Reproduction Model with Luminance Adaptation for Digital Cameras

Francisco Martínez-Verdú[a], Jaume Pujol[b], Meritxell Vilaseca[b] & Pascual Capilla[c]

[a] Departament Interuniversitari d'Òptica, Universitat d'Alacant
Alacant, Spain

[b] Centre de Desenvolupament de Sensors, Instrumentació i Sistemes (CD6),
Departament d'Òptica i Optometria, Universitat Politècnica de Catalunya
Terrassa, Barcelona/Spain

[c] Departament Interuniversitari d'Òptica, Universitat de València
Burjassot, València/Spain

Abstract

From real spectroradiometric data, we propose an algorithm to obtain camera opto-electronic conversion functions (camera OECFs) with the free lens aperture N from the opto-electronic conversion spectral functions (OECSFs). Working in the linear range of the inverse *OECFs*, we have found that the slope vs. lens aperture function is fitted by a second order polynomial. This happens also to the offset vs. lens aperture function. Therefore, we have included the inverse *OECFs* with luminance adaptation into a basic reproduction model, composed by a 3x3 transform between the raw RGB space and CIE-XYZ space, opening the possibility of transforming any digital camera into an absolute tele-colorimeter.

Introduction

A digital image capture device (scanner or camera) is not a tool for measuring color as a spectrophotometer or a tele-spectroradiometer. Although it encodes the spectral information enclosed in a scene into three RGB color channels, the RGB digital data associated to a visual stimulus are not the same that would encode a human observer, who is characterized by the CIE-1931 XYZ standard observer[1,2].

The color characterization of digital image capture devices consists of calculating the colorimetric profile between RGB device space and the CIE-1931 XYZ space associated to the same color stimulus under uncontrolled illumination conditions, both variations of chromaticity and intensity of the illumination. Of this way, the digital image capture device should perform as an absolute tele-colorimeter because the color output data would be in cd/m^2, i.e., the color device would be simultaneously a colorimeter and a luminance meter. From digital output levels DOL_k (k = R, G, B color channels) we could obtain the absolute tristimulus values CIE-XYZ (in cd/m^2), such as are obtained by a tele-spectradiometer (Eq.1).

$$\mathbf{t}_{\mathbf{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = K_m \mathbf{T}_{\mathbf{XYZ}}{}^{t}\mathbf{c} \qquad (1)$$

where K_m is 683 lm/W, $\mathbf{T}_{\mathbf{XYZ}} = [\,\bar{\mathbf{x}}\ \bar{\mathbf{y}}\ \bar{\mathbf{z}}\,]_{41x3}$ is the color-matching functions in matrix format and $\mathbf{c}$ = diag($\mathbf{L}$)·ρ is the color stimulus, resulting of the spectral reflectance ρ of the object and the light source or illuminant $\mathbf{L}$ in W/sr·m^2.

The basic colorimetric profile[3] is a 3x3 matrix $\mathbf{M}$ which should associate the RGB relative colorimetric values or $\mathbf{t'}_{\mathbf{RGB}}$ with the relative tristimulus values $\mathbf{t'}_{\mathbf{XYZ}}$ respect to the equi-energy stimulus $\mathbf{E}$ = [1, 1, ..., 1]^t (Eq. 2). This matrix can be obtained by regression methods[4] between the color-matching functions of the color device and the standard observer CIE-1931 XYZ. Of this way, the estimated relative tristimulus values XYZ should be as follows:

$$\hat{\mathbf{t}}'_{\mathbf{XYZ}} = \mathbf{M}\,\mathbf{t}'_{\mathbf{RGB}} \quad \text{with} \quad \mathbf{T}_{\mathbf{XYZ}}{}^{t} = \mathbf{M}\,\mathbf{T}_{\mathbf{RGB}}{}^{t} \qquad (2)$$

If our purpose is to get an estimation absolute, in cd/m^2, of the tristimulus values XYZ, we must link a group of luminances associated to the equi-energy stimulus or illuminant $\mathbf{E}$ with the corresponding RGB data of the color device. This relationship is denoted as camera opto-electronic conversion function (OECF). For any scale exposure series –varying the lens aperture or f-number N of the zoom lens or the photosite integration time t–, the OECFs are described as follows:

$$\mathbf{t}'_{\mathbf{RGB}} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} OECF_R(L) \\ OECF_G(L) \\ OECF_B(L) \end{bmatrix} \qquad (3)$$

where L is the luminance of the object inside the scene.

The standard ISO 14524 gives an algorithm to obtain this photometric function with fixed lens aperture N or photosite integration time t and any different illumination to the illuminant $\mathbf{E}$. This standard is used in the standard ISO 17321[6] to obtain the relative colorimetric profile associated to a digital still camera (DSC) measuring previously their spectral sensitivities. Finally, the relative colorimetric profile is obtained inverting the camera OECFs as follows:

$$\hat{\mathbf{t}}'_{\mathbf{XYZ}} = \frac{1}{L_{\mathrm{E}}}\mathbf{M}\begin{bmatrix} OECF_R^{-1}(R) \\ OECF_G^{-1}(G) \\ OECF_B^{-1}(B) \end{bmatrix} \quad (4)$$

where L_{E} is luminance of the adapted white[7] or perfect white diffuser inside the scene.

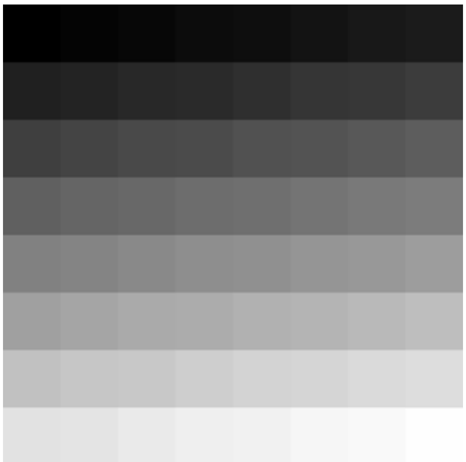

Figure 1: A gray scale test pattern captured appropriately with lens aperture N_0 in order to prevent the saturation of the white sample.

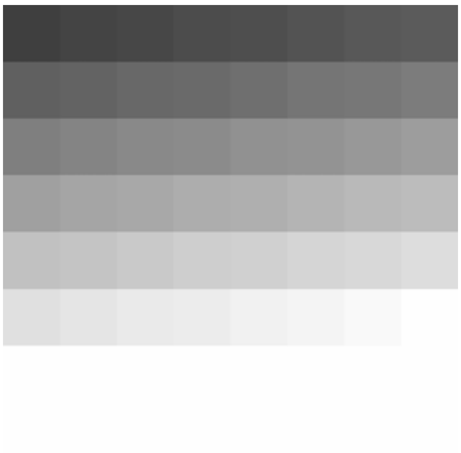

Figure 2: The gray scale test pattern captured with a lens aperture $N_1 < N_0$.

On other hand, we propose in this work a general algorithm of luminance adaptation to obtain the camera OECFs with illuminant **E** giving free the lens aperture *N* of the zoom lens. Of this way, we can adapt the relative and shorter dynamic range of device response into the real dynamic range of luminance of any scene. For instance, we have a gray scale test pattern (Fig. 1) which is captured optimally with (*N*, *t*) configuration in order to the white sample is not saturated. If we decrease the lens aperture *N*, i.e. the exposure level is raised, the RGB data would be now different (Fig. 2) but the absolute tristimulus values XYZ remain fixed. If we increase the lens aperture *N*, i.e. the exposure level is decreased, the RGB data would be now different (Fig. 3) but the absolute tristimulus values XYZ remain now fixed. How we can compensate the variation of the lens aperture *N* to obtain always the same absolute tristimulus values XYZ?

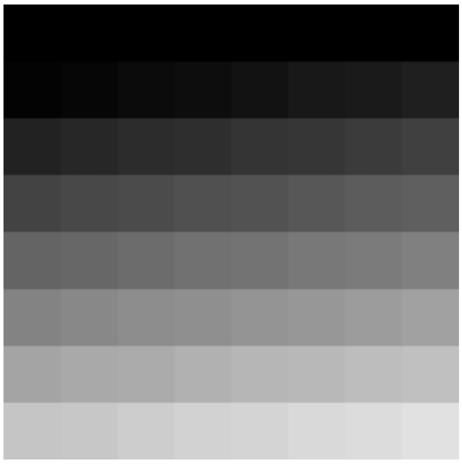

Figure3: The gray scale test pattern captured with a lens aperture $N_2 > N_0 > N_1$.

From real spectroradiometric data and an alternative spectral characterization of digital image capture devices, we shall simulate the responses of a gray scale test pattern with the illuminant **E** giving free the lens aperture *N* of the zoom lens. Because some OECFs vs. *N* relationships will be obtained, the scene-referred colorimetry obtained applying the basic colorimetric profile (Eq. 4) will be absolute (in cd/m^2) not relative unlike ISO 17321.

Spectral Characterization

The experimental set-up for the spectral characterization is a variant[8] of the method A of the ISO 17321. Our digital image capture device consisted of a Sony DXC-930P 3CCD-RGB camera connected to a Matrox MVP-AT 850 frame grabber, inserted into a PC unit. Target radiance was varied using the entrance/exit slits of a CVIS Laser Digikröm monochromator with constant spectral resolution, assembled to an Osram HQI T 250W/Daylight vapour fluorescent lamp. Among the fixed initial conditions, which might alter the color output, we set the white balance to 5600 K in manual menu-mode (offset value) and configured the gain and the offset of the analog-digital converter (ADC) to work with the raw response space. The target radiance $L_{e\lambda}$ was measured by a Photo Research PR-650 tele-spectraradiometer in the 380-780 nm wavelength range at 10 nm steps, maintaining the photosite integration time at t_0 = 20 ms (offset value) with some selected f-numbers *N*. Previously, we proved that the variation of *N* in the spectral characterization warranted the radiometric reciprocity law[9,10], i.e., identical values of spectral exposure yielded identical responses even if the lens aperture *N* change. The spectral exposure H_λ, averaged in the exposure series ($L_{e\lambda}$, N, t = 20 ms) for each monochromatic image was given by[9-11]:

$$H_\lambda \propto \frac{L_{e\lambda}}{N^2} t \quad [\mathrm{J}] \qquad (5)$$

The opto-electronic conversion spectral functions (*OECSFs*), that is, the normalized digital output level $NDOL_\lambda$ vs. H_λ curves for RGB channel, were fitted mathematically by sigmoid functions, defined by four parameters $\{a,b,c,d\}$ as follows:

$$NDOL_{\lambda k} = \frac{DOL_{\lambda k}}{2^{bits}-1} \quad , \quad k = R,G,B$$
$$NDOL_{\lambda k} = a_{\lambda k} + \frac{b_{\lambda k}}{1+\exp\left(-\frac{H_\lambda - c_{\lambda k}}{d_{\lambda k}}\right)} \qquad (6)$$

With this radiometric formalism, a new response model is proposed from the univariance principle:

$$DOL_{\lambda k} = \left(2^{bits}-1\right) \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} NDOL_{\lambda k}\, \Delta\lambda$$
$$DOL_{\lambda k} = \left(2^{bits}-1\right) \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} H_\lambda\, r_k(\lambda, H) \Delta\lambda \qquad (7)$$

where $r_k(\lambda, H)$ is the complete spectral responsivity[8] of the color-channel k.

Colorimetric Profile with Luminance Adaptation

With this model, we have proved[8] that our digital camera has not an adapted, ideal or equi-energy white balance[7], so this result is used to transform the digital output levels into relative RGB values:

$$R = \frac{NDOL_R}{bal_R};\ G = \frac{NDOL_G}{bal_G};\ B = \frac{NDOL_B}{bal_B} \qquad (8)$$

Like ISO 17321, with the support of ISO 14524, we propose then a reproduction model with luminance adaptation calculating the inverse of the camera opto-electronic conversion functions (OECFs) from the obtained *OECSFs* (Eq. 6). If, for any (N, t) scale exposure series, it is verified that $R = OECF(L)$, $G = OECF(L)$ and $B = OECF(L)$, where L is the luminance of an object, we can simulate the responses of a gray scale test pattern by:

$$\frac{NDOL_k}{bal_k} = \frac{1}{bal_k} \sum_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \frac{L_e}{N^2} t_0\, r_k\left(\lambda, \frac{L_e}{N^2} t_0\right) \Delta\lambda \qquad (9)$$

where L_e is the uniform radiance of the adapted white in the position of the object and it is obtained from the luminance L_E of the adapted white as follows[12]:

$$L_e = \frac{L_E}{K_m \left(\bar{\mathbf{y}}^t \cdot \mathbf{E}\right)\Delta\lambda} = \frac{L_E}{683 \cdot 21.3714 \cdot 5} \qquad (10)$$

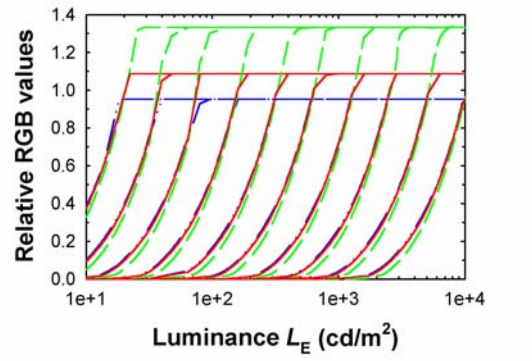

Figure 4: Balance of luminance adaptation of our digital image capture device. Each triad of OECFs curves belongs to a (N, fixed t) scale exposure series: from left to right, N = {1, 1.4, 2, 2.8, 4, 5.6, 8, 11.2, 16, 22.4}. Solid line: Red channel; dashed line: Green channel; dash-dot-dot: Blue channel.

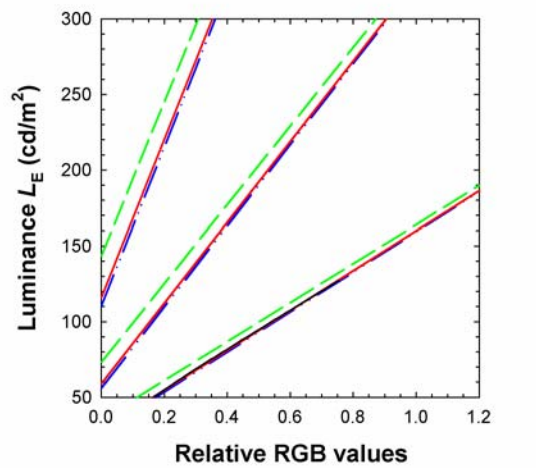

Figure 5: Linear representation of the inverse OECFs of the previous figure for the values N = 5.6, 4 and 2.8. Solid line: Red channel; dashed line: Green channel; dash-dot-dot: Blue channel.

The obtained *OECFs* (Fig. 4), each one of them associated to different dynamic ranges or N-scale exposure series, show linear mid-range, so we can invert the graphs to obtain the slope m and the offset h for each straight line or "linear" inverse *OECFs* (Fig. 5):

$$OECF_R^{-1}(R) = m_R(N) \cdot R + h_R(N)$$
$$OECF_G^{-1}(G) = m_G(N) \cdot G + h_G(N) \qquad (11)$$
$$OECF_B^{-1}(B) = m_B(N) \cdot B + h_B(N)$$

We have found that the relationships m_k vs. N and h_k vs. N are second-polynomial (Fig. 6 and 7):

$$m_k(N) = m_{0k} + m_{1k}N + m_{2k}N^2$$
$$h_k(N) = h_{0k} + h_{1k}N + h_{2k}N^2 \quad (12)$$

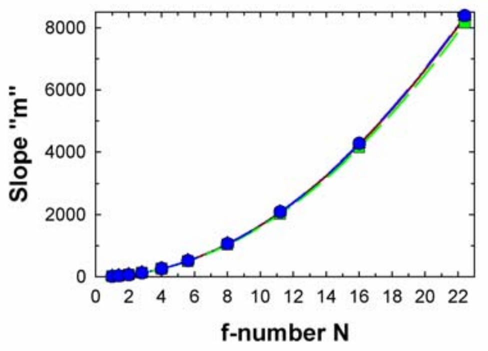

Figure 6: Second polynomial fitting of the slope "m" of the linear inverse OECFs vs. f-number N of the zoom lens. (Circles: B channel; squares: G channel; triangles: R channel)

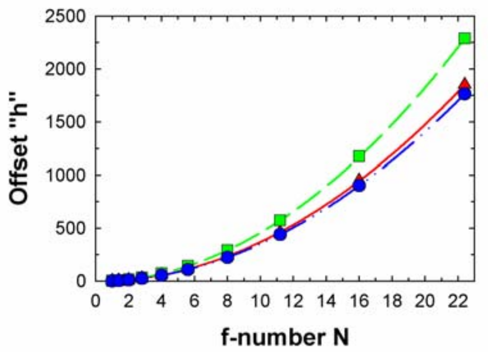

Figure 7: Second polynomial fitting of the offset "h" of the lineal inverse OECFs vs. f-number N of the zoom lens. (Circles: B channel; squares: G channel; triangles: R channel)

So, we now may describe a colorimetric profile with luminance adaptation as follows:

- Original-referred image data[7] (Eq. 1):

$$\mathbf{t_{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \frac{\text{cd}}{\text{m}^2} \quad (13)$$

- Scene-referred image data[7]:

$$\hat{\mathbf{t}}_{\mathbf{XYZ}} = \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix} = \mathbf{M}\left\{ \begin{bmatrix} m_R(N) & 0 & 0 \\ 0 & m_G(N) & 0 \\ 0 & 0 & m_B(N) \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} h_R(N) \\ h_G(N) \\ h_B(N) \end{bmatrix} \right\} \quad (14)$$

where $\mathbf{M}$ is the 3x3 transform by regression methods[4] between the color-matching functions of our digital camera[8] and the standard observer CIE-1931 XYZ (Eq. 2).

With this new reproduction model for digital cameras and following the standard ISO 17321, we can face the calculation of the DSC color analysis accuracy index[13] and the DSC color rendering of the natural scenes, converting any digital camera into an absolute tele-colorimeter.

Conclusion

The colorimetric characterization of digital image capture devices that we propose consists of transforming the RGB digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions. So, at the first stage, a gray balance (Eq. 8) has been applied over the RGB digital data to convert them into RGB relative colorimetric values. At a second stage, an algorithm of luminance adaptation has been included for the first time (Eqs. 9-14). With this algorithm, we can change suitably the lens aperture or f-number N of the zoom lens without changing the absolute tristimulus specification CIE-XYZ estimated from the colorimetric profile between RGB and XYZ color spaces. With these previous steps, the color reproduction level of our digital image capture device can be compared with that obtained with a tele-spectoradiometer, both in a raw state and with a model of color correction because the color-matching functions $\mathbf{T_{RGB}}$ of our camera are not verified the Luther condition[14,15].

Acknowledgements

This research was supported by the Comisión Interministerial de Ciencia y Tecnología (CICYT) (Spain) under grants TAP99-0856.

References

1. G. Sharma, H.J. Trussell, IEEE Trans. Image Process. 6, 901 (1997).
2. M.J. Vhrel, H.J. Trussell, IEEE Trans. Image Process. 8, 1796 (1999).
3. D.H. Brainard, Handbook of Optics Vol. I, 2nd Ed., OSA, Washington, 1995, chapter 26.
4. G.D. Finlayson, M.S. Drew, J. Electron. Imaging 6, 484 (1997).
5. ISO 14524:1999. Photography - Electronic still picture cameras: Methods for measuring opto-electronic conversion functions (OECFs).
6. ISO WD 17321-1 (2001). Graphic technology and photography - colour characterisation of digital still cameras (DSCs) - Part 1: Stimuli, metrology, and test procedures. Archive PDF, URL: http://www.pima.net/standards/iso/tc42/WG20/WG20_POW.htm.
7. ISO WD 12231 (2001). Photography. Electronic still picture imaging. Terminology Archive PDF, URL:

http://www.pima.net/standards/iso/tc42/wg18/wg18_POW.htm.
8. F. Martínez-Verdú, P. Pujol, P. Capilla, J. Imaging Sci. Technol. (accepted, in press), 2002.
9. F. Martínez-Verdú, et al., Proc. SPIE, 3648, 280 (1999).
10. F. Martínez-Verdú, P. Pujol, P. Capilla, J. Electron. Imaging (sent with second revision), 2001.
11. G.C. Holst, CCD Arrays, Cameras and Displays, SPIE, Bellingham, 1998, pg. 34.
12. G. Wyszecki, W.S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Ed., John Wiley and Sons, New York, 1982, pg. 737.
13. J. Holm, I. Tastl, S. Hordley, Proc. CIC, 8, 279 (2000).
14. R. Luther, Z. Tech. Phys. 8, 540 (1927).
15. B.K.P. Horn, Comput. Vis. Graph. Image Process. 26, 135 (1984).

Biography

Francisco Martínez-Verdú received his BS in Physics from the University of Valencia in 1993 and a Ph.D. in Physics from Polytechnic University of Catalonia at Terrassa (Barcelona) in 2001. Since 1998 he has taught Color Science at School of Optics & Optometry in the University of Alicante (Spain). His work has primarily focused on the device calibration and characterization, above all digital cameras and scanners, Industrial Colorimetry, Color Management and Imaging. He is a member of the IS&T and the Spanish Optics Society. E-mail: Verdu@ua.es.