Robust Spectral Implementation of High-Fidelity Printer Characterization for Cross-Media High-Dynamic-Range Imaging Applications

Mei-Chun. Lo, Jin-Ling. Lin, Chong-Zhi Guo, and Hsin-Kai Ma
Department of Information Management, Shih Hsin University, Taipei, Taiwan

Abstract

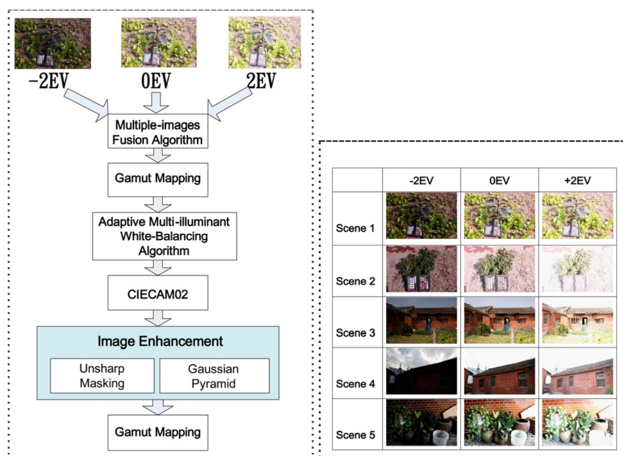
*This research introduces a multi-spectral type of High-Fidelity (Hi-Fi) colorant color separation algorithm for printing/printer system using more than four inks (colorants). This Hi-Fi colorant separation algorithm, derived for six-colorant CMYKOG printer systems, finds the best colorant combination to reproduce spectra of every color, concerned in high-dynamic-range of original images for an accurate color -matching or –reproduction application. This work revised and extended a previous research, which carried out a seven-ink of CMYKRGB FM printing characterization of presses, only used in the conventional Graphic Arts. An Epson 9900 inkjet printer, having the capability of a six-colorant set, CMYKOG, was spectrally characterized for High-Fidelity (Hi-Fi) multi-color printer simulation. The superset of CMYKOG was divided into three subsets, including two five-colorant groupings of CMYKO and CMYKG, and one four-colorant grouping of CMYK. The spectral printer characterization applied a polynomial regression approach with singular value decomposition method (SVD). The mean ΔE*00 values were 0.98~1.17 and 1.06~1.33 found in the forward and the reverse processes respectively. Also 0.0008 ~ 0.0011 and 0.0009 ~ 0.0024 of the mean RMSE values were obtained for the forward and the reverse spectral transform respectively. It implies the spectral reflectance of every color in test datasets was satisfactorily reconstructed. Moreover, to robustly perform a feasible approach of spctral color management for Hi-Fi printer simulation in cross-media color reproduction system, a GUI-based of HDR (High-Dynamic-Range) image-fusion module were also be introduced to produce original HDR complex color images. It integrated algorithms of: 1) a multi-raw-processed-image fusion process based on both luminance and gray-balancing strategies; 2) a multiple-conversing-points type of gamut-mapping; 3)Adaptive Multi-illuminants white-balancing; 4) the CIECAM02 color appearance modeling; 5) a Gaussian pyramid type of image enhancement; and 6) a logarithmic HDR tone mapping; and finally an ideal simulated CIEXYZ type of spectra sensing model which adopts interim AdobeRGB connection reference space, combined with CIE 1931 2° standard observer. Consequently, a robust spectral type of cross-media color reproduction system, based on a colorimetric approach of HDR and Hi-Fi (High-Fidelity) was implemented in the study.*

Introduction

Since metamerism issue is concerned under all possible illumination conditions happened in real world. Additionally, High dynamic range (HDR) imaging has become an actively research for producing High-fidelity (Hi-Fi) color reproductions. Therefore, for accurate cross-media HDR imaging applications, the actually exact solution is to provide a detailed description of spectra properties of the scene-referred HDR color images. A complete set of "HDR+Hi-Fi" cross-media imaging module was proposed in this research. It integrated algorithms, including: 1) a multi-raw-images fusion [1], 2) a multiple-conversing-points (MCP) type of gamut-mapping [2-3]; 3) an adaptive multi-illuminants white balancing imaging rendition [4]; 4) the CIECAM02 color appearance model, an image enhancement (IE); 5) a logarithmic HDR tone mapping[5], and a spectra sensing model, equipped with the CIE XYZ three-band filters; and finally 6) a multispectral type of Hi-Fi five-ink CMYKOG printer model.

HDR Image-Fusion Module

Figure 1 illustrates the basic concept of each major step in computation framework for the proposed HDR imaging module, using multi-images fusion strategy.



(a) (b)

***Figure 1**. (a) HDR image-fusion module for three raw digital images; (b) Test scene image sets.*

Multiple-Images Fusion Algorithm

The proposed module, based on the scheme suggested by Kao et al. [1], performed image fusion on three raw image data directly. The camera successively captured three images with a normal (0EV), half (-2EV) and double exposures for high dynamic range scenes in question, The normal exposure setting was initially determined by the best auto exposure which could produce the best luminance value distribution to fit the dynamic range of camera's CCD sensor. The multi-images fusion model processed three considered images via a global motion stabilization algorithm. Through bypassing every overexposure/underexposure pixel of the test images, it estimated the misalignment or shift of absolute coordinates, and compensated the offset between images with different exposures taken from the same scene.

Additionally, the proposed multi-raw-images fusion was a luminance-based process. It applied an ENL (Equivalent Neutral Luminance) strategy to correlate RGB data of the used camera with measured luminance *Y*, by using results obtained from gray patches of a gray-scale test target. The ENL is similar to the END (Equivalent Neutral Density, which is practically applied in the advanced color reproduction system in traditional Graphic Arts [7].

Multi-illuminants White Balancing+CIECAM02

Human eyes are very good at locally adapting to distinct illuminants in the same HDR scene by saccadic eye movement. However, digital cameras often have great difficulties in auto white-balancing in mixed multi-illuminants situations. Therefore, as a part of cross-media HDR color image processing and rendering procedure, a locally adaptive white/gray balancing method (white-point conversion) [4], was also proposed here to plug into the multi-images fusion module. The model was based on the defined CIECAM02 color appearance connection space. Here, the adopted white point of reference view condition was the standard illuminant D50, practically used in the Graphic Arts industry. Therefore, via a preliminary established gray-balancing LUT datasets which were obtained from calibrating and characterizing under various illuminants of interest, the model correlated the camera/RGB to the illuminant-independent representation of appearance- correlates data, such as red-green and yellow-blue opponent dimension (*a* and *b*), lightness (*J*), and chroma (*C*), hue quadrature (*H*), colorfulness (*M*), and brightness (*Q*).

Image Enhancement Algorithms

Preliminarily, two enhancement algorithms of un-sharp masking (USM) and Gaussian pyramid (GP) were separately derived and tested in the first stage. The USM is a very conventional method used to improve edge sharpness of images in the Graphic Arts color reproduction process [7]. The GP was original used as a tone-mapping model which is based on a multi-level representation of the human visual system [8]. Here, it was applied as an image enhancement model to improve the rendition of image details.

Integration of HDR Image-Fusion Module

Finally, the proposed image-fusion module was derived. As shown in Figure 1(a). It was based on the standard Adobe RGB working color space specified in D50 reference white, and integrated models of, 1) multi-images fusion (MIF), 2) multiple-converge-points (MCP) gamut-mapping, 3) adaptive illuminant-independent white-balancing (IIWB), 4) CIECAM02, 5) image enhancement (IE), and further 6) MCP gamut-mapping.

Of all nonlinear mapping, logarithmic and exponential mapping are among the most straightforward. To provide a baseline result against the proposed module may be compared, a very fundamental logarithmic tone mapping operator [6] was also implemented and linked with multi-images fusion module. It was expected maybe the mechanism of image-fusion module, presented in the previous section, could be further modified and really provide better improved visual performances via being compared with the one implemented using logarithmic or exponential mapping. The logarithmic tone mapping function (LTMF) implemented here is given in Equation (1) as follows.

$$L'_d(x, y) = \frac{\log(1 + L_w(x, y))}{\log(1 + L_{\max})} \quad (1)$$

Here, L_w and $L_{\max}$ are input pixel luminance and the maximum luminance on original image respectively; and L'_d the estimated luminance of the reproduction image.

Therefore, to provide a cross test against visual performances of different phases of image-fusion modules, two stages of experiments were conducted. The 1st stage was preliminary conducted for the comparisons between two image-enhancement models of Gaussian pyramid (GP) and USM, which were also applied in the image-fusion modules. As the results obtained apparently showed the GP performed much better than the USM, the GP model was further tested in a later stage of image-fusion process. Totally, a set of 5 scene images, shown in Figure 1(b), were captured using Canon450D and processed using these different tested modules considered. In the later 2nd stage, according to the algorithms applied in the image-fusion modules, five different phases of modules were implemented. All modules were equipped with both CIECAM02 and GM. Table 1 lists the differences among these phases.

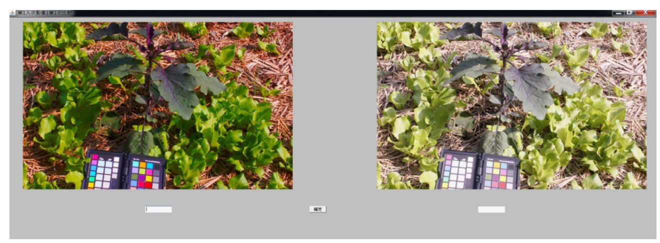


Figure 2*. The experimental viewing configuration for a paired comparison.*

Table 1: Summary of experimental phases for testing image-fusion modules in the 2nd stage experiment.

Phase	Tone mapping	Multi-Images fusion	IIWB	Gaussian Pyramid
1	yes	-	yes	-
2	yes	-	yes	yes
3	-	yes	yes	-
4	-	yes	yes	yes

A panel of twenty observers attended the experiments, using the paired comparison method. They judged and rated the visual color-fidelity quality of each HDR processed softcopy image in a pairs which displayed side-by-side, against to each other, on a seven category scales of ordinal values from 1 (“pleasingly acceptable”) through 4 (“Acceptable”) to 7 (“awfully unacceptable”). An Adobe RGB type of LCD (EIZO ColorEdge CG221W), which was calibrated and characterized in the specified D_{50} reference white-point, was used to display (as shown in Figure 2) test images. The one in each pair gave a better color-fidelity would have a smaller value. Table 2 summaries five phases of models’ performances (in terms of z-score) from the combined visual results of five scene-referred HDR images’ evaluation.

Figure 3 demoes the HDR color-fidelity rendition results from one set of scene images, rendered from five different phases of image-fusion modules tested. The obtained results significantly show that the image-fusion module from phase 4 outperformed the others. Phase 4 was ranked the 2nd. It implies that an image captured using a normal exposure, by properly applying an optimized tone-mapping operator and combined with a well-performing image-enhancement model, could also be satisfactorily reproduced as a representation of scene-referred HDR image, and used for a further advanced HDR imaging application.

Table 2: Summary of experimental phases for testing image-fusion modules in the 2nd stage experiment (in z-score).

Scene Image	Phase 1	Phase 2	Phase 3	Phase 5
1	-3.8	0.4	1.5	4.4
2	-1.7	2.1	-0.8	4.6
3	-2.1	1.6	-1.4	3.3
4	-0.2	3.5	-0.1	3.0
5	-1.3	2.7	-2.0	2.5
Average	-1.8	2.0	-0.5	3.5
Rank	4	2	3	1

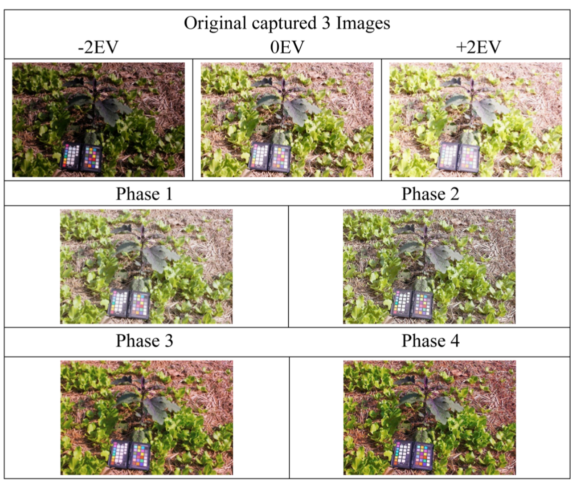


***Figure 3**. Illustration of five phases of image-diffusion for high-dynamic range images.*

Multispectral CIEXYZ Sensing Model

An ideally CIEXYZ type of multispectral sensing model was derived based on an extensive training from the analysis of color spectra of Munsell Book Glossy Database which contains a full set of 1600 color patches [9]. The proposed simulated model is equipped with a popular triad response of the 1931 CIEXYZ color-matching functions in the range of 380 to 730 nm at interval of 10 nm. To carry out the derivation of spectra recovery model, a SVD (Singular Value Decomposition) method was firstly applied to find an optimized set/number of basic vectors. It was characterized under the standard illuminant D50. Then, via a set of coefficients approximated by using the well-known Winner-inverse solution as an estimator to minimize MSE (Mean Square Error), this spectra sensing model, by equipped with the simulated CIEXYZ three-band filters, could estimate the spectral radiance/reflectance of tested color objects. The Winner-inverse used here is an estimator to minimize MSE (Mean Square Error) of the spectral radiance of every pixel between the original HDR images (which were produced from the outperforming image-fusion module (i.e. Phase 4)) and the predicted HDR images (which were rendered using the destination device tested afterword). Finally, the spectral reflectance of every pixel on HDR images, which were produced from previous stage of image fusion module and profiled with known XYZ values under a specified D_{50} viewing condition, could be approximately rebuilt using this spectra sensing model.

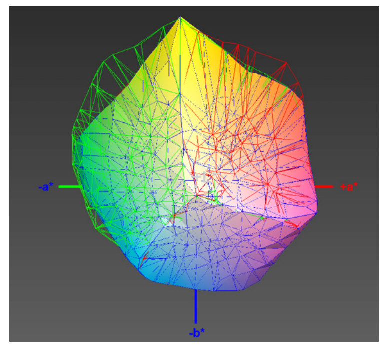


***Figure 4**. Illustration of the use of Hi-Fi colorants, Green and Orange to extend the gamut only achieved using standard CMYK colorants (solid with natural coloring: 4-colorrant gamut; wireframes with colors: 6-colorant super-gamut (green: CMYKOG subset), red: CMYKO subset, and blue: CMYK subset)).*

Hi-Fi Printer Device Characterization

Subdivision Approach for Six-Colorant Printer Process

The printer characterization model in this paper was extended from previous works [3-4], which multi-spectrally modeled a heptatonic CMYKRGB printing process. An Epson 9900 inkjet printer, having the capability of a six-colorant set, CMYKOG, was spectrally characterized for High-Fidelity (Hi-Fi) multi-color printer simulation. The approach applied in 7-colornat model was originally based on the scheme suggested by Boll [10]. This research clarified a new spectral design, and revised to model color behavior of 6-colorant CMYKOG printer device. It is useful, based on 5-colorant set instead of 4-ink set, for spectral recovery in compatible with most of colorimetric hard-copy reproduction system. This Hi-Fi 6-colorant printer model optimally estimated the color properties, in terms of its spectra, of color-sample surface from the scene-referred HDR images which were produced via the integrated outperforming multi-images fusion module (i.e. obtained from Phase 4) presented earlier. As shown in Figure 4, this 6-colornats printer model extends the color gamut, especially regions of orange to green, beyond what can be achieved in the conventional CMYK printing/printer system. The superset of CMYKOG was initially divided into three subsets, including two 5-colorant groupings of CMYKO and CMYKG, and one 4-colornats grouping of CMYK. Each 5-colorant subset was used to produce a dataset of 1716 print patches, which are randomly distributed in the CIELAB color space; while the CMYK subset produced an IT8.7/4 training/test printing/printer target with 1617 color patches. Each subset was characterized [4] separately to define the transform between device-independent colorimetric data and device-independent ink data in its own corresponding subgamut of color space. This approach resulted in the production of every pixel from input HDR images would be processed with one of 4- or 5-colorant datasets.

Broadband and Narrowband Approaches

Two approaches of broadband and multispectral (MS) narrowband were integrated to explore in the characterization 6-colorant of CMYKOB printer device. As similar to earlier derived 7-colorant CMYKRGB approach, both narrowband and broadband models numerically applied both a 3rd-order and a 2nd-order with 3rd-order polynomial regression equations, respectively. Models all incorporated with SVD technique [6]; and each carried out both processes of a forward and a reverse transform. The forward maps the device-dependent data (i.e. FADs, Fractional Dot Areas of four or five primary colorants for a color considered in each subset tested) to their device-independent values (i.e. CIEXYZ, CIELAB, or CIELCh); while the reverse transforms device-independent values (i.e. CIEXYZ, CIELAB, or CIELCh) into device-dependent data (i.e. FDAs). The broadband type of 2nd-SVD model (referred as 2nd-SVD-BB later) was derived from previous works [4-5, 7-8]. Also, by following works done previously, a KCR (Key Component Replacement) algorithm which is similar to the GCR (Gray Component Replacement) technique in theory was also implemented in each of subsets in this work for the 3rd-SVD-MS algorithm. The 4-colornat CMYK subset has the key component of black; whereas the two 5-colorant subsets, CMYKO and CMYKG have different key components of orange and green respectively. Therefore, The KCR refers, e.g. in CMYK, CMYKO and CMYKG subgamuts, to reduce key components K, O, and G respectively (which are produced using complementary colorants of C & M & Y, M & Y (for this set, the combination maybe would be→ less Y + more M), and C & Y respectively), and substitute them with colorimetrically corresponding equivalent amounts of black (K), orange (O), and red (R) colorants respectively.

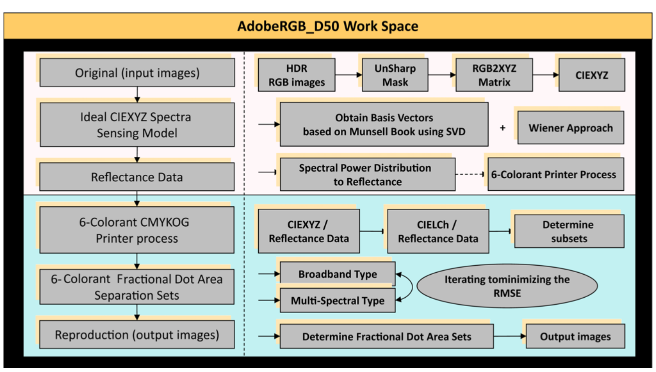


Figure 5. Illustration of the basic flow of spectral Hi-Fi colorant separation algorithm using HDR image-fusion images.

By combined the previous presented HDR image-fusion module and the CIEXYZ type of spectra sensing model with the Hi-Fi spectral printer characterization model, the whole set of namely "HDR+Hi-Fi" imaging model can be derived. Figure 5 provides a clear concept and flow chart of each major step in this computational model. The derived polynomial forms for both 3rd-SVD and 2nd-SVD algorithms are very similar to the ones proposed in the previous paper [11]. The multi-spectral 3rd-polynomial algorithm, was based on 5 parameters of spectral reflectance $R_{\lambda C}$, $R_{\lambda M}$, $R_{\lambda Y}$, $R_{\lambda K}$ and $R_{\lambda E}$, instead of 4 parameters of spectral reflectance $R_{\lambda C}$, $R_{\lambda M}$, $R_{\lambda Y}$, $R_{\lambda E}$, to plugin for the derivation of matrix length and coefficient terms; here *E* stands for extra colorant, i.e. key colorant used in each of two 5-colornat subsets.

The prediction performances of derived Hi-Fi printer model were evaluated in terms of measures of Average (i.e. mean E_{00}) Max (i.e. maximum E_{00}),"ΔE_{00} >6 Count", and mean RMSE (root mean square error) tested using their corresponding test targets (E_{00} is color difference of CIEDE2000). E_{00} was calculated between XYZ values of the predicted color-patch and those of the original target color-patch in question. Table 3 lists prediction performances of the spectral Hi-Fi 6-colorant printer model proposed here, using each of 4- and 5-colorant subsets, for both forward and reverse transforms.

Table 3: Summary of Prediction performances of the multi-spectral 2nd-SVD models, in terms of mean ΔE_{00}, of four derived Models for transform processes of both the forward (denoted as F) and the reverse (denoted as R) under the D_{50} condition.

Subset	CMYK		CMYKO		CMYKG	
Process	F	R	F	R	F	R
Max	7.59	3.00	5.88	8.39	5.25	6.64
Average	1.16	1.33	0.98	1.98	1.06	1.92
ΔE_{00} >6 Count	2	0	0	21	0	7
RMSE (Mean)	0.0001	0.0018	0.0008	0.0018	0.0009	0.0036

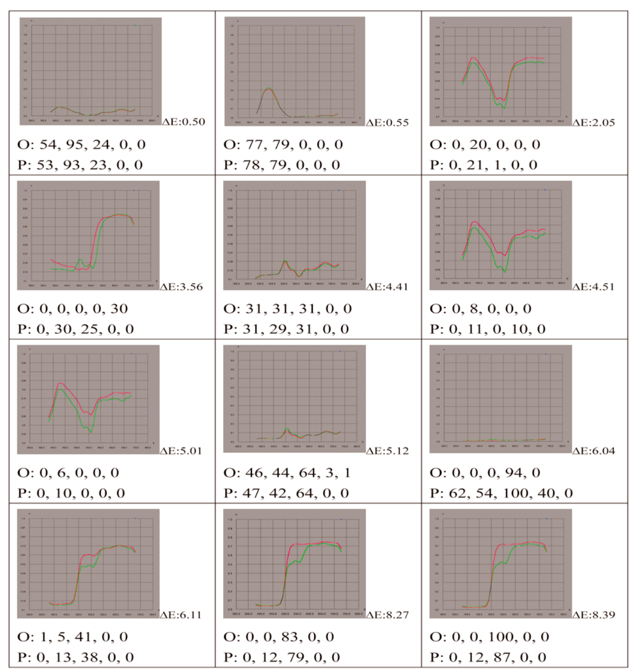


Figure 6. Examples of spectral reflectance (SR) estimated, and comparisons between the original and the predicted (red line: the Originals; green line: the Predicted).

From the Mean ΔE_{00}, It shows, generally, the 6-colorant performed reasonably satisfactory, However, form the investigation of both the Max ΔE_{00} and “$\Delta E_{00} > 6$” data, it seems that some test color samples didn’t have reasonable predictions. Therefore the proposed spectral Hi-Fi model was also tested for the spectral recovery of some typical color chips in CMYKO subset.. Fig. 6 illustrates results in the spectral reflectance estimation. It clear shows that even the samples having the spectral estimation error of “$\Delta E_{00} = 8.39$”, still the spectral reflectance between both the original and the predicted are not significantly different.

“HDR + Hi-Fi” Cross-media Color Transform

Finally, the spectral Hi-Fi 6-colorant printer characterization was tested. It linked the previously presented HDR image-fusion module with the ideal CIEXYZ spectra sensing model, to perform a “HDR +Hi-Fi” spectral cross-media imaging. Here, four pseudo-spectral test images were generated, via AbobeRGB D50 reference working space. Figure 7 shows the original HDR images (HDR) which were obtained from image-fusion model, and both the 4-colorant CMYK (4C) and the 6-colorant CMYKOG (6C) reproduced images, reconstructed using the proposed spectral printer model derived. Those reproduced 4- and 6-colorant images look very similar to the original HDR images when viewed under the illuminant D50 simulator. However, by a further close evaluating on color- and detail-renditions of green, orange and also shadow areas on those tested images, with the comparisons with the original HDR, it could be seen that the 6-colorant model clearly had better color- and detail-renditions than the 4-colorant model.

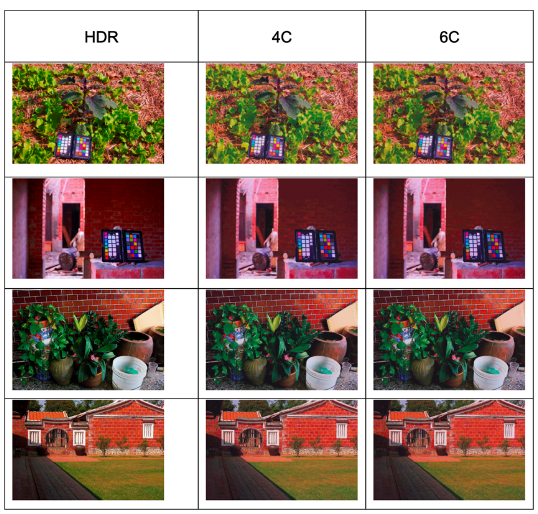


***Figure 7**. Illustration of rendition performances of both 4-colorant and 6-colorant printer models.*

Conclusions

A novel 6-colorant spectral Hi-Fi printer characterization model was proposed. Additionally a well-designed multi-images fusion module was also proposed in this paper. The integration of both models can satisfactorily perform a spectral “HDR+Hi-Fi” color transform across HDR imaging devices for an accurate color -matching or –reproduction application.

Acknowledgement

This research has mainly supported by the National Science Council of Taiwan for financial assistance.

References

[1] W.C. Kao, C.C. Hsu, L.Y. Chen, C.C. Kao, and S.H. Chen, Integrating Image Fusion and Motion Stabilization for Capturing Still Images in High Dynamic Range Scenes, IEEE Trans. Consumer Electronics, vol. 52, no. 3, pgs. 735-741 (2006).

[2] M.C. Lo, J.C. Chiang, and L. Shi, Color Separation for 7-ink Printing Using FM Screening, TAGA proceeding, pgs. 716-735 (1997).

[3] [M. C. Lo, R. Chiang, The Characterization Models for Multi-colored CMYKRGB, TAGA Proceeding, pgs. 242-254 (1998).

[4] M.C. Lo, J.L. Lin and X.K Ma, A Multi-spectral Approach of Cross-media HDR Imaging Technique for Food Store Scenes under Multi-illuminants Using a Locally Optimized Automatic White Balancing Method, AIC 2010, Interim Meeting of the International Color Association – Color and Food: From the Farm to the Table, Mar del Plata, Argentina, pgs. 596-599 (2010).

[5] M.C. Lo, T.H. Hsieh, R.K. Perng , and J.Q. Chen, High-Dynamic Range Imaging Techniques Based on Both Color-Separation Algorithms Used in Conventional Graphic Arts and the Human Visual Perception Modeling, Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 7537 75370M-1~75370M-8 (Electronic Imaging 01/2010).

[6] E. Reinhard, S. Pattanaik, G. Ward, and P. Debevec, High Dynamic Range Imaging (Morgan Kaufmann Pub., 2005) .

[7] J.A.C. Yule, Principle of Color Reproduction (John Wiley& Sons, Inc., 1976).

[8] S.N. Pattanaik, J.A. Ferwerda, M.D. Fairchild, and D. P. Greenberg, A Multiscale Model of Adaptation and Spatial Vision for Realistic Image Display, SIGGRAPH 98 Conference Proc., ACM SIGGPAPH, pgs. 287-298 (1998)

[9] J. Orava, The Reflectance Spectra of 1600 Glossy Munsell Color Chips. (http://spectral.joensuu.fi/databases/download/munsell_spec_glossy_all.htm

[10] Boll, A Color to Colorant Transformation for a Seven Ink Process. IS&T’s Third Technical Symposium on Prepress, Proofing, & Printing, 3, 31-36 (1993).

[11] M.C. Lo, C.L. Chen, and T.H. Hsieh, Characterization of High-Fidelity Color Printing Devices Using illuminant-independent Approaches for Color Imaging Application, NIP 24: 24th International Conference on Digital Printing Technologies, pgs. 597-602 (2008).

Author Biography

Mei-Chun Lo holds a Ph.D. (1995) from the Department of Computer Studies and also a M.Sc. (2001) in Multimedia and Internet Computing (2001) from Loughborough University in England, and M.Sc. at the Institute of Graphic Arts Technology (1985) from Chinese Culture University, Taiwan. From 2005 to now, she is currently a full professor of the Department of Information Management at Shih Hsin University. She has been researching and developing web-based cross-media HDR color management system for digital archiving application and Graphic Arts. She is member of the Chinese Association of Graphic Science &Technology, the Graphic Arts Technology Foundation (Now is PIA/GATF), the Graphic Arts Technical Association (TAGA), the Color Association of Taiwan.