Optimizing color accuracy of a filter-based multispectral camera via iccMAX framework for digital achieves

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Abstract

This study aims to optimize the color accuracy of a filter-based multispectral camera via iccMAX framework. The spectral and color accuracy of camera-to-spectralPCS and camera-to-sRGB conversions were estimated and the resulted errors are acceptable. iccMAX late-binding processing elements also were tested to apply four different illuminants to a spectral image to simulate its color appearance on a virtual sRGB display. The color accuracy of the late-binding processing were estimated.

Introduction

Advances in sensors, filters and image processing are driving the evolution of multispectral imaging from expensive one-off systems for military applications and satellite remote sensing to affordable, practical, commercial systems for use in everything from medical imaging, forensic science to industrial inspection. Multispectral imaging has been applied to the field of art conservation and art history since the early 1990s [1-8]. It is a non-invasive imaging technique which is welcomed by conservators and art historians. Multispectral camera is capable of collecting a series of images of an object with both spatial and spectral information. It is successfully used in art examination and identifying artists' materials (e.g., pigments and binders). The identification of pigments in polychrome artworks and archaeology is necessary to gain a deep understanding of the materials and the painting technique applied. Conservators and art historians can use these information to select proper conservation procedures and to reconstruct the artists' workshop practices. However, it is not yet popular in digital archives as the multispectral imaging devices are normally expensive and no standard format cannot be used to characterize the spectral images for further applications such as digital museum and multispectral printing. As more and more cost effective multispectral imaging devices are available and ICC is currently working on iccMAX for connecting the spectral images with perceptual colors [9-11], it is the time to study how accuracy the new ICC system can be used for spectral imaging on digital archives.

This study aims to optimize the color accuracy of a filter-based multispectral camera via iccMAX framework. The spectral and color accuracy of camera-to-spectralPCS (i.e., spectral profile connection space) and camera-to-sRGB conversions were estimated and the resulted errors are acceptable. iccMAX late-binding processing elements also were tested to apply four different illuminants to a spectral image to simulate its color appearance on a virtual sRGB display. The color accuracy of the late-binding processing were estimated.

Apparatus

The spectral camera used in this study was Pixelteq SpectroCam VIS-NIR (Figure 1-right). It contains a filter wheel holding 8 easily changeable filter segments, digital progressive scan CCD scientific imager and operating in Visible / Near Infrared (VIS/NIR) range. In this study, we used two sets of spectral filters, one set starts from 400nm to 680nm in 40 nm interval. The other set starts from 420nm to 700nm in 40 nm. The bandwidth of each spectral filter is about 20nm. Figure shows the spectral transmittances of the 16 VIS filters measured by a spectrophotometer. The image format of the spectral image is 12bit PNG file in 1392×1040 resolution. All measurement were done under a Macbeth Spectra Light III light booth (Figure 1-middle).

Figure 1. From left to right: the X-rite Colorchecker SG chart, the Macbeth Spectra Light III light booth and the Pixelteq SpectroCam VIS-NIR.

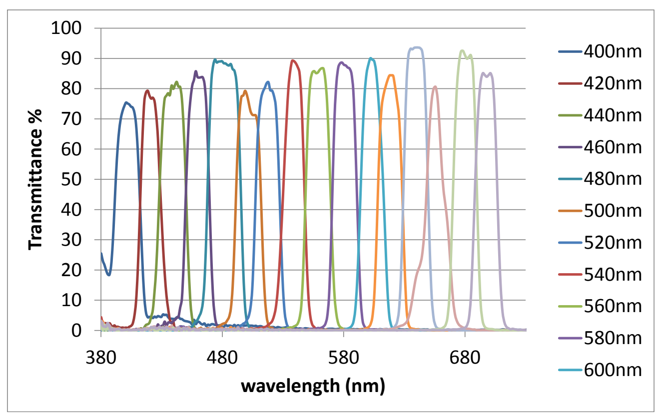

Figure 2. Spectral transmittances of 16 VIS filters.

This spectral camera can use Fast Mode or Index Mode. The latter allows the user to set exposure time and gain for each channel. To achieve the best image quality, we set the exposure time and the gain value solely for each channel. The criteria of the adjustment is to set exposure time first to meet 80% gray level for white patch at '5E' position on an X-rite ColorChecker SG chart (Figure 1-left). If the exposure time is up to its limit, adjust gain value to fulfil the criteria. In the Macbeth Spectra Light III light booth, there are at least four illuminants, D65 simulator, A, TL84 and CWF (Cool White Fluorescent), can be chosen. We selected tungsten lamps as the light source for image capturing as it provides smooth spectral radiance between adjunct wavebands. Figure 2 is the spectral transmittances of the 16 VIS filters. It were measured by a Rainbow Light TSM-01 spectral transmittance meter with a tungsten light source. As can be seen, the transmittances of the filters are 80% on average, the shapes can be roughly approximated by super Gaussian functions. There are very little spectral crosstalk between each filter. The filter with 660nm peak wavelength is sharper than all the others.

ICC Max

ICC (The International Color Consortium) color management meets the goal of creating, promoting and encouraging the standardization and evolution of an open, vendor-neutral, cross-platform color management system architecture and components. As we know that the current architecture works well in many areas, it has established an architecture for interoperable and unambiguous communication of color between devices, but some needs cannot be accommodated within ICC v4, such as spectral processing, unsupported transforms, measuring geometry other than $0^o/45^o$, alternative illuminants and observers. ICC is in the process of defining a new color management system about standard encoding color profiles and defining color management workflows under the name “iccMAX”.

iccMAX is developed in ICC Labs, primarily by members of the Architecture Working Group, that goes beyond D50 colorimetry and enable new ways of communicating about light, color and appearance, which provides a platform for defining spectrally based color management workflows with the ability to use spectrally based Profile Connection Spaces (PCSs) as well as flexibility directly encode color transforms as programmable scripts to solve the challenges for color management, such as different light sources, characteristics of surfaces, variations in observer, variations in reproduction intent, using material connection to determine material amounts as well as appearance, supporting for bi-spectral and multi-angle measurement and processing and so on. iccMAX profiles will show v5 in the header to distinguish them from v4 and v2. iccMAX profiles will also have class, sub-class, versioning and header information that differs from v4.

Spectral reflectance estimation using a D2Bx profile

iccMAX provides several new features which can be used for characterizing a multispectral camera. To characterize the color of an imaging device, three methods are commonly used. There are tone curves with color mixing matrix, polynomial regression, and color look-up table (CLUT) with interpolation. The CLUT-based approach suffers from huge LUT size when the number of channels is too high. Polynomial regression cannot be applied in ICC version 4. However, it can be easily implemented by Calculator Elements in the iccMAX. The ISO TC130/WG7 /No.115 white paper gave an example of polynomial regression of a CMYK device in Appendix F.2. The method can be used for a multispectral camera. However, it cannot deal with segmented tone characteristics. Besides, the coefficient matrix would be huge if we take interaction of each channel into account. The “tone curves with color mixing matrix” method therefore is highly recommended as the profile size is smaller and the computation cost is relatively lower for the multispectral imaging applications. The following sections will introduce our method on spectral reflectance estimation using the 16-channel multispectral camera with iccMAX profiles. In iccMAX, D2Bx means a forward transform from device space (denoted as D) to SpectralPCS (denoted as B). For a camera, its inverse transform is not needed. Therefore, only D2Bx was implemented in this study. In the D2Bx symbol, ‘x’ represents ICC Reproduction Rendering Intent. In this study, “ICC Absolute Colorimetric” intent is chosen which is referred to ICC No.3 intent. The applied Tag Signature in the iccMAX profile therefore is named as ‘D2B3’.

Tone curve estimation

There are several ways to use an iccMAX profile to perform tone linearization. Most compact way is to use Calculator Elements to apply gamma, gain and offset to the input signals. The Calculator Elements, including curves, matrix, CLUT and tint data, can be used by main functions which use a text nomenclature for expressing the sequences of operations to perform. The first row of Figure 3 represent an operation which inputting 16 channel signals to memory stack. The second row means to apply 2.2 gamma to each of the input signals. The third row indicates that the output of the last operation will be multiplied by a matrix (denoted as ‘mtx’) which is stored at the first position (i.e., number 0) of SubElements. The final row means 36 spectral data will be output.

```
<MainFunction>
{
in(0,16)
2.2 gamma(16)
mtx(0)
out(0,36)
}
</MainFunction>
```

Figure 3. Use a gamma operator in main function to transform input signals.

The main function also can operate input signals of each channel individually. However, it is not suitable for a multispectral camera with complex tone characteristics.

$$linD_i = (a \cdot D_i + b)^{\gamma} + c \quad (1)$$

$$linD_i = a \cdot \log\left(b \cdot D_i^{\gamma} + c\right) + d \quad (2)$$

$$linD_i = a \cdot b^{c \cdot D_i + d} + e \quad (3)$$

$$linD_i = a \cdot \left(b \cdot D_i + c\right)^{\gamma} + d \quad (4)$$

To perform tone linearization for each input channel, SegmentedCurve is recommended. There are at two type of SegmentedCurves, SampledSegment and FormulaSegment. The former uses a 1D loop-up-table to transfer input signal to linear space. It will make the profile bulky especially for a multi-channel device. The latter uses predetermined parameters to define a function for tonal linearization. iccMAX provides 4 function types as Equation 1 to Equation 4 for the linearization. In the equations, D_i and $linD_i$ represent the input and linearized camera signal, respectively. γ, a, b, c, d represent parameters of the tone function. The first type (denoted as FunctionType “0”) is used in this study. In addition, to avoid the impact of out-of-range input signals, the curves are divided into three segmented depended on the input values. From negative infinity to 0, the output will be 0. From 0 to 1, the type 1 function will be applied. From 1 to infinity, the output will equal to 1. Note the in-range input signals is normalized to [0 1] range before the processing.

IccXML is a utility based on SampleICC that converts an ICC profile to an XML encoding, and back from XML to a binary .icc file. The above mentioned FormulaSegments can be expressed in XML as Figure 4

```
<SegmentedCurve>
    <FormulaSegment Start="-inf" End="0.0" FunctionType="0">1.0 0.0 0.0 0.0
    </FormulaSegment>
    <FormulaSegment Start="0" End="1.0" FunctionType="0"> γ a b c
    </FormulaSegment>
    <FormulaSegment Start="1.0" End="+inf" FunctionType="0">1.0 0.0 0.0 1.0
    </FormulaSegment>
</SegmentedCurve>
```

Figure 4. Three FormulaSegments to construct a SEGMENTEDCURVE.

The tone curves can be estimated based spectral radiance or spectral reflectance of a 12-level grayscale in an X-rite ColorChecker SG chart. The former regards spectral power distributions, the camera's exposure time and gain values as variables. If we regard the spectral camera as a spectral radiometer, the approach is useful. However, the interaction of the variables are difficult to be accurately estimated. Therefore, the latter method which relates the spectral reflectance of grayscale in the SG chart is recommended especially for digital archives which only measure object color spectra. As the latter method estimates the camera responses in a relative way, the above mentioned variables can be ignored. However, the profile is valid only under the characterized conditions. It means the spectral photos must be taken under the same lighting and camera setting as we characterized the camera previously.

The following steps were taken for estimating the parameters of the Equation 1.

1. Turn on the light booth (illuminant A) and the spectral camera. Warm-up at least 10 minutes. The SG chart was placed at the center of the booth. The f-stop in our study was 5.6. The lighting/measuring geometry is set as 0/45 to eliminate specular reflection.
2. Use real-time viewing mode, check the image histogram of the central white patch in the SG chart.
3. Adjust the exposure time first to meet 80% gray level. If the maximum exposure time cannot achieve the goal, heighten the gain value to increase the gray level. Each channel will perform the adjustment individually.
4. Take and store the spectral photos in 12-bit PNG format.
5. Read the 12-level grayscale from the center of the SG chart images. After normalizing the gray level into [0 1] range and averaging the center pixel values of each patch, the resulted input signal denotes as Di. 'i' represents spectral channel. There are 16 channels from 400 to 700nm in roughly 20nm bandwidth.
6. Use pre-measured spectral reflectance of the 12 grayscale. Interpolate into the 16 wavebands as target linDi, and regard the Di as input signals, then solve the parameters of Eq. 1 using a Matlab function of least squared curve fitting (i.e., 'lsqcurvefit').

Blue spots in Figure 5 indicate the reflectance sample points of the 12 grayscale of the 16 channels. We found that using 4 parameters for Equation 1 would cause overfitting. The lightness L* black patch will be overestimated about 15 ΔL^* which is not acceptable. To solve this problem, we added a constraint (b = 0) in the curve fitting, and it shows excellent results. Red lines in the Figure 5 illustrate the curve fitting using the optimal parameters. The mean values of gamma, a and c, except the unusually 400nm tone curve, are 1.04, 1.16 and -0.07, respectively.

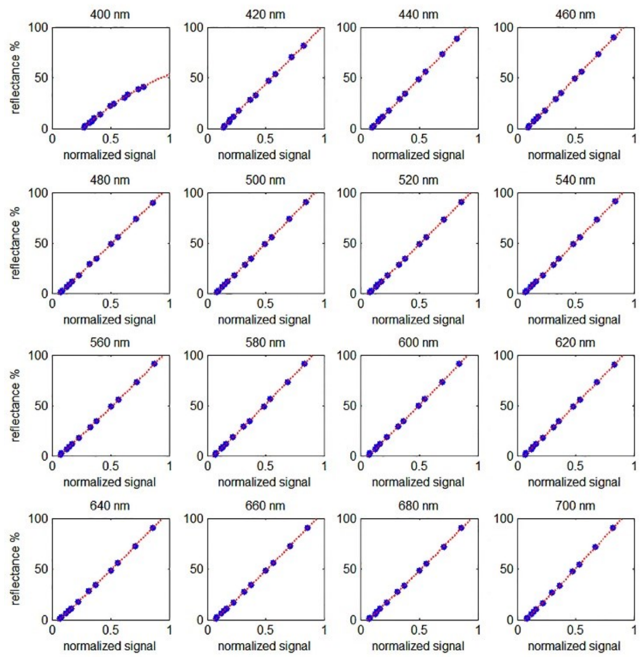

Figure 5. Least squared curve fitting using Equation 1 with 12 grayscales of the SG chart in 16 channels respectively.

Derive the color mixing matrix

In a D2B3 conversion, a color-mixing matrix is needed to convert linear multi-channel camera signals ($linD_i$) to the corresponding spectral reflectances. It can be done in at least two ways:

1. **Polynomial regression** between the linear signals and their corresponding spectral reflectances: As the number of spectral bands is normally much higher than the number of camera channels, it need a large data base to avoid overfitting.
2. **Pseudo-Inverse** of the scaled spectral response functions: Equation 5 is a typical multispectral camera model. E_λ represents spectral radiance of the light source, R_λ denotes spectral reflectance of an object, $T_{i,\lambda}$ is the spectral transmittance of the i-th filter, and the S_λ represents spectral sensitivity of the monochromatic CCD sensor. If we want the linear camera signal $linD_i$ matching the spectral R_λ. Both of them can be cancelled out as Equation 6. The E_λ and S_λ are unknown, however, the mean values of $E_\lambda \times S_\lambda$ can be estimated by Equation 7. It means to convert a spectral reflectance to the linear camera signal, all we need are the spectral transmittance $T_{i,\lambda}$ and the scaling factor c_i shown in the Equation 7.

$$linD_i = \sum^{\lambda} E_\lambda R_\lambda T_{i,\lambda} S_\lambda \Delta\lambda \quad (5)$$

$$1 = \left(\overline{E}_\lambda \cdot \overline{S}_\lambda\right) \sum^{\lambda} T_{i,\lambda} \Delta\lambda \quad (6)$$

$$c_i = \left(\overline{E}_\lambda \cdot \overline{S}_\lambda\right) = 1 / \sum^{\lambda} T_{i,\lambda} \Delta\lambda \quad (7)$$

We took the pseudo-inverse approach to derive the color-mixing matrix. Figure 2 show the spectral transmittance of all filters in about 1nm resolution. Ideally, the matrix in the D2B3 should be an inversion of the c_i scaled T matrix. If we perform the pseudo-inverse using the scaled T matrix (referring to Figure 2), the results will be a color mixing matrix like Figure 6. Compare Figure 2 and Figure 6, the major difference is that the latter has negative values at both sides of the super Gaussian functions.

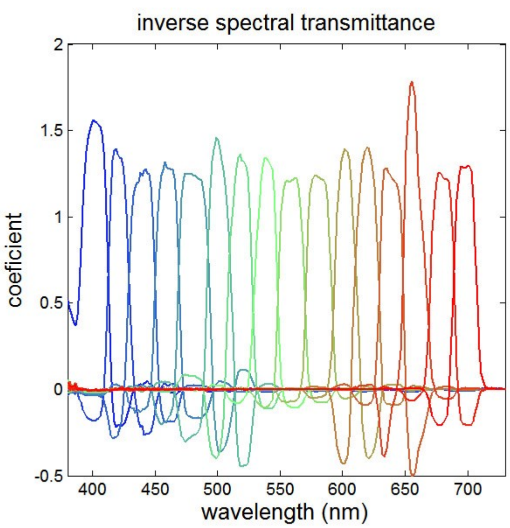

Figure 6.. Pseudo-inverse of the spectral transmittance matrix.

In this study, the SpectralPCS of the camera is 380 to 730nm with 10nm interval. Therefore we must down-sample the T matrix. However, we found the shape of the reduced T matrix is different from the original T matrix. According to Nyquist–Shannon sampling theorem, a low-pass spatial filter must be applied before the down-sampling. To test the effect of low-pass filtering, 4 cases were tested.

1. **Case 1:** Step 1- direct down-sample to 36 bands. Step 2 scale each of the curves to 1. Step 3- pseudo-inverse. The result is shown in Figure 7-Case 1.
2. **Case 2:** Step 1 - scale each of the curves to 1. Step 2- pseudo-inverse of the matrix. Step 3- down-sample to 36 bands. The result is shown in Figure 7-Case 2.
3. **Case 3:** Step 1 - scale each of the curves to 1. Step 2- pseudo-inverse of the matrix. Step3 – apply a low-pass filter with **20nm** width. Step 3- down-sample to 36 bands. The result is shown in Figure 7-Case 3.
4. **Case 4:** Step 1 - scale each of the curves to 1. Step 2- pseudo-inverse of the matrix. Step3 – apply a low-pass filter with **40nm** width. Step 3- down-sample to 36 bands. The result is shown in Figure 7-Case 4.

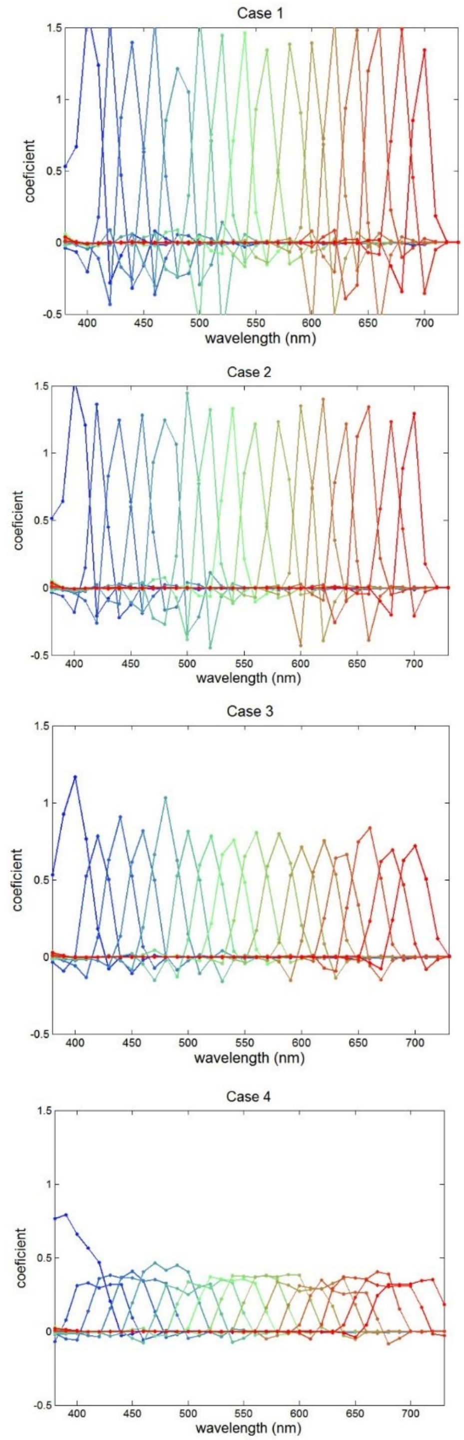

Figure 7. Four different inverse matrices. As can be seen, Case 3 and Case 4 which processed by low-pass spatial filters have more spectral overlay between each channel and have less negative parts.

We send 1 (maximum signal) to all 16 channel as a test. The results, referring to Figure 8, show that Case 3 and Case 4 which applied low-pass spatial filters are smoother in its spectral reconstruction. We also reset all channels to be 0 except give 1 to the channel at 540nm. The results, referring to Figure 9, show that Case 1 and Case 2 recovered the spectral reflectance sharply. But the curve for Case 4 is too smooth.

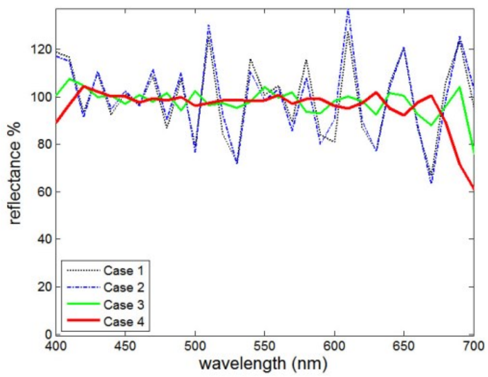

Figure 8. Spectral reconstruction of all 1 signals using four different color-mixing matrices.

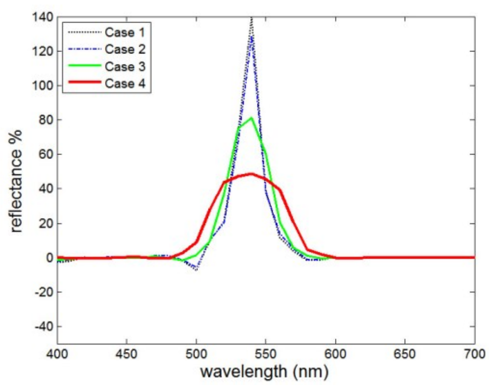

Figure 9. Spectral reconstruction of all 0 signals except one channel (at 540nm) using four different color-mixing matrices.

Results

Camera-to-SpectralPCS

The ICC official website provide a Reference iccMAX C++ source codes (denoted as RefIccMAX) for testing and study. The following test results are based on RefIccMAX v.0.17. The iccMAX profile can be convert to XML format in two-way using the previous mentioned iccXML. The first test generated a set of iccMAX profile based on MultiProcessElements which apply functions using two SubElements: (1) CurveSetElement and (2) MatrixElement. Figure 10 illustrates its XML codes.

Table 1 and Table 2 list the root mean squared errors (RMSE) of the spectral estimation and color differences of the 140 patches of the SG chart under five illuminants including D50, A, CWF, TL84 and white LED. As can be seen, Case 3 is the best where the mean error overall 5 different light sources are 2.23 ΔE_{00} only. In terms of the light sources, illuminant A is slighter better than all the others, and white LED is slighter worse than the others.

```
<MultiProcessElements InputChannels="16" OutputChannels="36">
    <CalculatorElement InputChannels="16" OutputChannels="36">
    <SubElements>
          <!--Element 0 -->
            <CurveSetElement InputChannels="16" OutputChannels="16">
          <!--Element 1 -->
            <MatrixElement InputChannels="16" OutputChannels="36">
        </SubElements>
        <MainFunction> {
        in(0,16)
        curv(0)
        mtx(1)
        out(0,36) }
        </MainFunction>
    </CalculatorElement>
</MultiProcessElements>
```

Figure 10. MultiProcessElements using two CurveSetElement and MatrixElement sub-elements.

Table 1: Camera-to-SpectralPCS errors (unit: CIEDE2000).

	Case 1				Case 2			
	mean	std	95%	max	mean	std	95%	max
RMSE	0.061	0.044	0.151	0.160	0.063	0.046	0.156	0.165
D50	2.45	2.31	7.73	12.55	2.84	2.10	7.48	12.29
A	2.21	1.80	6.12	10.09	2.53	1.63	5.87	9.99
CWF	2.39	2.07	7.37	11.46	2.62	1.85	7.05	11.14
TL84	3.70	2.20	8.92	12.91	4.63	2.45	8.75	12.36
W LED	2.61	2.62	9.43	13.26	3.11	2.31	9.00	12.82
avg.	2.67	2.20	7.91	12.05	3.15	2.07	7.63	11.72

Table 2: Camera-to-SpectralPCS errors (unit: CIEDE2000).

	Case 3				Case 4			
	mean	std	95%	max	mean	std	95%	max
RMSE	**0.029**	0.019	0.067	**0.087**	0.042	0.030	0.099	0.114
D50	2.34	2.27	7.52	12.56	2.62	2.21	7.81	13.30
A	2.08	1.75	6.01	10.19	2.33	1.71	5.88	10.96
CWF	2.26	1.89	6.29	11.37	2.37	1.95	6.27	12.29
TL84	**2.06**	2.11	7.04	11.64	2.59	1.81	6.42	11.80
W LED	2.42	2.51	8.84	13.02	2.59	2.43	8.29	13.64
avg	**2.23**	2.10	7.14	11.76	2.50	2.02	6.93	12.40

Camera-via-PCC-to-sRGB

The iccMAX provides late-binding processing elements which can apply illuminants different from standard ICC profile connection space (PCS) D50 illuminant. We applied D50, A, D65 and D93 PCC profile (profile connection condition) with 2 degree observers in either absolute colorimetry (denoted as Abs) or applied a

CIECAT02 chromatic adaption transform (denoted as CAT) to minimize color shift. We regarded a virtual sRGB display as the destination. The profile sequence is from camera via illuminants to RGB. After the illuminant transform, the LAB values will convert to sRGB using a B2A transform with a sRGB profile. The change of illuminant would bring some colors outside the sRGB gamut. Table 3 lists the color errors of the Camera-PCC-sRGB transforms. As can be seen, the native D50 is the best. Illuminant A-Abs and D93-Abs are worse than all the others, as they shift color towards yellow and blue, respectively. The outside-gamut errors significantly reduced by applying the chromatic adaption transform.

Figure 11 show a real multispectral example using the iccMAX Camera-PCC-sRGB framework to generate the absolution colorimetric images for A, D50, D65 and D93, respectively. The results are reasonable.

Table 3: Camera-via-PCC-to-sRGB errors (unit: CIEDE2000).

		mean	std	95%	max	outside gamut %
D50		0.42	1.21	3.35	5.79	18.0
A	Abs	2.00	3.67	11.18	12.37	45.7
	CAT	0.46	1.14	3.53	4.95	20.0
D65	Abs	1.17	2.31	6.67	8.06	21.4
	CAT	0.45	1.34	3.63	6.65	18.6
D93	Abs	2.47	4.62	14.27	16.13	36.4
	CAT	0.49	1.46	3.84	7.39	17.9

Conclusions

A commercially available multispectral camera was characterized using iccMAX profiles. How to optimize its tone linearization and color-mixing matrix are introduced. The spectral and color errors of both camera-to-spectralPCS and camera-via-PCC-to-sRGB conversions were estimated and the resulted errors are acceptable. The iccMAX is much powerful than the ICC v4 as the former provides freedom to store, to process a variety of image and viewing condition data. We like the calculation ability which allow the users to do image color processing or experiment by means of the iccMAX profile only. But the iccMAX is imperfect. There are some parts should be improved in the future. For example, the iccMAX store many useful data such as the power spectral distribution of an illuminant. However, most of them are not accessible by using the main functions. The instruction and examples about how to use the iccMAX profiles and the ReficcMAX also are not clear enough. iccMAX is much complex than the ICC v4. How to educate the users will be a great challenge in the future.

Figure 11. Camera-via-PCC-to-sRGB simulation (absolute transform). Top-left: illuminant A. Top-right: D50. Bottom-left: D65. Bottom-right: D93.

Acknowledgements

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