Recovering spectral data from digital prints with an RGB camera using multi-exposure method

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Abstract

The spectral data of a surface can be reconstructed from RGB camera response when reflectance spectrum of the surface and radiance spectrum of the light source are smooth enough. One factor that lowers the reconstruction performance of consumer level cameras is limited dynamic range. Details or intensity levels in low and high luminance regions can not be reliably detected from a single image. With multiple exposures it is possible to capture high dynamic range images. The aim of this study was to apply a multi-exposure method for spectral data reconstruction of prints and find how accuracy it is. Our intended application area is printed image digitization for image quality calculations. We measured the intensity levels and recovered spectral data of printed samples by taking two images using different exposure times. Based on the results multi-exposure method improves the accuracy of spectral data reconstruction of print samples compared to traditional methods and is the preferred choice for printed image digitization process.

Introduction

Spectral data provide the most useful information for color reproduction measurements. The spectral data of a sample can be measured by spectroradiometer. Spectroradiometer measurements are precise but time-consuming and point-wise. Point-wise measurements are not applicable for some applications. For example spatial variations of spectral data in a natural scene cannot be measured using a point-wise device. Respectively spectral information of a printed photograph is difficult to measure using a point-wise device.

Our intended application area is printed image digitization. This digitization process has been developed for our printed image quality calculation system [1]. The idea in our printed image quality calculation system is to digitize the printed image and calculate the quality of printed image by comparing the features of original digital image and printed images. When printed image quality is calculated the accuracy and spatial sampling frequency of colour measurement should be high enough. Earlier we have used (RGB to XYZ) characterised digital camera for spatial sampling of printed images [1]. In some other studies [2],[3] reflective scanners have been used for spatial sampling.

There are plenty of earlier studies where a RGB camera (spatially sampling device) is used as a spectral measurement device. This is possible because the spectral data of natural scenes, objects and illumination are smooth. It is a known fact that the dynamic range of consumer digital cameras is the limiting factor of their imaging performance. Often consumer digital cameras are not capable of detecting, in a single image, the entire intensity range hitting the sensor. Reliable detection is possible only if more than one exposure is used. In this paper we describe our experiments in which we investigated the performance of a multi-exposure method for spectral data reconstruction of printed samples.

In previous studies the reconstruction accuracy has been improved by increasing the number of response channels using different filter combinations. Valero et. al. [4] measured that two or three filters improved significantly the reconstruction performance. In some studies the number of channels was increased by producing images under spectrally different light sources [5].

The principal component analysis (PCA) is the traditional linear method for reconstruction of the spectral data from a camera response [5] or to analyse the dimensionality of a sample spectra set [6]. Other base function methods have also been studied. Li and Berns [7] studied the performance of ICA analysis compared to the PCA. Mansouri et. al. [8] studied the performance of Fourier and Wavelet bases.

The second linear method to estimate the spectral data from camera response is based on the camera's filter functions. Camera is a linear system which can be described by the Equation (1):

$$\mathbf{C} = \mathbf{RW} \tag{1}$$

where vector **C** is response of the camera, vector **R** is spectral data of the sample and matrix **W** contains filter functions for the camera's channels [9]. The filter functions can be measured using a monochromator or they can be estimated using different constraints [10] or parametric functions [12].

Spectral data can be estimated also without a need for basis or filter functions [9]. For example the spectra, **R**, can be directly estimated from the RGB values, **C**, using a transform matrix **M** (Equation 2). Solli et. al. [9] solved transform matrix **M** using Moore-Penrose pseudo-inverse of **R**.

$$\mathbf{R} = \mathbf{CM} \tag{2}$$

The accuracy of the methods has been further improved using different local weights. Agahian et. al. [12] used a weighted principal component analysis for reconstruction of reflectance spectra. The method increased the influence of training samples that were close to the testing sample when base functions were formed. The closeness metric which was used was the colour difference between training and testing samples.

Shen and Xin [13] assumed that training samples $\mathbf{u}_i$ closer to a testing sample **u** are usually more reliable and thus should contribute more to the estimation of the transformation matrix $\mathbf{W}_{\mathbf{shen}}$. They calculated weights α_i for $\mathbf{u}_i$ as:

$$\alpha_i = (2\pi)^{-3/2}\left|\Sigma_{\mathbf{UU}}\right|^{-1/2}\exp\left[-\frac{1}{2}(\mathbf{u}_i-\mathbf{u})^T\,\Sigma_{\mathbf{UU}}^{-1}(\mathbf{u}_i-\mathbf{u})\right] \tag{3}$$

where Σ_{UU} is covariance matrix of $\mathbf{u}_i$. By incorporating the weighting, the mean square error between the measured and the predicted spectra can be formulated as:

$$J = \frac{1}{L}\sum_{i=1}^{L}\left\| \mathbf{W}_{shen}\alpha_i\mathbf{u}_i - \alpha_i\mathbf{r}_i \right\|^2 \quad (4)$$

In this study we use the method of Shen and Xin [13] to test the performance of multi-exposure technology. We measure spectral data and camera response data for the printed samples. Then we evaluate the colorimetric and spectral performance of multi-exposure method compared to the traditional single-exposure method.

Spectral data

For performance evaluation of multi-exposure method we used the 180 colour patches of Gretag Macbeth DC test target (teaching samples) and the 24 colour patches of Gretag Macbeth CC test target (testing samples). The digital test target images were printed on six paper grades. Properties of these papers are listed in Table 1. Papers P1 and P2 were copy papers and papers P3 - P6 ink-jet papers. The gloss values for papers P3 and P4 were high compared to the other papers. Gloss values for papers P3 and P4 were 75 and 77.1 and for papers P1, P2, P5 and P6 were 2.8 – 6.6. We used Epson Stylus Pro 3800 ink-jet printer. Paper-specific ICC profiles were determined in Profilemaker Pro software before printing.

Table 1. Paper types, grammage and gloss

Paper	Paper type	Grammage (g/m^2)	Gloss (GU)
P1	copy paper	84	6.6
P2	copy paper	84	4.0
P3	ink-jet paper	186	75.0
P4	ink-jet paper	167	77.1
P5	ink-jet paper	101	2.8
P6	ink-jet paper	98	3.5

The spectral data of the printed samples were measured by the Photo Research PR-670 spectroradiometer. The measurement environment included two halogen lamps. The luminance level of a white reflector on the measurement plane was 2800 cd/m^2. The colour temperature of the light sources was 3097 K. The structure of measurement environment is shown in Figure 1.

The printed test samples were photographed by Canon EOS 5D camera with Canon EF 50 mm/2.5 lens. The aperture of the lens was F9. The photometric distortion of the lens and possible uneven illumination on the plane was compensated by the correction matrix. The correction matrix included pixel-wise correction factors for the camera image. The factor values were derived from the low-pass filtered image of the uniform grey-surface that was photographed on the measurement plane. Figure 2 shows an intensity image of correction factor matrix for green channel in our measurement environment. Compensation of uneven lighting because of optic is a important step for digitization process. Correction factors can be even more than 1,5.

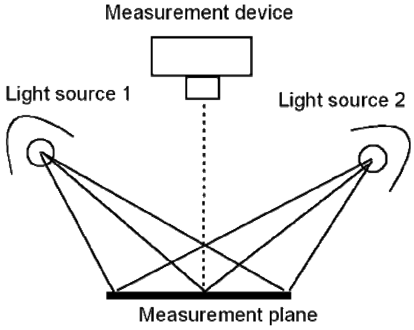

Figure 1. *The measurement environment includes two halogen lamps (3097 K), measurement plane for samples and measurement device holder perpendicular to the measurement plane*

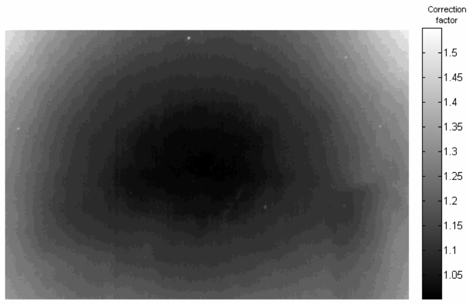

Figure 2. *Intensity image of correction factor matrix for green channel in our measurement environment*

Multi-exposure method

Our multi-exposure method produces an RGB intensity image by selecting intensity values from two images, I_1 and I_2, produced using different exposure times (1/40s and 1/80s). The purpose of the longer exposure (1/40s) image I_1 was to detect the lower intensity values of the samples and the purpose of the shorter exposure (1/80s) image I_2 was to detect the higher intensity values. The selected exposure times were based on the response of exposure 1/80 that produced the optimal single-exposure image in our lighting environment. This optimum image was defined so that the response values did not saturate.

The threshold for selecting the response of exposure 1/40 or 1/80 was intensity value of 0.5 (scale 0-1). If intensity value of exposure 1/40 was more than 0.5, the intensity of exposure 1/80 was selected for multi-exposure image and multiplied by factor of 2. If intensity of exposure 1/40 was smaller than 0.5, the intensity of exposure 1/40 was selected. Figure 3 shows a flow chart of process for estimating spectra $\hat{p}$ for pixel position (i,j) where I_{ME} is multi-exposure image with size of N x M pixels, I_C is pixel-wise correction matrix, I_{MEc} is corrected multi-exposure image and W is transformation matrix solved by the method proposed by Shen and Xin [13].

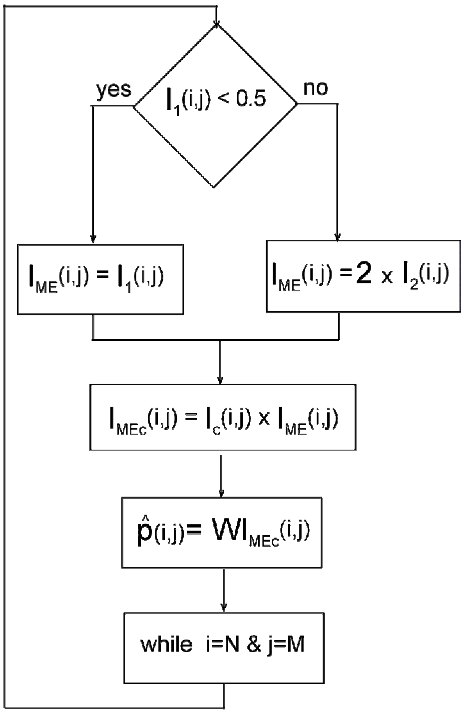

Figure 3. *Flow chart for spectra, $\hat{p}$, reconstruction in pixel position, (i,j), where I_1 is long-exposure image (1/40s) and I_2 is short-exposure image (1/80s), I_{ME} is multi-exposure image, I_C is pixel-wise correction matrix, I_{MEc} is corrected multi-exposure image and W is transformation matrix solved by the method proposed by Shen and Xin [13]*

Table 2 shows the minimum and maximum luminance values (cd/m^2) for the paper samples in our lighting environment. Minimum luminance values were measured from full-tone black patches and maximum luminance values were measured from the plain papers. Figure 4 shows the response of the camera with exposures of 1/40s and 1/80s. The response was measured from the transparency test target (Image Engineering TE241) using an integrating sphere (Image Engineering LE6). The illumination level of the integrating sphere was set to encompass the illumination scale in our lighting environment. Figure 5 shows the response of the camera in scale 0 – 600 cd/m^2. The added dotted lines show the minimum luminance levels for the paper samples. The added lines show the linearity level of the responses.

Table 2. Minimum and maximum luminance of the paper samples in test environment

Paper	Min luminance (cd/m^2)	Max luminance (cd/m^2)
P1	238	2384
P2	227	2429
P3	54	2614
P4	41	2554
P5	138	2436
P6	127	2421

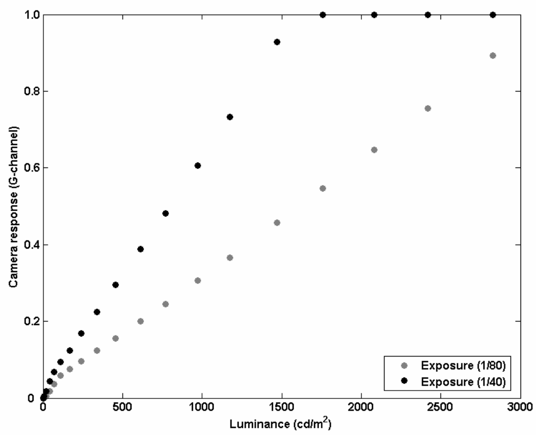

Figure 4. *Camera responses for exposures 1/80s and 1/40s in scale 0 – 3000 cd/m^2*

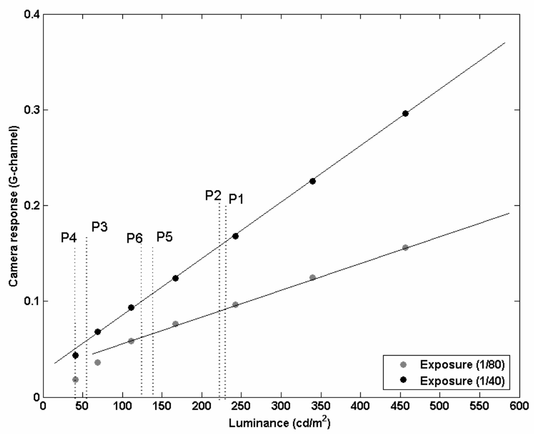

Figure 5. *Camera responses for exposures 1/80s and 1/40s in scale 0 – 600 cd/m^2*

Based on Table 2 the light absorption capability of paper depends strongly on the paper grade. The minimum luminance levels of the papers P1 and P2 were fivefold compared to the papers P3 and P4. The minimum luminance levels of the papers P5 and P6 were threefold compared to the papers P3 and P4. Based on Figure 5 the response of exposure 1/80 changes to be nonlinear after the luminance of 100 cd/m^2. Respectively, the response of exposure 1/40 starts to become nonlinear after the luminance of 50 cd/m^2. Based on this the usage of the exposure 1/40 expands the reliable detection area at low luminance levels.

Performance metrics for spectral reconstruction

Two measures were used for the performance assessment of the multi-exposure method: the spectral goodness-of-fit coefficient (GFC) [1] and the colorimetric CIEDE2000 color difference metric [11]. GFC is defined in Equation (5):

$$GFC = \frac{\sum_{\lambda=400}^{700} \hat{p}(\lambda)p(\lambda)}{(\sum_{\lambda=400}^{700} \hat{p}(\lambda)^2)^{1/2}(\sum_{\lambda=400}^{700} p(\lambda)^2)^{1/2}} * 100\,\% \tag{5}$$

where $\hat{p}$ are the reconstructed spectra and p measured spectra. Values range from 0 to 100 %. Valero [4] used the definitions: when GFC (%) > 99.5 % reconstruction is acceptable and when GFC (%) ≥ 99.99 reconstruction is almost-exact fit.

The second metric was CIEDE2000 color difference:

$$CIEDE2000 = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)} \tag{6}$$

where ΔL' is the lightness difference between samples, ΔC' is the chroma difference between samples and ΔH' is hue difference between two samples. Complete equations and descriptions for variables ΔL', ΔC', ΔH', S_L, S_C and S_H can be found in [11]. CIEDE2000 was calculated with reference to the spectra of the white patch in our lighting environment using default parameter values of k_L, k_C and k_H.

Spectral reconstruction results

Table 3 shows the CIEDE2000 color error and Table 4 shows the GFC values of the teaching samples for the single-exposure and multi-exposure methods. Table 5 and Table 6 show the values of testing samples. Figure 6 compares the mean and Figure 7 compares the maximum CIEDE2000 color error values between single- and multi-exposure methods for the testing samples.

Table 3. Mean and maximum CIEDE2000 colour error values for different paper grades using single-exposure (SE) and multi-exposure (ME) methods (teaching samples)

paper	Mean CIEDE2000		Max CIEDE2000	
	SE	ME	SE	ME
P1	1.16	**1.12**	**4.66**	4.82
P2	1.19	**1.05**	5.25	**4.65**
P3	1.81	**1.60**	8.29	**6.81**
P4	1.98	**1.66**	9.50	**6.75**
P5	1.32	**1.14**	**5.36**	5.96
P6	1.40	**1.17**	5.80	**3.64**

Table 4. Mean and minimum GFC values for different paper grades using single-exposure (SE) and multi-exposure (ME) methods (teaching samples)

paper	Mean GFC (%)		Min GFC (%)	
	SE	ME	SE	ME
P1	**99.967**	99.966	**99.571**	98.863
P2	**99.962**	99.964	**99.653**	99.122
P3	99.861	**99.892**	**97.648**	96.500
P4	99.824	**99.864**	**96.435**	94.931
P5	**99.955**	99.950	**99.214**	97.706
P6	99.950	**99.959**	**99.114**	99.238

Table 5. Mean and maximum CIEDE2000 colour error values for different paper grades using single-exposure (SE) and multi-exposure (ME) methods (testing samples)

paper	Mean CIEDE2000		Max CIEDE2000	
	SE	ME	SE	ME
P1	1.43	**1.37**	4.24	**3.14**
P2	1.44	**1.24**	3.84	**3.17**
P3	2.40	**2.04**	6.90	**3.57**
P4	2.15	**1.90**	6.08	**3.60**
P5	1.37	**1.30**	4.04	**2.72**
P6	1.76	**1.45**	5.33	**3.61**

Table 6. Mean and minimum GFC values for different paper grades using single-exposure (SE) and multi-exposure (ME) methods (testing samples)

paper	Mean GFC (%)		Min GFC (%)	
	SE	ME	SE	ME
P1	99.961	**99.968**	99.810	**99.892**
P2	99.826	**99.966**	99.580	**99.855**
P3	99.826	**99.857**	98.596	**99.008**
P4	99.826	**99.829**	**98.223**	97.692
P5	99.939	**99.945**	99.398	**99.589**
P6	99.934	**99.938**	97.385	**99.443**

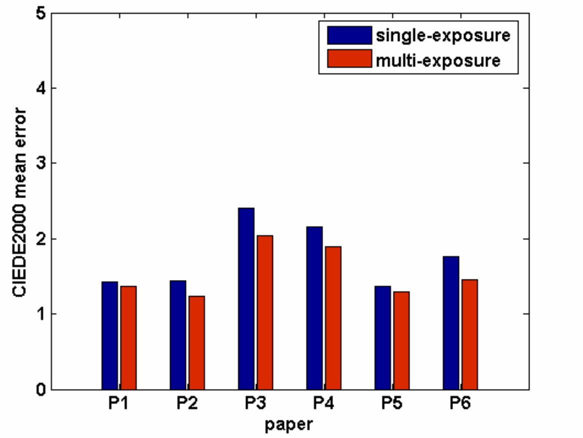

Figure 6. *CIEDE2000 mean colour error values of different paper grades using single-exposure and multi-exposure methods for testing samples*

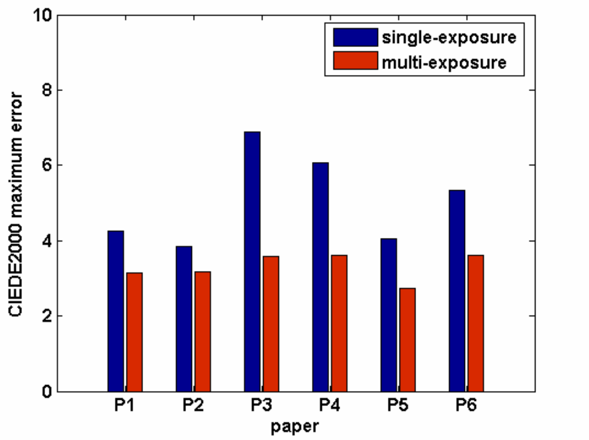

Figure 7. *CIEDE2000 maximum colour error values of different paper grades using single-exposure and multi-exposure methods for testing samples*

Based on the results the performance of the multi-exposure method is higher than the performance of the single-exposure method. In the case of the testing samples all values of the multi-exposure method were better than the values of the single-exposure method, excluding minimum GFC value of paper P4.

Mean GFC values were between 99.83% – 99.97% with multi-exposure method and 99.83% - 99.96% with single-exposure method for testing samples. Based on Valero [4] the average level of reconstruction is acceptable with both multi-exposure and single-exposure methods. Minimum GFC values were between 97.69% - 99.89 with multi-exposure method and 97.39% - 99.81% with single-exposure method. Based on Valero [4] the minimum GFC value with both multi-exposure and single-exposure methods is under acceptable level for some paper type.

Differences between mean CIEDE2000 colour error values with the single-exposure and multi-exposure methods were between 0.06 – 0.36 units. Differences between maximum CIEDE2000 colour error values were between 0.67 – 3.33. Based on the mean CIEDE2000 colour error for testing samples the multi-exposure method improved most the performance of paper P3.

Maximum CIEDE2000 colour error with the single-exposure method for paper P3 was 6.90 units. The colour patch was the darkest neutral (patch number 24) in the Gretag Macbeth CC test target. CIEDE2000 colour error for this patch with the multi-exposure method was 2.60 units. Figure 8 shows the measured spectra and the reconstructed spectra of this patch. Based on Figure 8 the multi-exposure method improves the reconstruction accuracy mostly in the area of low- and mid-wavelengths. Respectively, the reconstructed spectra of the single- and multi-exposure method equal each other in the area of long-wavelengths.

The second problematic patch with the single-exposure method was the dark brown (patch number 1) in Gretag Macbeth CC test target. Figure 9 shows the measured spectra and the reconstructed spectra of this colour patch for paper P5. When method was the single-exposure the reconstructed spectra differed from the measured spectra mostly in the area of long-wavelengths. The reconstruction accuracy of the multi-exposure method was high.

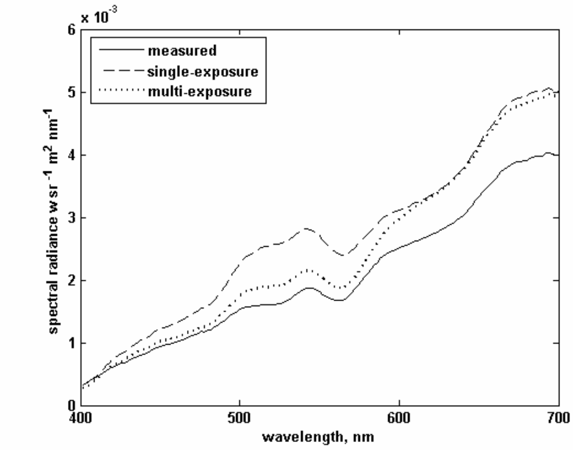

Figure 8. Spectral radiances for dark neutral patch (patch number 24) in Gretag Macbeth CC test target printed on paper P3

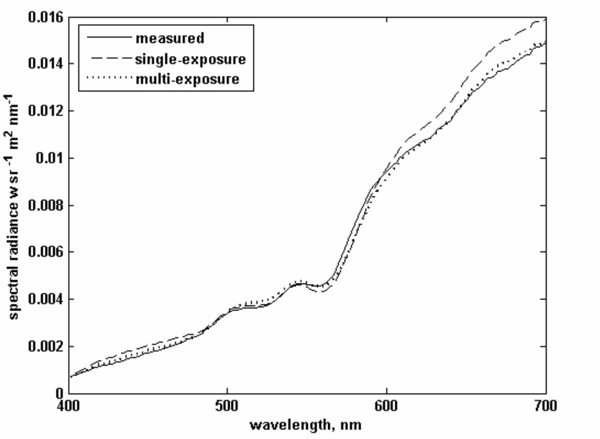

Figure 9. Spectral radiances for dark brown patch (patch number 1) in Gretag Macbeth CC test target printed on paper P5

Figure 10 shows the CIEDE2000 colour error values of paper P3 and Figure 11 shows CIEDE2000 colour error values of paper P5 for the testing samples (Gretag Macbeth CC target) ordered in ascending order by measured luminance values of the patches. Based on Figure 10 and Figure 11 the multi-exposure method improved mostly the reconstruction performance of the dark patches. The one problematic patch for the multi-exposure method was patch number 3. Figure 12 shows the measured spectra and reconstructed spectra for this light blue colour patch of paper P3.

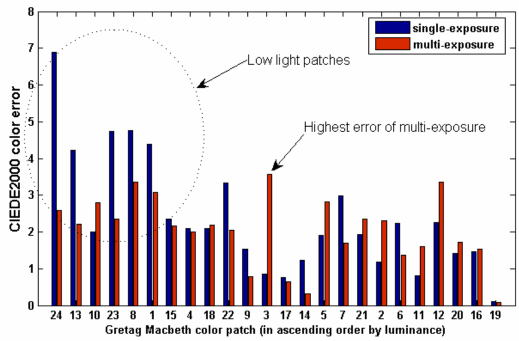

Figure 10. CIEDE2000 colour error values for paper p3 ordered in ascending order by measured luminance of patches

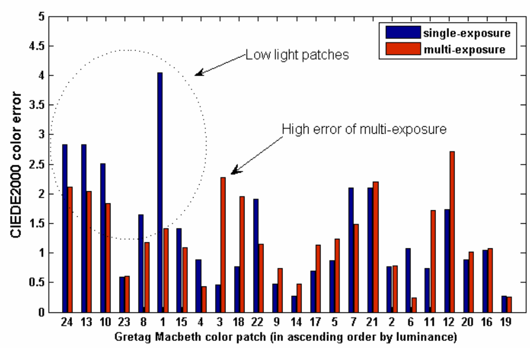

Figure 11. CIEDE2000 colour error values for paper p5 ordered in ascending order by measured luminance of patches

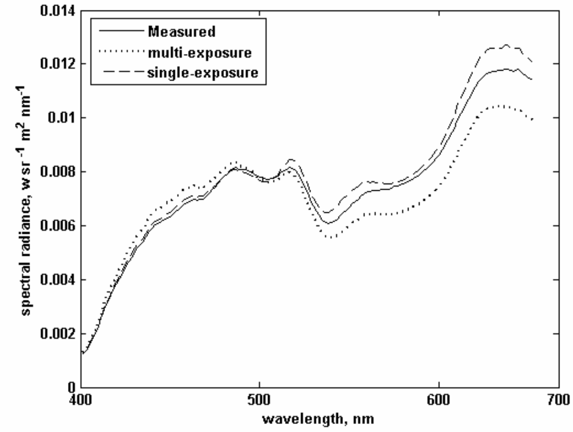

Figure 12. *Spectral radiances for patch number 3 printed on paper P3*

Conclusions

Based on the results the multi-exposure method improves the reconstruction performance. In particular the performance for reconstruction of dark colour patches with the Multi-exposure method was high compared to the performance of the single-exposure method. This was an expected result. The multi-exposure method detects the lower luminance levels more linearly than the single-exposure method does. Multi-exposure method is preferred choice for the module of colour measuring in printed image digitization system.

With special high dynamic range cameras the detection is linear over a wide luminance range. In that case the multi-exposure method would be worthless. Anyway the camera used in our study is a high-end product and multi-exposure method increased its performance even when the application specific requirements were pretty low compared to many other applications. For example the luminance range in natural scenes is much wider than in reflectance prints.

References

[1] M. Nuutinen, R. Halonen, T. Leisti, P. Oittinen, Reduced-reference quality metrics for measuring the image quality of digitally printed natural images, Proc. SPIE 7529, 75290I (2010).
[2] T. Eerola, J.-K. Kamarainen, T. Leisti, R. Halonen, L. Lensu, H. Kälviäinen, P. Oittinen, G. Nyman, Finding Best Measurable Quantities for Predicting Human Visual Quality Experience, Proc. IEEE International Conference on Systems, Man, and Cybernetics, p. 733-738 (2008).
[3] R. Halonen, T. Leisti, P. Oittinen, The Influence of Image Content and Paper Grade on Quality Attributes Computed from Printed Natural Images, Proc. NIP 24, p. 459-462 (2008).
[4] E.M. Valero, J.L. Nieves, S.M.C. Nasciment, K. Amano, D.H. Foster, Recovering Spectral Data from Natural Scenes with an RGB Digital Camera and Colored Filters, Color Research and Application, 32, 5 (2007).
[5] F.H. Imai, R.S. Berns, Spectral Estimation Using Trichromatic Digital Cameras, Proc. Int. Symp. on Multispectral Imaging and Color reproduction for Digital Archives, p. 42-49 (1999).
[6] S.M.C. Nascimento, D.H. Foster, K. Amano, Psychophysical estimates of the number of spectral-reflectance basis functions needed to reproduce natural scenes, J. Opt. Soc. AM. A, 22, 6 (2005).
[7] Z. Li, R.S. Berns, Evaluation of Linear Models for Spectral Reflectance Dimensionality Reduction, Proc. ICIS, p. 288-291 (2006).
[8] A. Mansouri, T. Sliwa, J.Y. Hardeberg, Y. Voisin, Representation and Estimation of Spectral Reflectances Using Projection on PCA and Wavelet Bases, Color research and application, 33, 6 (2008).
[9] M. Solli, M. Andersson, R. Lenz, B. Kruse, Color Measurements with a Consumer Digital Camera Using Spectral Estimation Techniques, Proc. 14th Scandinavian Conference on Image Analysis, vol. 3540 of Lecturel notes in Computer Science, p. 105-114 (2005).
[10] K. Barnard, B. Funt, Camera Characterization for Color Research, Color research and application, 27, 3 (2002).
[11] M. Thomson, S. Westland, Colour-Imager Characterization by Parametric Fitting of Sensor responses, Color research and application, 26, 6 (2001).
[12] F. Agahian, S.A. Amirshahi, S.H. Amirshahi, Reconstruction of Reflectance Spectra Using Weighted Principal Component analysis, Color research and application, 33, 5 (2008).
[13] H.-L. Shen, J.H. Xin, Colorimetric and Spectral Characterization of a Color Scanner Using Local Statistic, Journal of Imaging Science and Technology, 48, 4 (2004).
[14] S. Westland, C. Ripamonti, Computational Color Science using MATLAB, (John Wiley & Sons, Ltd, England 2004) 207 p.

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