Target-less Scanner Color Calibration

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Abstract

The lack of a scanner calibration target representative of the image medium (substrate and colorants) often limits the accuracy of scanner color calibration. In this paper, a color calibration method is presented for photographic input media that does not require a calibration target. Using characteristic spectral measurements from the image(s) to be scanned, a model for the spectra on the medium is obtained through a principal component analysis. The spectral sensitivity of the scanner provides a model for its operation. By using a set-theoretic estimation method that combines the models for the scanner and the medium, the spectral reflectance of the input corresponding to a given set of scanner RGB values can be determined. This provides a spectral calibration for the scanner, which can readily be transformed into a color calibration under any suitable viewing illuminant. Results from simulations and actual calibrations demonstrate the value of the new method.

1. Introduction

The goal of scanner calibration is to provide a transformation from the scanner measurements (typically, RGB values in three channel scanners) to a device independent color space (such as CIE XYZ space) or to spectral reflectance (from which tristimuli can be readily computed). Most present day color scanners are not colorimetric devices in that they do not satisfy the Luther-Ives [1, 2] criterion. Thus, the CIE XYZ color matching functions cannot be expressed as linear combinations of the spectral sensitivity of these devices and a linear calibration transformation matrix cannot be used to transform from scanner RGB to CIE XYZ tristimuli [3, 4, 5]. Often, however, very accurate calibration is possible for a single input medium (combination of substrate and colorants) because there are only three degrees of freedom in the spectra of the input medium which are captured through the use of three scanner channels [6]. In order to obtain these precise calibrations, it is also necessary that the calibration transform be represented by general non-linear functions (as opposed to simple matrices) that are capable of representing the complex relation between the scanner RGB values and the colorimetric values [6]. Higher order polynomials, neural networks, and 3-D look-up tables are therefore commonly used for the purpose of scanner calibration [7].

Typical scanner color calibration is done empirically by scanning a pre-measured calibration target and determining the transformation that maps the scanner RGB values to the measured colorimetric values for the calibration target. The calibration is accurate over the medium represented by the calibration target (i.e., composed of same substrate, same colorants, and same color separation method if there are more than three colorants), but its performance over other media is significantly poorer.

In practice, lack of calibration targets for each scanned medium limits the accuracy of the empirical scanner calibration method. At present, scanner calibration targets are available only from a handful of manufacturers of photoprocessing products [8]. In addition printed images that are to be scanned, need not correspond to the same type and batch of substrate and colorants that were used in the targets.

This paper presents a model-based scanner calibration method, which unlike the empirical calibration, does not require a calibration target. Instead, the method utilizes models for the medium and the scanner to obtain a calibration transformation. First, from direct measurements or indirect estimation methods spectral models are obtained for the scanner and for the medium of interest. The calibration is then performed by determining for each set of scanner RGB values, a feasible reflectance spectrum for the given medium that would give rise to specified RGB values. The calibration process thus defines a transformation from scanner measurements to spectra (on the given medium) that result in those measurements. The spectra can be readily used to obtain tristimuli under any desired viewing illuminant, which is an additional advantage over schemes that transform scanner measurements into tristimuli under a particular viewing illuminant.

While useful models are clearly not available for arbitrary media, the Beer-Bouger law and Kubelka-Munk theory provide useful models for photographic transparencies and prints, which fortunately constitute a significant fraction of scanned inputs. In this paper, we present a target-less method for calibration for these media.

2. Spectral Model for Photographic Media

The Beer-Bouger law provides a useful model for the spectral transmittance of photographic transparencies, and the Kubelka-Munk model (with scattering terms for the colorants set to zero) provides a useful model for photographic prints [9, Chap. 7] . In either case, the spectral transmittance/reflectance of a print sample can be represented mathematically by

$$r(\lambda) = r_p(\lambda) \exp\left(-\sum_{i=1}^{3} c_i d_i(\lambda) \right) \qquad (1)$$

where λ denotes wavelength, $r_p(\lambda)$ is the reflectance (or transmittance) of the substrate, $\{c_i\}_{i=1}^3$ and $\{d_i(\lambda)\}_{i=1}^3$ are the concentrations and spectral densities of the cyan, magenta, and yellow dyes, respectively[1].

For computational purposes, the spectra may be represented by N-vectors consisting of N uniformly-spaced samples over the wavelength interval of interest. Using this sampled representation, (1) becomes

$$\mathbf{r} = \mathbf{r}_p \otimes \exp\left(-\mathbf{Dc}\right) \qquad (2)$$

where $\mathbf{r}_p$ is the spectral reflectance of the paper substrate, $\mathbf{D} = [\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3]$ is the matrix of colorant densities at maximum concentrations, $\mathbf{c}$ is the vector of normalized colorant concentrations corresponding to the reflectance $\mathbf{r}$, $\otimes$ represents the term by term multiplication operator for N-vectors, and the bold lower case terms represent the spectral N-vectors for the corresponding quantities in (1).

Using this notation, the set of reflectance spectra producible on the medium can be expressed as

$$S_0^{med} = \{\mathbf{r} = \mathbf{r}_p \otimes \exp(-\mathbf{Dc}) \;\mid\; \mathbf{c} \in \mathbb{R}^3, 0 \le c_i \le 1\} \qquad (3)$$

3. Scanner Model

Typical color scanners produce a three-band image in red, green and blue channels. The process of recording the color with the scanner can be modeled at each pixel in terms of the scanner's spectral sensitivity as

$$t_i = \int_{-\infty}^{\infty} m_i(\lambda)\, r(\lambda)\, d\lambda \qquad i = 1, 2, 3 \qquad (4)$$

where t_i represents the scanner response for the i^{th} channel, $r(\lambda)$ is the spectral reflectance of the pixel being scanned, and $m_i(\lambda)$ is the overall spectral sensitivity of the i^{th} scanner channel that incorporates the spectral transmittance of the color filter and other optical components, the illuminant spectral irradiance, and the detector sensitivity.

Once again by representing the spectral quantities in (4) as N-vectors composed of uniformly-spaced samples, the scanner model can be compactly written as

$$\mathbf{t} = \mathbf{M}^T \mathbf{r} \qquad (5)$$

where $\mathbf{t} = [t_1, t_2, t_3]^T$ is the vector of scanner RGB responses, $\mathbf{r}$ is the $N \times 1$ vector of reflectance samples, $\mathbf{M}$ is an $N \times 3$ matrix whose i^{th} column $\mathbf{m}_i$ is the spectral sensitivity of the i^{th} channel.

4. Model-based Scanner Calibration

The RGB values obtained from the scanner provide information regarding the reflectance spectrum of the pixel scanned. Given the vector $\mathbf{t}$ of scanner RGB values, it can be inferred that the reflectance spectrum of the pixel lies in the set

$$S^{scn}(\mathbf{t}) = \{\mathbf{r} \mid \mathbf{M}^T \mathbf{r} = \mathbf{t}\} \qquad (6)$$

of all possible reflectances that produce the scanner response $\mathbf{t}$.

Combining this information with the knowledge of the scanned image medium, one can deduce that the reflectance spectrum of the pixel lies in the intersection $S_0^{med} \bigcap S^{scn}(\mathbf{t})$ of the sets predicated by the scanner model and the model for the medium. For a single photographic medium and typical scanner sensitivities, it is unlikely that “scanner metamers”, i.e., different reflectance spectra that appear identical to the scanner will be encountered[2]. Therefore, the intersection represents a singleton (one-element) set and the reflectance spectrum can be estimated if an algorithm is available for obtaining a point in the intersection.

In order to illustrate this idea graphically, a synthetic example was created with 1) two samples ($N = 2$) for representing spectra, 2) a medium following (3) with a single dye, and 3) a single channel scanner. This example is shown in Fig. 1. The two axes of the graph represent samples of the “reflectance” spectrum at the two wavelengths. The set of feasible spectra on the given medium is shown by the solid curve in Fig. 1. The scanner response corresponding to a given dye concentration (0.3) was computed and the set of all spectra that result in this given scanner response was computed. This set is shown by the broken straight line in Fig. 1. Note that while there are several spectra that can produce the given scanner response, only one of these lies in the set of feasible spectra on the given medium and this spectrum is the point of intersection of the solid curve and the broken line in Fig. 1.

[1] Note that conventionally the logarithm to the base 10 is used in defining density, but for notational simplicity the natural logarithm is used throughout this paper.

[2] In the presence of “scanner metamers”, the notion of what constitutes a valid scanner calibration itself becomes debatable.

Set-theoretic estimation [10] addresses the problem of determining an element in the intersection of a number of constraint sets. The most powerful and useful set-theoretic estimation algorithms are variants of the method of successive projections onto convex sets (POCS) [10]. The POCS method determines an element lying in the intersection of a number of closed-convex sets by starting with an arbitrary point and successively projecting onto the sets till convergence is achieved.

The set $S^{scn}(\mathbf{t})$ is a closed convex set (under the normal Hilbert space structure on $\mathbb{R}^N$) but the set S_0^{med} is not a convex set (in the same Hilbert space). Therefore, the POCS method cannot be directly applied to the model-based scanner calibration problem. Note, however, that the set S_0^{med} is closed and convex in the density domain. The problem can therefore be formulated in the generalized product space framework proposed recently in [11]. By introducing a suitable Hilbert space structure over the space of reflectance spectra that "convexifies" the set S_0^{med}, the POCS algorithm can then be used. Only the final algorithm for the model based scanner-calibration shall be described here, details of the derivation can be found in [12], where application of the product space formulation to other problems in color science is also described.

5. Practical Implementation

To implement the model-based scanner calibration method in practice, the models for the scanner and the medium need to be known. The scanner model is defined solely by its spectral sensitivities, which may be determined either by direct measurement or through an estimation using independent targets [13]. If data for the substrate and dyes is available from the manufacturer, the model of the medium can be obtained from that data. However, in order for the method to be really useful, the medium model needs to be derived directly from the image(s) to be scanned.

Since pure cyan, magenta, and yellow tone prints are not normally available in images, the densities corresponding to the dyes cannot be directly measured. Note, however, that the spectra in the model of (3) can be rewritten in terms of density as

$$\ln(\mathbf{r}_p) - \ln(\mathbf{r}) = \sum_{i=1}^{3} c_i \mathbf{d}_i \qquad (7)$$

The left hand side in the above equation represents the density corresponding to the reflectance $\mathbf{r}$ relative to the white paper reflectance $\mathbf{r}_p$. From the above equation, it is clear that these paper-relative spectral densities are linear combinations of the dye densities $\{\mathbf{d}_i\}_{i=1}^{3}$. Hence, the paper-relative spectral densities lie in a three dimensional space (excluding noise effects), and principal components analysis can be used to determine an orthonormal set of basis vectors for this space. This set of vectors serves as "principal dye" densities and are a linearly transformed version of the actual dye densities. This idea of utilizing principal components analysis in the density domain has been used earlier in [14, 15].

The "principal dye" densities can be determined from a small number of spectral measurements on the scanned images themselves and therefore do not require a calibration target. While the concentrations corresponding to the real dye densities in (3) were subject to simple upper and lower bounds, similar bounds cannot be obtained for "concentrations" corresponding to the virtual dyes obtained from the principal components analysis. The information in the bounds is therefore lost in this method. If $\mathbf{O} = [\mathbf{o}_1, \mathbf{o}_2, \mathbf{o}_3]$ is the matrix of the (orthogonal) virtual dye densities obtained through the principal components analysis, the constraint set

$$S^{med} = \{\mathbf{r} = \mathbf{r}_p \otimes \exp(-\mathbf{O}\mathbf{c}) \mid \mathbf{c} \in \mathbb{R}^3\} \qquad (8)$$

can be used to describe producible spectra on the given medium (strictly speaking, this set is a super-set of the producible spectra).

The model for the medium can be then used along with the scanner model to obtain a calibration as follows. Corresponding to each scanner measurement $\mathbf{t}$, a spectral reflectance estimate $\hat{\mathbf{r}}$ is obtained by computing a feasible spectrum lying in the constraint sets S^{med} and $S^{scn}(\mathbf{t})$. An outline of the complete algorithm used for this estimation is given in Table 1[3].

The results of applying this model-based scanner calibration method to a simulated scanner and to an actual scanner are described in the next two sections. In both cases, the Kodak IT8 photographic target [8] is used for testing the model-based calibration scheme. The reflectance spectra for the 264 patches in the Kodak IT8 target were measured independently using a spectrophotometer. The reflectance of the white patch in the gray-wedge on the target is used as the reflectance of the paper substrate $\mathbf{r}_p$ in computing paper-relative spectral densities. The first three principal components of the 264 densities account for 97.2% of the signal energy in density space, and are used as the (orthonormal) densities $\mathbf{o}_1, \mathbf{o}_2, \mathbf{o}_3$ of three principal dyes constituting the prints. These principal dye densities are shown in Fig. 3.

6. Simulation Results

A three channel color scanner is "synthesized" by defining sensitivities for its channels as the combination of the Wratten [16] WR-26 red, WR-49 green, and WR-52 blue

[3]Note that the averaging step (5) in the algorithm is a computational simplification of the true POCS algorithm.

1. Set $\mathbf{M}$ as the spectral sensitivity of the scanner, $\mathbf{r}_p$ as the white paper reflectance of the scanned medium, $\mathbf{O}$ as the matrix of orthonormal principal dye densities for the scanned medium, and $\mathbf{t}$ as the set of scanner RGB values for which a calibration is desired.

2. Initialize $i = 0$; and spectral estimate $\mathbf{r}_i = (\mathbf{M}^T)^\dagger \mathbf{t}$, where $\dagger$ indicates the pseudo-inverse. Set components of $\mathbf{r}_i$ that are zero or negative to a small positive value and values above unity to 1.

3. Determine nearest point in $S^{scn}(\mathbf{t})$ the set of spectra that produce the given scanner measurement

$$\mathbf{x} = (\mathbf{M}^T)^\dagger \mathbf{t} + \left(\mathbf{I} - (\mathbf{M}^T)^\dagger (\mathbf{M}^T)\right) \mathbf{r}_i)$$

4. Determine "nearest point" in S^{med} the set of spectra that can be produced on the given medium (using appropriate distance metric)

$$\mathbf{y} = \exp\left(\ln(\mathbf{r}_p) - \mathbf{O}\mathbf{O}^T\left(\ln(\mathbf{r}_p) - \ln(\mathbf{r})\right)\right)$$

5. Obtain next estimate of reflectance by averaging the points in the two sets

$$\mathbf{r}_{i+1} = (\mathbf{x} + \mathbf{y})/2$$

   Set components of $\mathbf{r}_{i+1}$ that are zero or negative to a small positive value.

6. Update iteration count: $i = i + 1$

7. Check for convergence: If $\mathbf{r}_i$ is not in $S^{med} \bigcap S^{scn}(\mathbf{t})$ return to 3 otherwise proceed to 8.

8. Set $\hat{\mathbf{r}} = \mathbf{r}_i$. This is the estimate of the reflectance on the given medium corresponding to the scanner measurement $\mathbf{t}$.

Table 1: Algorithm for model-based scanner calibration.

filters with a cool white fluorescent lamp (the scanning illuminant). The resulting scanner sensitivities for the three channels are shown in Fig. 2. In order to test the model-based calibration scheme, scanner RGB values $\mathbf{t}$ are generated using the model of (5) and the measured reflectance $\mathbf{r}$ for each patch on the Q60 target. A spectral reflectance estimate $\hat{\mathbf{r}}$ corresponding to the scanner measurement $\mathbf{t}$ is then obtained using the algorithm of Table 1

To estimate the accuracy of the model-based calibration scheme, the computed spectrum $\hat{\mathbf{r}}$ is compared with the actual spectrum $\mathbf{r}$. Two metrics are used for this comparison: 1) the normalized mean squared spectral error defined (in dB) as

$$\text{MSE}_{spec} = 10 \log_{10}\left(\frac{\text{E}\{\| \mathbf{r} - \hat{\mathbf{r}} \|^2\}}{\text{E}\{\| \mathbf{r} \|^2\}}\right), \qquad (9)$$

where $\text{E}\{\cdot\}$ denotes the average over the spectral ensemble (in this case the Q60 target spectra), and 2) the ΔE^*_{ab} color-difference [17] under CIE D50 daylight illuminant.

For the simulated model-based scanner calibration, the mean squared spectral error is -33.84 dB and the ΔE^*_{ab} error has an average value of 0.62 and a maximum value of 2.59 over the 264 patches in the Q60 target. The value of the ΔE^*_{ab} errors is quite small and comparable/better than the accuracy typically obtained for scanner calibration. The small values of the spectral errors also indicate that the model-based scanner calibration approach is successful in providing a spectral calibration.

7. Experimental Results

The model-based spectral scanner calibration was also tested on an actual three channel UMAX color scanner with 10 bits per channel. Since the scanner sensitivities for the red, green, and blue channels were not directly available, these were first estimated by the principal eigenvector technique[4] described in [13]. The estimated sensitivities are shown in Fig 4. The model-based calibration was performed for the Kodak IT8 in a manner identical to that employed for the simulation and the same metrics computed for evaluation of the calibration accuracy. The mean squared spectral error was -29.35 dB and the average and maximum ΔE^*_{ab} errors were 2.18 and 11.63, respectively. For comparison, the scanner was also calibrated directly using a neural network based technique with the complete Kodak IT8 as the training set. The average and maximum ΔE^*_{ab} errors (over the Kodak IT8 target) for the direct calibration were 1.05 and 4.40, respectively.

One may note that the errors in the model-based calibration of the UMAX scanner are larger than those obtained in the simulations. One probable cause of the larger

[4]Information on the internal scanner matrixing was not available and therefore the POCS technique described in [13] could not be employed.

errors is the estimation error in the scanner sensitivity. An inspection of Fig. 4 shows that the estimated sensitivities for the UMAX scanner have a number of negative and positive lobes which are highly improbable in the actual scanner. Other potential causes include measurement noise and deviations from the scanner model of (5) due to fluorescence, stray light and other nonlinear effects [18].

While the errors in the model-based calibration are larger than those for the direct calibration, the model-based calibration is still useful as it provides a complete spectral calibration and also a means for calibration when is no target is available for the scanned medium. With improved estimates of the scanner spectral sensitivity, one would expect improvement in the accuracy of the model-based calibration.

8. Conclusions

In this paper, we presented a model-based scanner calibration scheme, which allows spectral calibration of a color scanner for a given medium without requiring a calibration target on that medium. Simulation results indicate that good accuracy can be obtained for spectral and color calibration if the scanner's spectral sensitivity is accurately known. Experimental results obtained with an actual scanner with estimated spectral sensitivity result in moderate accuracy.

The model-based calibration scheme can be readily used in several other applications. In particular, the model-based calibration framework can be used to obtain spectrophotometric data for photographic media from densitometers, colorimeters, and color cameras which can also be represented by the model in (5).

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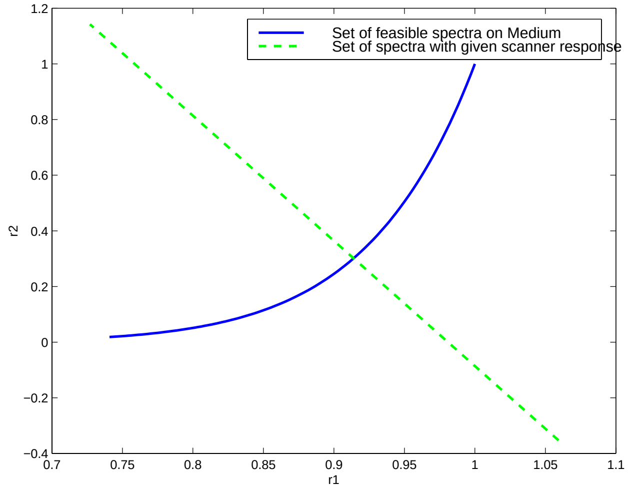

Figure 1: *Synthetic two-dimensional example illustrating model-based scanner calibration.*

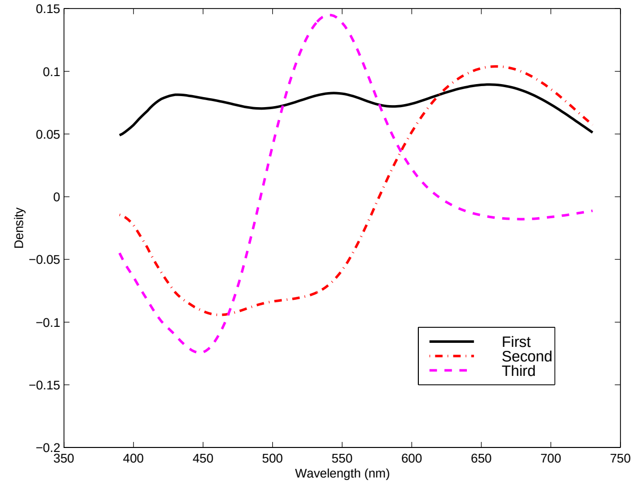

Figure 3: *Densities for the three principal dyes.*

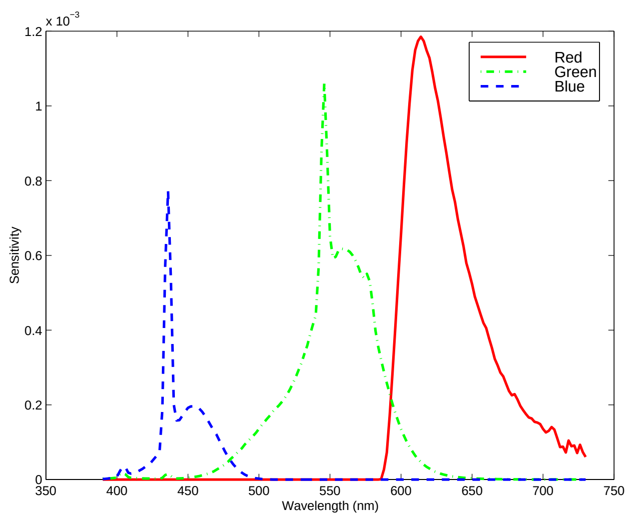

Figure 2: *Sensitivities for the simulated scanner channels.*

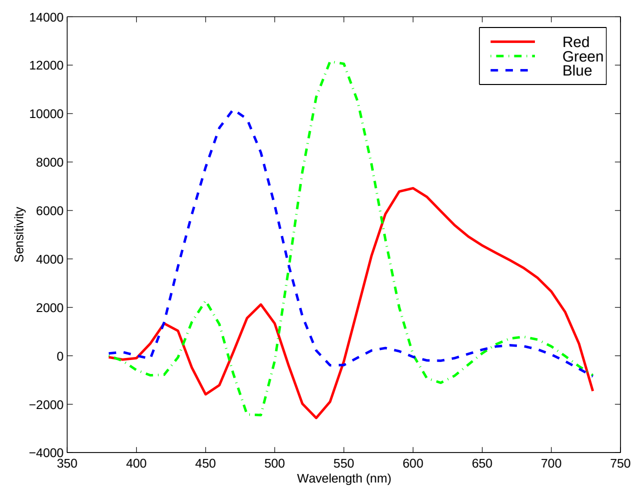

Figure 4: *Estimated sensitivities for the UMAX scanner.*