DIY absolute tele-colorimeter using a camera-projector system

Giuseppe Claudio Guarnera
NTNU
Gjøvik, Norway
giuseppe.guarnera@ntnu.no

Simone Bianco
University of Milan-Bicocca
Milan, Italy
simone.bianco@disco.unimib.it

Raimondo Schettini
University of Milan-Bicocca
Milan, Italy
schettini@disco.unimib.it

(a) Absolute XYZ values captured by a professional 2D color analyzer (ground truth). **(b) Absolute XYZ values estimated by our technique.** **(c) Measured ground truth (background of each square) and our estimates (circles at the center of each square).**

ABSTRACT

Image-based reflectance measurement devices allow to lower costs and increase the speed of reflectance acquisition. Unfortunately, by using digital cameras instead of gonio-reflectometers some issues arise, since consumer camera sensors are designed to produce aesthetically pleasing images, rather than delivering an accurate colorimetric reproduction of the scene. We present a novel approach for colorimetric camera characterization, which exploits a commonly available projector as a controllable light source, and with a limited number of photographs is able to accurately relate the camera sensors response to the known reflected radiance. The characterized camera can be effectively used as a 2D tele-colorimeter, suitable for image-based reflectance measurements, spectral prefiltering and spectral up-sampling for rendering, and to improve color accuracy in HDR imaging.

CCS CONCEPTS

• **Computing methodologies** → **Reflectance modeling**; **Computational photography**; *Image-based rendering*;

KEYWORDS

DSLR camera, Colorimeter, Tristimulus Values, HDR, Reflectance

1 INTRODUCTION

Radiometric functions such as BRDF, SVBRDF and BTF are commonly used to describe the appearance of real world materials and allow to achieve high photo-realism. However, accurately measuring the reflectance properties of a material, with devices such as gonio-reflectometers, can be expensive and time consuming.

In the last 20 years a number of image-based measurement setups have been developed [2]. They trade accuracy for increased versatility, higher throughput and lower costs, by taking a series of photographs of a surface and requiring mainly off-the-shelf components. Common designs range from single-camera devices, where the light source moves across a hemisphere of directions, to measurement domes, where up to hundreds cameras observe the sample from different view points. However, the typical design of consumer camera sensors focuses on good contrast and vivid colors, largely disregarding the colorimetric accuracy of the acquired scene.

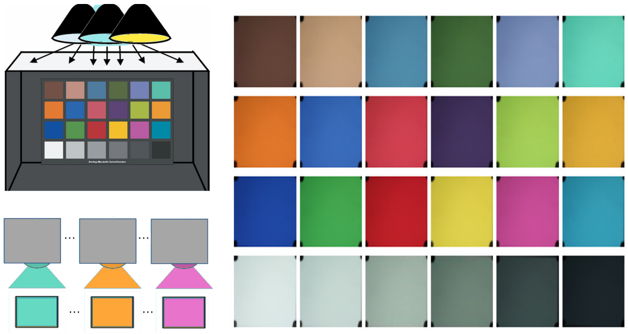
In order to use a DSLR for color and reflectance measurements, acquired RGB values must be converted into meaningful radiometric and colorimetric data. Color characterization techniques aim to establish a relationship among the sensor responses to a set of colors and the corresponding colorimetric values (CIE XYZ). To derive such a relationship, many techniques make use of a reflective color target with a limited number of color patches (*e.g.* 24 on a GretagMacbeth ColorChecker®), illuminated by a small set of illuminants (3~7 on most light booths) (Figure 1 (a), top). The sparse sampling of the incident lighting spectra and surface reflectance leads to inaccurate results and limits them to low dynamic range imaging, since only the relative spectral power distribution is preserved. These approaches should be used only in similar illumination conditions to those selected for characterization.

In our work, we abandon the color target/light booth paradigm and make use of a projector, used as a controllable light source. By modulating the relative and absolute spectral distribution of the light beam, a virtually infinite number of illuminants can be used to characterize a camera (Figure 1 (a), bottom). Such a freedom in designing the illuminants to use for camera characterization, not only allows us to reduce the sampling in the spectral reflectance space, even to a single spectrally neutral target, but also removes any bias when the characterized camera is to be used in new lighting conditions. Furthermore, by preserving the absolute scale of the illuminant, our technique provides accurate absolute XYZ values on a physical scale (cd/m^2) even from a single shot, with multiple shots delivering higher accuracy.

Previous Work. Only a few techniques aim to estimate absolute XYZ values. Verdu *et al.* [4] measured the sensor's characteristics

---

, ,
.



(a) (b)

Figure 1: (a) Standard color target / light booth setup (top) and the proposed setup with a projector serving as controllable light source (bottom). (b) Projected XYZ tristimulus values of a standard color checker, as reflected by the target.

with a monochromator, a device based on a white integrating sphere, illuminated by monochromatic light (*i.e.* a single wavelength λ at a time). Their setup includes a standard light booth and color checker; the ground truth is measured with a spectro-radiometer. To reduce the error in the estimates, the colorimetric profiles derived from the acquired data require an additional linear correction step. Kim and Kautz [3] proposed an ad-hoc transparent target, suitable for HDR imaging. The XYZ values are computed from the RGB values acquired with a HDR sequence, using a 3x3 matrix derived through linear least-squares. Our approach does not derive the XYZ values directly from the RGB values. Instead, we break down the task in order to preserve the absolute scale and to explicitly account for many factors, simply embedded in the 3×3 matrix computed by [3].

2 PROPOSED TECHNIQUE

We use as target an A4 white uncoated professional photo paper, without bleaching (roughly lambertian and spectrally neutral). To fairly compare with previous methods, in this work we limit the characterization set to the 24 illuminants which reflected by the target produce the XYZ values of a physical ColorChecker® (figure 1 (b)), and demonstrate that they suffice to outperform prior art.

The ground truth XYZ values can be measured by a 2D telecolorimeter, or estimated from the spectral reflectance $S(\lambda)$ of the target and the lighting spectra $I(\lambda)$.

For each reflected tristimulus value a HDR sequence is acquired, by varying the exposure time t or the lens f-number on the standard scale. The acquired RAW RGB values are normalized by accounting for real world device characteristics, such as noise floor n, saturation level S, areas beneath the sensor spectral sensitivity curves, lens fall-off. All the terms are estimated by our pipeline.

We compute the absolute XYZ values as:

$$[X,Y,Z]^T cd/m^2 = \mathcal{M}\cdot\mathcal{T}\left([L(R),L(G),L(B)]\right)^T cd/m^2 \qquad (1)$$

where $\mathcal{M}$ is the colorimetric characterization matrix, $\mathcal{T}$ is a polynomial transformation, and $L(R)$, $L(G)$, $L(B)$ are the luminance estimates obtained individually from each channel of the camera.

Given the set of neutral tristimulus values $X_i = Y_i = Z_i$, $i = 1,\ldots,\#_{stimuli}$ and the corresponding HDR photographs (Figure 1 (b), bottom row), for each pixel p_i in the sensor lattice we have:

$$[R|G|B]_{p_{i,t,N}} \propto \left[\mathcal{F}_{R|G|B}(T, Y_i, C_{R|G|B}, t, N)\right]_p + n \qquad (2)$$

since $Y = \sum_{\lambda\in\omega} I(\lambda)S(\lambda)\triangle\lambda$, under the hypothesis $X = Y = Z$, where ω is the visible spectrum of the light, $\mathcal{F}_{R|G|B}$ are the per-channel sensor responses to the luminance, T is the lens transmittance, and $C_{R|G|B}$ are the sensor spectral sensitivity curves. To model the sensor response to the luminance Y, the normalized values $[R', G', B']_{i,t,N}$ are fitted to the corresponding known luminance values Y_i, $i = 1,\ldots,\#_{stimuli}$, for a given pair $\{t, N\}$. From Eq. 2, their inverse are readily derived:

$$\mathcal{F}^{-1}_{R|G|B}\left(R'|G'|B', t, N\right) = L(R|G|B) = Y\, cd/m^2 \qquad (3)$$

The matrix $\mathcal{M}$ is found by means of non-linear optimization [1], using the data derived from all the color patches in Figure 1 (b):

$$\mathcal{M} = \arg\left(\min_{M\in\mathbb{R}^{3\times P}} median(E) + mean(E) + max(E)\right) \qquad (4)$$

$$E = \left\|[X,Y,Z]^T - M\cdot\mathcal{T}([L(R),L(G),L(B)])^T\right\|_1 \qquad (5)$$

where $||\cdot||_1$ is the L_1 norm, $\mathcal{T}$ is the same as in Eq. 1, and P is the number of polynomial terms given in output by $\mathcal{T}$.

3 RESULTS AND CONCLUSION

We compared the estimated absolute XYZ values from a characterized, inexpensive Canon 40D camera with the measurements of a costly professional 2D Color Analyzer (about 30K USD), for a set of scenes with complex geometry, spatially varying reflectance and light sources with different spectral power distributions (see the teaser figure for some examples). Our estimates show an average Normalized Root Mean Square Deviation of less than 1.6% using a single shot, and less than 1.3% with multiple exposures. The measured colorimetric error ΔE_{00} in most cases is below a perceptible difference, thus making our technique suitable in a wide range of applications, including image-based measurements of reflectance; in rendering, to provide accurate input data for spectral prefiltering and spectral upsampling of input textures; characterization of HDR imaging; to provide more accurate illumination estimation.

REFERENCES

[1] Simone Bianco, Francesca Gasparini, Alessandro Russo, and Raimondo Schettini. 2007. A new method for RGB to XYZ transformation based on pattern search optimization. *IEEE Transactions on Consumer Electronics* 53, 3 (2007), 1020–1028.

[2] D. Guarnera, G.C. Guarnera, A. Ghosh, C. Denk, and M. Glencross. 2016. BRDF Representation and Acquisition. *Computer Graphics Forum* 35, 2 (2016), 625–650.

[3] Min H. Kim and Jan Kautz. 2008. Characterization for High Dynamic Range Imaging. *Computer Graphics Forum* 27, 2 (2008), 691–697.

[4] Francisco Martínez-Verdú, Jaume Pujol, and P Capilla. 2003. Characterization of a digital camera as an absolute tristimulus colorimeter. *Journal of Imaging Science and Technology* 47, 4 (2003), 279–295.