Accurate Estimation of the Non-Linearity of Input-Output Response for Color Digital Cameras

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Abstract

Many color digital camera systems exhibit a non-linearity between the input intensity and the output response of the color channels. Although the sensor (CCD) material responds to light intensity in a linear way a non-linearity is often added by the camera manufacturer. Recent research[1] has highlighted that in order to be able to estimate this non-linearity (sometimes termed gamma) it is necessary to know the spectral sensitivities of each of the color channels. The input to the non-linearity for a channel is the raw channel response and the output is the processed channel response and this is inconsistent with the commonly held assumption that the input-output non-linearity and the camera spectral sensitivities curves can be estimated independently. This research employed a computational model of a camera system with known channel spectral sensitivities and non-linear response. Camera output values were computed for a range of surfaces (defined by spectral reflectance factors) and illumination (defined by spectral power distributions). Different techniques to estimate the non-linearity of the channels were evaluated. These techniques included methods based upon the Luminance and mean reflectance of a set of neutral samples and methods based upon a knowledge (or estimation) of the spectral sensitivities of the channels. The results showed that the difference between the channel-sensitivity-based estimates of the non-linearity and the Luminance- or reflectance-based estimates were small. However, the effect was significant when the linearization was used as part of a device-characterization process. A case study demonstrated that an accurate linearization can reduce characterization errors by approximately 10% compared with traditional techniques.

Introduction

Traditional device characterization involves two main processes. Firstly, the camera system is used to ascertain sensor values for targets with known color characteristics, i.e. known illuminant and reflectance spectra or known CIE XYZ values. Secondly, these sensor values are transformed to match the target CIE values. This transformation is commonly achieved using a linear transform. Since many color digital camera systems exhibit a non-linearity (sometimes termed gamma) between the input intensity and the output response of the color channels, a linearization process is highly desirable before attempting the linear transform. Even when non-linear transforms are employed it is still considered beneficial to linearize the camera response values.[2] In this study we will use the term gamma to refer to the nature of the non-linearity of the input-output relationship.

Previous studies[3,4] have suggested a simple approach to linearization which uses Luminance or mean spectral reflectance of a series of grey samples to correct the input-output non-linearity of the device. However, recent research[1] has highlighted that in order to robustly estimate this non-linearity it is necessary to know the spectral sensitivities of each of the color channels. The input to the non-linearity for a channel is the raw channel response and the output is the processed channel response and this is inconsistent with the commonly held assumption that the input-output non-linearity and the camera spectral sensitivities curves can be estimated independently.

This research employed a computational model of a camera system with known channel spectral sensitivities and non-linear response. Different techniques to estimate the non-linearity of the channels were evaluated. These techniques included methods based upon the Luminance and mean reflectance of a set of neutral samples and methods based upon a knowledge (or estimation) of the spectral sensitivities of the channels. A case study will be demonstrated to compare the accuracy of characterization with application of different linearization techniques.

Background

An insight into the nature of the gamma-like input-output non-linearity: Suppose a uniforYm surface of known spectral reflectance $P(\lambda)$ is captured under an illuminant with known spectral power distribution $E(\lambda)$, by a three-channel imaging system (Equation 1) with spectral sensitivities $S_R(\lambda)$, $S_G(\lambda)$, $S_B(\lambda)$. Thus,

$$R = \sum E(\lambda) S_R(\lambda) P(\lambda)$$
$$G = \sum E(\lambda) S_G(\lambda) P(\lambda) \qquad (1)$$
$$B = \sum E(\lambda) S_B(\lambda) P(\lambda)$$

where the raw channel responses are *R*, *G* and *B* for the red, green and blue channels respectively. The channels are subject to a possibly gamma relationship, represented by a function *f*, to generate the actual output responses *R'*, *G'* and *B'*. Equation 2 shows an example for the blue channel; similar functions of non-linearities are assumed to exist for red and green channels.

$$B' = f(B) \qquad (2)$$

The input-output non-linearity function *f* can be estimated, for the green channel, from pairs of data (*B*, *B'*) obtained from a small number of measurements. Note, however, that in order to compute the raw channel input (*B*) the spectral sensitivity of the channel is required (Eq. 1). However, the Luminance *L* (defined by Equation 3 where $V(\lambda)$ is the luminous efficiency function) for each surface is often used instead of the actual channel input *B* to determine the input-output non-linearity function *f*.

$$L = \sum E(\lambda) V(\lambda) P(\lambda) \qquad (3)$$

If the Luminance is identical to (or a linear transform of) the actual channel input *B* of the system, the gamma estimated using the Luminance values will be identical to the true gamma that we would estimate if the values of *R*, *G* and *B* were known.

Assume that three achromatic surfaces P_1, P_2, P_3 used for gamma estimation have reflectance spectra invariant to wavelength (Figure 1). The ratio of the actual input to the channel to each surface is identical to the ratio of the Luminance for each surface,

$$B_1 : B_2 : B_3 \equiv L_1 : L_2 : L_3 , \qquad (4)$$

so that whether the actual camera responses are linearized to B_1, B_2 and B_3 or L_1, L_2 and L_3, the estimated parameter of the non-linearity will be the same. If we consider three surfaces where the spectral reflectance changes with wavelength (Figure 2), however, then Equation 4 is no longer valid.

The reflectance spectra shown in Figure 2 are quite typical of those for real grey surfaces. The variation of reflectance (and hence color signal) at wavelengths longer than the band of wavelengths to which the blue channel is sensitive will contribute to differences in the Luminance values for the three surfaces. Similarly, for the red channel short wavelengths that are not 'seen' by the red channel will contribute the Luminance signal.

The extent to which Equation 4 is true depends partly upon the degree to which the reflectance spectra of the samples used in the linearization process change with wavelength. It is for this reason that neutral samples are commonly used. However, we note that if the actual spectral sensitivity of the channels was known (so that the raw channel responses *R*, *G* and *B* could be computed, then colored samples could be used to estimate the non-linearity of the channels.

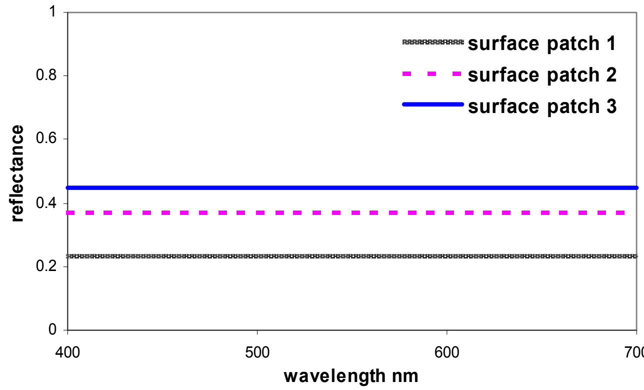

Figure 1. Reflectance spectra of three hypothetical grey surfaces with equal spectral reflectance across the wavelength spectrum.

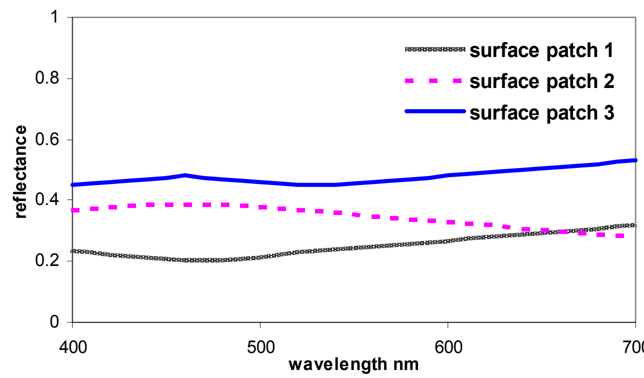

Figure 2. Reflectance spectra of three hypothetical grey surfaces with spectral reflectance that varies with wavelength

Experimental

A computational camera system is modeled with known channel spectral sensitivities $S_R(\lambda)$, $S_G(\lambda)$ and $S_B(\lambda)$ (Figure 3). Raw camera output values were computed for a collection of the neutral Munsell surfaces (specifically N6/ to N9/ with 0.5 value interval) defined by spectral reflectance factors $P(\lambda)$, and illumination $E(\lambda)$ (defined by spectral power distribution of CIE illuminant D_{65}, A and F_{11}) according to Equation 1.

Camera systems with raw channel responses and in the presence of random noise (Gaussian distribution with mean zero and standard deviation, *SD* = 0.025) were evaluated.

The raw channel response (with or without noise) for each surface-illuminant combination were subject to a (gamma-like) input-output non-linearity with value 1.8. Thus, the computed camera output values *R′*, *G′* and *B′* are related to the raw camera outputs by a power law with exponent $\gamma = 1.8$.

$$R' = R^{\gamma}$$
$$G' = G^{\gamma} \quad (5)$$
$$B' = B^{\gamma}$$

Different techniques to estimate the non-linearity of the channels were evaluated. These techniques included methods based upon the Luminance and mean reflectance of a set of neutral Munsell samples and methods based upon a knowledge of (or estimation of) the spectral sensitivities of the channels. Figure 3 shows the spectral sensitivities of the three channels that we used in our model.

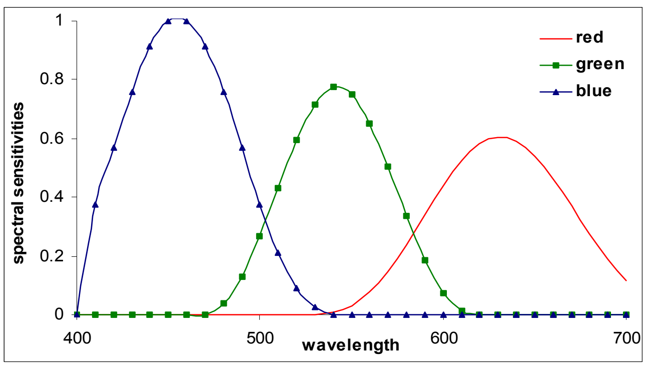

Figure 3. A set of known spectral sensitivities of a camera system

For the case where the Luminance or mean reflectance of the samples was used, the value of γ as estimated for Equations 6 and 7 respectively using linear algebra to perform a least-squares fit.

$$R' = L^{\gamma}$$
$$G' = L^{\gamma} \quad (6)$$
$$B' = L^{\gamma}$$

$$R' = P^{\gamma}$$
$$G' = P^{\gamma} \quad (7)$$
$$B' = P^{\gamma}$$

For the case where the camera spectral sensitivities are assumed to be known, then Equation 5 was used to estimate gamma.

The impact of any errors in the estimation of the non-linearity were evaluated by performing a complete characterization of the camera system and inspecting the resultant errors in the *R′G′B′*→ *XYZ* transform.

The characterization procedure was conducted as follows for each technique of estimating the non-linearity:

1. Estimate the non-linearity for the system using the Munsell grey samples.
2. Apply the estimates of the non-linearity to the measured system outputs for the Macbeth DC ColorChecker to yield the linearized *RGB* values.
3. Compute the coefficients of a polynomial transform that maps *RGB*→*XYZ* based upon the *RGB* and *XYZ* values of the Macbeth DC ColorChecker samples.
4. Compute the CIELAB color difference between the actual *XYZ* values and the *XYZ* values obtained from steps 1-3 for the Macbeth DC ColorChecker samples.
5. Use the polynomial transform obtained from the Macbeth DC ColorChecker samples to compute *XYZ* values for the samples in the Macbeth ColorChecker and compute CIELAB color differences between the actual and predicted values.

The procedure adopted used the Macbeth DC ColorChecker samples to test the memorization performance of the characterization procedure and the Macbeth ColorChecker samples to test the generalization performance[5]. The polynomial was implemented by a 3 × 16 transform which had been found to give best performance in some related studies.

Results

Tables 1-3 show the estimated non-linearity of the channels using the different techniques and under various illuminants. Note that the true input-output non-linearity of each channel is 1.8.

Table 1. Non-Linearity Estimations Under Illuminant D_{65}

	R channel	G channel	B channel
Spectral sensitivities	1.8000	1.8000	1.8000
Luminance	1.8087	1.8044	1.8146
Mean reflectance	1.7708	1.7644	1.7729

Table 2. Non-Linearity Estimations Under Illuminant A

	R channel	G channel	B channel
Spectral sensitivities	1.8000	1.8000	1.8000
Luminance	1.8177	1.8044	1.8135
Mean reflectance	1.7768	1.7615	1.7695

Table 3. Non-Linearity Estimations Under Illuminant F_{11}

	R channel	G channel	B channel
Spectral sensitivities	1.8000	1.8000	1.8000
Luminance	1.7938	1.8076	1.8087
Mean reflectance	1.7539	1.7657	1.7658

The method based upon the spectral sensitivities of the camera system performs perfectly since the spectral sensitivities used in the model were known exactly. Tables 1-3 show that estimations using mean reflectance tend to exhibit greater error than the estimations using Luminance. In addition, there appears to be some effect of illumination with the F_{11} illuminant producing the worst results. It therefore appears that the use of Luminance or mean reflectance in the estimation of the non-linearity will generate errors. The characterization tests were designed to explore the practical significance of these errors.

Tables 4 and 5 show the characterization performance for the Macbeth DC ColorChecker and the Macbeth ColorChecker respectively based upon linearization by the various techniques.

Tables 6 and 7 show results for similar experiments but using a more realistic camera model where the raw camera responses were subject to random noise.

Since the *RGB*→*XYZ* transformation is not perfect, characterization errors will still be obtained with an accurate input-output non-linearity response estimation. It is important to compare and contrast the magnitude of the characterization errors between different linearization techniques. This study demonstrated that an accurate linearization can reduce characterization errors by approximately 10% compared with traditional techniques.

Table 4. Comparison of Memorization Performance With Different Linearization Techniques

	Spectral sensitivities	Luminance	Mean reflectance
Median ΔE_{ab}	0.1039	0.1041	0.1056
Maximum ΔE_{ab}	0.6178	0.6195	0.6252

Table 5. Comparison of Generalization Performance With Different Linearization Techniques

	Spectral sensitivities	Luminance	Mean reflectance
Median ΔE_{ab}	1.5807	1.6775	1.6931
Maximum ΔE_{ab}	2.6699	2.8270	2.8726

Table 6. Comparison of Memorization Performance With Different Linearization Techniques (With Random Noise SD = 0.025)

	Spectral sensitivities	Luminance	Mean reflectance
Median ΔE_{ab}	0.2427	0.2429	0.2441
Maximum ΔE_{ab}	0.7105	0.7149	0.7304

Table 7. Comparison of Generalization Performance With Different Linearization Techniques (With Random Noise SD = 0.025)

	Spectral sensitivities	Luminance	Mean reflectance
Median ΔE_{ab}	1.6501	1.7417	1.7597
Maximum ΔE_{ab}	3.1059	3.3054	3.3188

Discussion

This study has described a computational model of a camera system with known channel spectral sensitivities and non-linear response. Different techniques to estimate the non-linearity of the channels were evaluated. These techniques included methods based upon the Luminance and mean reflectance of a set of neutral samples and methods based upon a knowledge (or estimation) of the spectral sensitivities of the channels. The results showed that the difference between the channel-sensitivity-based estimates of the non-linearity and the Luminance- or reflectance-based estimates were small. However, the effect was significant when the linearization was used as part of a device-characterization process. A case study demonstrated that an accurate linearization can reduce characterization errors by approximately 10% compared with traditional techniques. This analysis is currently being extended for real camera systems. The technique may have particular applicability to low-end color camera systems where there is a significant non-linear response.

The correct estimation of the non-linearity of the camera's input-output response requires measurement of the camera's channel spectral sensitivities. However, even crude estimates of these sensitivities may yield more accurate estimates of the non-linearity than the use of the Luminance or mean reflectance methods.

References

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Biography

Vien graduated from The Hong Kong Polytechnic University with a BSc degree in Textile Chemistry. She then obtained a MSc in Colour Imaging at the Colour & Imaging Institute at University of Derby. She is currently a postgraduate student in the Colour & Imaging Institute working on methods for device characterization and multispectral imaging.