case of the xerographic imaging system, however, an independent target consisting of 216 uniform patches was printed and used as an independent test set. The spectra for this test target patches were directly measured using a spectrophotometer. From these measurements, CIELAB values under CIE illuminant D50 were computed and the neural network trained for the xerographic imaging system (with the IT8-type target) was used to recover estimates of spectral reflectance for each of the patches. The computed SMSE for these estimates is 0.000062 (−31.16dB). The high accuracy indicates that the spectrum recovery works uniformly well and is not restricted to the training target alone.

As an alternate metric for the accuracy of recovered spectra, color-differences between the original spectra and the estimates recovered from colorimetry were computed under CIE illuminants D50, D65, and A. The color differences were evaluated in ΔE_{ab}^{*1} and ΔE_{94}^{*15} units. The mean, 95%-ile, and maximum values for these color differences are listed in Table 2 for each of the imaging processes. The numbers in the table reinforce the conclusion from the SMSE. The mean color errors are quite small across the different illuminants, indicating once again that the recovered spectra are close to the original. The 95%-ile point for the color errors is also quite small in most cases, though, as illustrated by the maximum errors there are a few patches for which significant color errors in the reconstruction may be encountered. The accuracy is well within the variability encountered in imaging systems over time and is sufficient for most applications.

Table 2: Color difference statistics of recovered spectral reflectances under different viewing illuminants.

Illum.	Metric	Statistic	Process			
			Photographic	Lithographic	Xerographic	Inkjet
CIE D50	ΔE_{ab}^*	Mean	0.90	0.54	0.58	0.41
		95%-ile	3.29	1.57	1.39	1.08
		Max.	6.87	2.99	10.80	2.44
	ΔE_{94}^*	Mean	0.52	0.35	0.36	0.29
		95%-ile	1.67	0.97	0.73	0.69
		Max.	4.52	2.74	7.93	2.30
CIE D65	ΔE_{ab}^*	Mean	0.89	0.56	0.56	0.43
		95%-ile	3.12	1.66	1.41	1.16
		Max.	6.54	3.00	10.61	2.44
	ΔE_{94}^*	Mean	0.51	0.36	0.35	0.30
		95%-ile	1.58	1.16	0.71	0.81
		Max.	4.55	2.57	7.63	2.26
CIE A	ΔE_{ab}^*	Mean	0.92	0.65	0.68	0.46
		95%-ile	3.46	2.15	1.60	1.30
		Max.	7.48	3.64	12.16	2.70
	ΔE_{94}^*	Mean	0.52	0.44	0.42	0.32
		95%-ile	1.82	1.47	1.02	0.96
		Max.	4.00	3.51	9.56	2.56

5. APPLICATIONS ENABLED BY SPECTRAL RECOVERY

The proposed method for spectrum recovery for color documents can be applied in several applications. Typical color calibration workflows compute colorimetry for captured documents under a specified viewing illuminant, with the CIE illuminant D50 being the commonly used illuminant in the graphic arts. Colorimetric information by itself is, however, incomplete in several respects. The primary limitation of colorimetric information is that it is directly bound to one viewing illuminant. Thus if one wishes to produce a reproduction of the document being scanned that matches the original document under a different viewing illuminant from the one for which calibration is performed, the colorimetric information is insufficient. Full spectral information for the original document, solves this problem by allowing colorimetry under any viewing illuminant to be computed[‡]. The method proposed in this paper can therefore be used to recover spectral information from a colorimetric representation provided the imaging system used to produce the document has been characterized in advance. The computed spectral representation can be used to determine colorimetry under a different viewing illuminant if required, thus allowing a matching reproduction to be produced under any specified illuminant. Availability of the spectral information also enables exploration of spectral matching of the original with multi-ink printing. Additional uses of spectrum recovery can be found in the simulation of imaging systems where the colorimetric information is clearly insufficient. For example in modeling chromatic aberration in a color capture device (or even in the human eye), the full spectral information enables more realistic simulations. As illustrated in the earlier example, the method can also be used to determine metameric pairs corresponding to different image production systems under a specific viewing illuminant, which can then be evaluated for differences under viewing illuminants different from the one under which they match. This can be used to evaluate the robustness of color output from an imaging system to changed in viewing illuminant.

6. CONCLUSIONS

In this paper, we demonstrate that in document capture applications where the input is often a color reproduction from an imaging system, recovery of spectral reflectance is often possible from a colorimetric record of

[‡]Additional factors which may influence the matching, such as gloss and surface texture are ignored here.

the document or more generally, from any (suitable) three channel recording such as one obtained from a color scanner. The feasibility of such recovery is first illustrated in an abstract framework. The recovery is enabled by the fact that most color imaging systems exercise only three degrees of freedom in the creation of color which are uniquely captured in the colorimetry. An empirical method for the recovery of spectral reflectance from colorimetry based on neural networks is developed. Experimental results demonstrate the success of the method developed for a number of common imaging processes. The recovered spectra for each of the imaging processes are close approximations of the actual spectra, both in terms of spectral mean-squared differences and in terms of color differences under common viewing illuminants.

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