Analysis of Multispectral Image Capture

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Abstract

Multispectral image capture (*i.e*, more than three channels) facilitates both more accurate tristimulus estimation and possibilities for spectral reconstruction of each scene pixel. A seven-channel camera was assembled using approximately 50 nm bandwidth interference filters, manufactured by Melles Griot, in conjunction with a Kodak Professional DCS 200m digital camera. Multichannel images were recorded for the Macbeth ColorChecker chart as an illustrative example. Three methods of spectral reconstruction were evaluated: spline interpolation, modified-discrete-sine-transformation (MDST) interpolation, and an approach based on principal-component analysis (PCA). The spectral reconstruction accuracy was quantified both spectrally and by computing CIELAB coordinates for a single illuminant and observer. The PCA-based technique resulted in the best estimated spectral-reflectance-factor functions. These results were compared with a least-squares colorimetric model that does not include the spectral-reconstruction step. This direct mapping resulted in similar colorimetric performance to the PCA method. The multispectral camera had marked improvement compared with traditional three-channel devices.

Techniques

The use of multispectral cameras can lead to dramatically improved colorimetric accuracy in comparison with three-channel devices.[1,2] In addition, these systems can readily be used to estimate the spectral properties of each scene element using linear modeling techniques.[3-5] Defining scenes spectrally yields many advantages. These include multiple illuminant and multiple observer trichromatic calculations (necessary for color appearance modeling), system design optimization, high-accuracy color printing, and optimal separation algorithms for multi-ink printing.

Recently, the choice of filters has received considerable attention, both for multispectral and three-record image acquisition.[6, 7] However, these filters are often unrealizable using current manufacturing techniques. Alternatively, one can use currently available filter materials and evaluate various methods of signal reconstruction. This is the approach taken in this research.

For applications that do not require simultaneous acquisition of all records, such as document or artwork imaging, a multispectral camera can be formed by acquiring several frames using a set of optical filters. A set of seven interference filters manufactured by Melles Griot was chosen to sample the visible wavelength range at intervals of approximately 50 nm. This equal-interval sampling does not favor the characteristics of any particular radiation sources, nor class of object spectra (e.g., manufactured colorants or natural objects). On the other hand, the transmittance functions impose a reduced spectral-frequency bandwidth on the acquired signals. The input device selected for this study was the Kodak Professional DCS 200m (monochrome) digital camera. The lower sensitivity of the CCD imager in the short wavelength regions, coupled with the throughput of the filters results in a wide range of relative spectral sensitivities, as shown in Fig. 1.

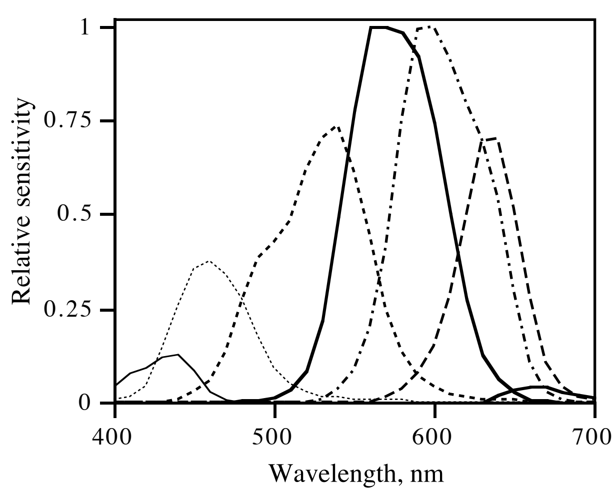

Figure 1. The spectral sensitivity of each of the seven filter/sensor channels.

Methods based on signal interpolation, and statistical modeling of the spectral reflectance factor database were applied to the problem of estimating the spectral reflectance factors from the seven camera signals. Since each of the optical filter spectral transmittance curves has a similar shape, we can think of the image collection, prior to detection, as a spectral filtering followed by a sampling operation with $\Delta\lambda = 50\text{nm}$.[8] This view of image acquisition lends

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itself to spectral reconstruction via interpolation schemes such as cubic-spline and modified-discrete-sine-transformation (MDST)[9] interpolation.[10] The latter method relies on properties of the sine-transform (and Fourier-transform) representations of a signal. Simple extrapolation is applied to the sine transform of an input array, followed by inverse transformation. An interpolated signal can then be extracted from the resulting data.

Principal component analysis (PCA) was also used to reconstruct spectral reflectance factor functions from camera signals. This required the calculation of the first five characteristic (column) vectors of a set of Munsell Book of Color samples. The spectral reconstruction for a given sample is computed by

$$\mathbf{f} = \Phi\ \mathbf{a} + \mu_{\mathbf{f}}, \qquad (1)$$

where, $\Phi = [\mathbf{e}_1, \mathbf{e}_2, ..., \mathbf{e}_5]$, $\mu_{\mathbf{f}}$ is the mean spectral vector, and $\alpha^{\mathbf{T}} = [\mathbf{a}_1, \mathbf{a}_2, ...\mathbf{a}_5]$ is the set of five scalar weights associated with the sample to be reconstructed spectrally. The scalars can be found by

$$\alpha = \left[\Phi^{\mathbf{T}}\Phi\right]^{-1}\Phi^{\mathbf{T}}(\mathbf{f} - \mu_{\mathbf{f}}). \qquad (2)$$

The term $\left[\Phi^{\mathbf{T}}\Phi\right]^{-1}\Phi^{\mathbf{T}}$ can be interpreted as a matrix of spectral sensitivity functions that could be used to analyze a sample, **f**, for subsequent spectral reconstruction. For the multispectral camera, however, the spectral reconstruction needs to be based on the camera signals, **s**. This can be achieved by computing a least-square (5 x 7) matrix, **M**, to transform the camera signals into estimates of the scalar coefficients α. The spectral reconstruction is then given by,

$$\mathbf{f} = \Phi\ \mathbf{M}\ \mathbf{s} \qquad (3)$$

where $\mathbf{s}^{\mathbf{T}} = [s_1, s_2, ..., s_7]$. Equation (3) does not include the mean vector, $\mu_{\mathbf{f}}$, since the principal components used in our reconstruction were calculated as the eigenvectors of the second moments about zero, rather than the usual covariance matrix about the mean.

One benefit of a multispectral camera is to enable a more-accurate colorimetric analysis of a scene compared with typical trichromatic devices. From estimated spectral reflectance factor data, CIELAB coordinates for each color sample can be calculated for any illuminant and observer of interest. If only colorimetric data are required, one can bypass the spectral reconstruction step and derive a direct mapping from the seven camera signals to CIELAB coordinates based on a least-square fit to equations of the form,

$$L^* = \sum_{i=1}^{7} a_i r_i^{b_i}, \qquad (4)$$

and in similar fashion for *a** and *b** where r_i is the camera signal for the *ith* filter image. (One could also derive higher-order transformations.)

Experimental

The Kodak Professional DCS 200m digital camera with Nikon 28mm lens was mounted on a copy stand with four tungsten-halogen bulbs. The camera records a 1000 pixel x 1500 pixel digital image at eight bits (256 levels) per pixel. Each multispectral image consisted of seven frames corresponding to the seven interference filters. Camera calibration was performed in two parts. First the photometric response was evaluated at the center of the image field for each filter using neutral Munsell color samples. The camera exposure time used for each frame was chosen so as to yield the maximum signal for a reference white sample (in digital count value) without causing signal clipping due to saturation of the CCD imager. The ideal signals for each of the neutral samples was calculated by cascading the measured source spectral power distribution with the camera/filter channel responses, shown in Fig. 1. The photometric response correction for each channel was accurately fitted with a second-order polynomial.

The four lamp directions and locations were adjusted so as to yield approximately uniform illumination over the image area. Investigation of the digital images for a uniform barium-sulphate coated card, however, indicated that the effective illumination varied over the field. A set of seven digital images of this reference card were recorded, and transformed via the above photometric calibration equations to yield estimates of the effective illumination intensity for any image position.

A set of seven image frames were recorded of a Macbeth ColorChecker chart using the filters and camera settings described above. The 24 average digital signal values, corresponding to each color patch of the chart, were extracted from each of the seven records. These were then corrected both for the position-dependent illumination and camera photometric response. For example, the fourth filter compensation (centered at 560 nm) for the camera photometric response was given by

$$q_{i,j} = -0.0129 + 0.569\, p_{i,j} + 1.99\, p_{i,j}^2\ , \qquad (5)$$

where $p_{i,j}$ is the camera signal for the color sample at location (*i,j*), on a [0-1] scale, and $q_{i,j}$ is the corrected signal. The effective illumination variation was corrected for by

$$r = \frac{q_{i,j}}{w_{i,j}} \qquad (6)$$

where $w_{i,j}$ is the transformed signal for the reference white card at location (i, j), that had been similarly transformed via Eq. (5). Note that this approach assumes that any mean dark-current detector signal is accounted for in Eq. (5). The set of signals corresponding to r in Eq. (6) for each image frame were used as input to subsequent signal processing to reconstruct the spectral reflectance factor of each color sample or directly estimate colorimetric values.

Results

The camera signals were used to estimate the spectral reflectance factor of each sample of the ColorChecker using the PCA-based technique and the two interpolation methods, MDST and cubic spline. An example of the reconstruction accuracy of the three methods is shown in Fig. 2 for the Cyan sample. For all of the chromatic samples and most of the neutral samples, the PCA-based technique produced the most accurate spectral reconstructions. The poor results for the two interpolation techniques were expected given the spectral width of the seven channels which limits the high spectral-frequency components in the detected signal.

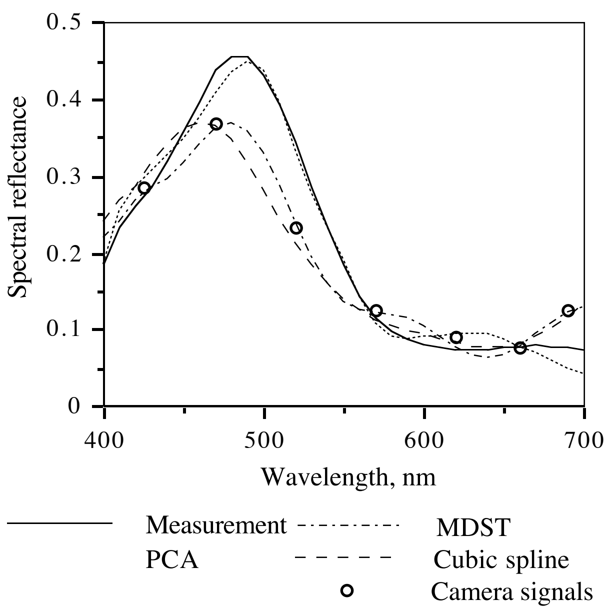

Figure 2. The spectral reconstruction using principal component analysis (PCA), modified-discrete-sine-transformation (MDST) and cubic spline interpolation, from camera signal values, for the Cyan sample.

A colorimetric comparison of the reconstruction methods was made by using the estimated spectral reflectance factors to compute CIELAB coordinates for each color sample for CIE illuminant A and the 2°observer. The reference coordinates were those computed from spectrophotometric measurements of the samples taken at 10 nm intervals. The results expressed in terms of ΔE^*_{ab} are summarized in Table 1, as are those for the least-square colorimetric model of Eq. (4). Consistent with the spectral analysis, the PCA technique was the most accurate spectral-reconstruction method, colorimetrically. The direct-mapping method also resulted in accurate colorimetric estimations. As a benchmark, Katoh optimized a 3CCD color-video camera to estimate the colorimetric coordinates of the ColorChecker.[11] His model consisted of a nonlinear photometric stage followed by a linear 3x3 transformation to tristimulus values. The ΔE^*_{ab} results were as follows: 5.6 average, 3.3 standard deviation, 14.0 maximum By using the appropriate method, multispectral imaging can yield marked improvement compared with trichromatic devices.

Table 1: ΔE^*_{ab} color-difference values for Macbeth ColorChecker samples derived from the recorded multispectral camera, for CIE illuminant A and the 2° observer, using several methods.

Sample	*PCA*	*MDST*	*Spline*	*CIELAB Model*
Dark Skin	1.7	5.2	6.3	1.1
Light Skin	1.1	6.8	7.2	1.7
Blue Sky	4.3	5.5	6.2	2.3
Foliage	1.6	3.8	5.4	2.5
Blue Flower	2.1	2.9	2.6	1.0
Bluish Green	2.3	11.3	13.4	1.7
Orange	1.5	12.6	15.7	2.6
Purplish Blue	3.2	2.8	5.2	1.7
Moderate Red	2.0	15.1	18.2	1.3
Purple	3.6	3.6	6.4	1.9
Yellow Green	0.8	8.3	13.3	2.1
Orange Yellow	3.1	7.6	11.0	2.4
Blue	2.4	5.4	6.9	3.3
Green	3.2	13.5	17.0	3.6
Red	1.2	16.3	19.6	2.1
Yellow	0.4	7.1	12.7	3.8
Magenta	1.0	13.3	15.9	1.3
Cyan	3.4	14.2	18.2	5.1
White	2.2	4.8	5.7	3.9
Neutral 8	1.2	5.1	5.6	2.3
Neutral 6.4	1.0	4.1	4.4	1.6
Neutral 5	1.6	3.1	3.2	1.2
Neutral 3.5	4.0	2.8	2.7	2.7
Neutral 1.5	4.7	4.3	3.2	0.6
Average	2.2	7.5	9.4	2.2
Std. Dev.	1.2	4.3	5.5	1.1
Max.	4.7	16.3	19.6	5.1

Conclusions

Multispectral image capture can greatly improve the colorimetric accuracy for image capture in comparison to trichromatic methods. The current results are consistent with previous research. Of greater interest is the accuracy of the spectral reconstructions using readily available digital hardware and optical components. Accurate spectral data can be used to for a variety of spectral-based research needs and the practical solution to four- and multi-ink color printing with greatly improved color quality, particularly with respect to invariant matching for multiple illuminants and observers.

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