Influence of Technology, Color Architecture and Bit-depth of Optoelectronic Imaging Sensors used as Color Measurement Instruments

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ABSTRACT

Digital image capture devices cannot be used directly as instruments for color measurement. The main stages for characterizing a digital image capture device as an instrument for color measurement are the spectral and spatial characterization and the color transformation from the RGB device dependent space to a device independent space such as CIE-XYZ. We performed the spatial and spectral characterization and the color transformation of an 8 bit CMOS camera, a 3-CCD 8 bit camera, a 1-CCD 12 bit camera and a 1-CCD 10 bit camera in order to analyze the influence of technology (CMOS – CCD), color architecture (1-CCD – 3-CCD) and bit-depth (8, 10 and 12 bits) in the performance of optoelectronic imaging sensors in color measurement. We analyzed the performance of the different optoelectronic imaging sensors as systems for color measurement by means of minimum, maximum and mean CIE-L*a*b* color differences. The results obtained so far indicate that optoelectronic imaging sensors with CCD technology and high bit-depth give rise to a considerably better performance as systems for color measurement.

1. INTRODUCTION

An optoelectronic digital image capture device cannot be used directly as an instrument for color measurement: one must first obtain its spatial, spectral and colorimetric characterization[1]. Recently, we developed a complete system for the characterization of image capture systems in order to convert them into useful color measuring instruments, that is, absolute tristimulus colorimeters[1,2,3,4]. In the spatial characterization, several techniques that allow us to considerably reduce the contribution of the noise sources inherent to optoelectronic digital image capture devices (e.g. dark current, shot noise and PRNU) are applied to achieve pixel responses from a flat field of illumination with a low spatial variation along the image sensor (flat-field correction matrix)[2,3]. The spectral characterization consists in obtaining the spectral sensitivities and the color-matching functions for the different channels (RGB) of the device[4]. The colorimetric characterization consists in calculating the colorimetric profile between the RGB space of the device and the CIE-1931 XYZ standard space[5].

This global characterization, which allows the RGB digital data to be transformed into estimated XYZ tristimulus values, depends greatly on the raw RGB space of the image capture device, which also varies due to many factors, ranging from the basic components (e.g. the optoelectronic sensor's technology (CCD or CMOS), the color architecture and the bit-depth) to the optical variables (e.g. the f-number and the zoom lens) and electronic variables (e.g. gain, offset, matrixing and white balance). In this work we analyze the influence of the technology, color architecture and bit-depth of optoelectronic imaging sensors used as color measurement instruments.

2. METHOD

We performed the spatial and spectral characterization and color transformation of an 8 bit CMOS color camera (PixeLINK PL-663), a 3-CCD 8 bit color camera (SONY DXC-390P), a 1-CCD 12 bit color camera (QImaging RETIGA) and a 1-CCD 10 bit color camera (QImaging QICAM), in order to analyze the influence of technology (CMOS – CCD), color architecture (1CCD – 3CCD) and bit-depth (8, 10 and 12 bits) on the performance of optoelectronic imaging sensors in color measurement.

In the spatial characterization equal pixel responses of the image sensor to a flat field of illumination are obtained by correcting the response of each pixel[2]. We apply a linear algorithm to correct the flat-field response of the optoelectronic imaging sensor, which is based on calculating the gain G(i,j) and offset O(i,j) matrixes, from which the corrected digital level for each pixel $DL_c(i,j)$ is obtained from the initial digital level DL(i,j) according to the following expression:

$$DL_c(i,j) = O(i,j) + G(i,j) \cdot DL(i,j) \qquad (1)$$

The gain and offset matrixes can be obtained as follows:

$$G(i,j) = \frac{DL_b - DL_o}{DL_b(i,j) - DL_o(i,j)} \qquad O(i,j) = DL_0 - G(i,j) \cdot DL_0(i,j) \qquad (2)$$

where DL_b and DL_0 are the mean digital levels and $DL_b(i,j)$ and $DL_0(i,j)$ are the digital levels corresponding to pixel (i,j) of the reference and dark images. The reference image corresponds to an image with a mean digital level situated in the middle of the linear dynamic range and the dark image is the image obtained in the total absence of light.

The spectral characterization is obtained experimentally by measuring the optoelectronic conversion spectral functions (OECSF) that relate the digital response (relative digital level $RDL_{\lambda k}$, λ = wavelength, k = R, G, B channels) of the optoelectronic sensor to the spectral exposure level[4] ($H_{\lambda k}$), for the different channels (RGB). The optoelectronic conversion spectral functions are fitted by a symmetric sigmoid function (3) whose parameters ($a_{\lambda k}$, $b_{\lambda k}$, $c_{\lambda k}$ $d_{\lambda k}$) allow us to obtain the relative spectral sensitivities.

$$RDL_{\lambda k} = a_{\lambda k} + b_{\lambda k} / \left[1 + \exp\left(-\left(H_{\lambda k} - c_{\lambda k}\right)/d_{\lambda k}\right)\right] \qquad (3)$$

The optoelectronic sensor's gray balance and the relative scaling of the spectral sensitivities allow us to obtain the color-matching functions[4] $\mathbf{T_{RGB}}$ which are the starting point for the colorimetric characterization.

The aim of colorimetric characterization is to transform the RGB digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions[5]. The proposed characterization model may be broken down into two portions. The first portion is the basic colorimetric profile M. It is obtained from the application of a gray balance to the raw RGB digital data to convert them into RGB relative colorimetric values, the calculation of a transformation matrix (by a maximum ignorance by least-square regression method[6]) (4) which permits us to transform the RGB device dependent codification to CIE-XYZ device independent codification, and finally the insertion of a luminance adaptation algorithm in the basic colorimetric profile in order to achieve a high system luminance working range. Luminance adaptation algorithm is based on determining the optoelectronic conversion functions (OECF) that relate the digital response of the optoelectronic sensor to different luminance levels associated with the equal-energy stimulus for different values of the f-number of the zoom lens.

$$M = T^t_{XYZ} \cdot T_{RGB} \cdot \left(T^t_{RGB} \cdot T_{RGB}\right)^{-1} \qquad (4)$$

The second portion is a color compensation model, which consists in a linear correction that includes the mismatch of the color-matching functions of the optoelectronic sensor and the systematic errors made during the whole characterization.

The performance of the different optoelectronic imaging sensors as systems for color measurement is analyzed by means of minimum, maximum and mean CIE-L*a*b* color differences of samples, measured with the imaging sensor system and with a conventional telespectroradiometer.

3. RESULTS

The spatial characterization of optoelectronic imaging sensors makes it possible to considerably correct the contribution of the noise sources inherent to them (e.g. dark current, shot noise and PRNU), obtaining pixel responses with a low spatial variation along the image sensor from a flat field of illumination (Figure 1). This will allow us to obtain color measurement systems based on optoelectronic imaging sensors with a high spatial uniformity and resolution.

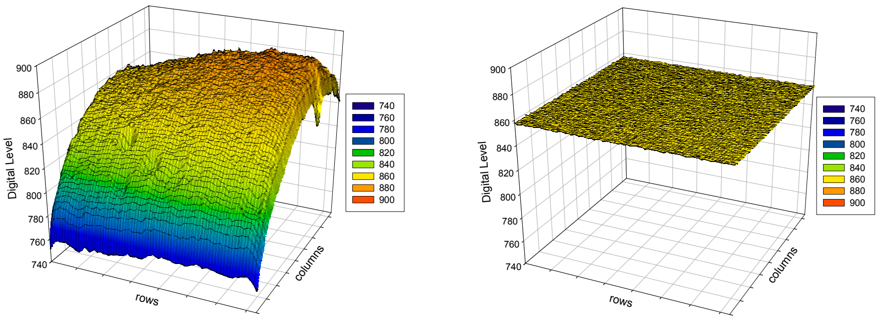


Figure 1. Mesh plot of digital levels for the red channel over the CCD before (left) and after (right) applying the spatial characterization to an image from a flat field of illumination, by the QImaging QICAM Color 1CCD – 10 bits.

The spatial uniformity improvement of the image sensor from a flat field of illumination obtained when the spatial characterization is applied to the raw images is similar, for the same color technology (1 or 3 CCD) and for both types of sensors analyzed: CCD and CMOS. In the case of 1 CCD (both 10 and 12 bit-depth), we found that, in the manufacturers' recommended conditions of gain and offset, the linear dynamic range of the blue channel has two regions of different slopes (Figure 2). This is a great drawback for an optoelectronic imaging sensor to be used as a system for color measurement. It is necessary to consider these two linear regions separately in order for the blue channel to obtain a spatial uniformity improvement similar to that of the red and green channels.

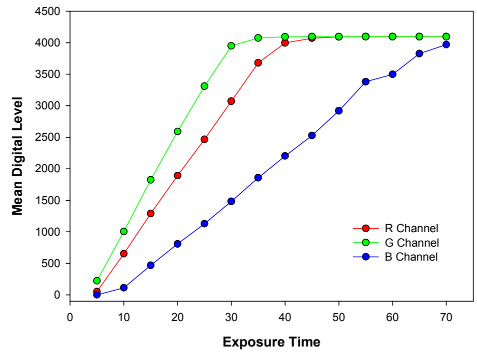
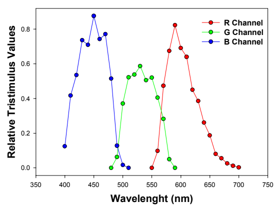
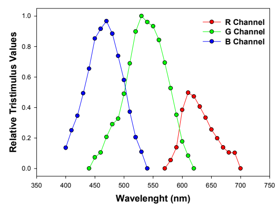


Figure 2. Mean digital level vs. exposure time for R, G and B channels, for the QImaging RETIGA Color 1 CCD – 12 bits.

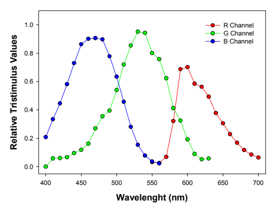
The color matching functions of the different image capture devices analyzed are obtained by means of spectral characterization. For the CCD cameras the green channel shows greater sensitivity in comparison with the red and blue ones than for the CMOS one, which has a rather sensitive red channel. A different bit-depth does not give rise to a difference that can be associated with bit-depth in color matching functions. The 3 CCD and 1 CCD color architecture does show, however, several significant differences between their color matching functions. The two main differences are the width of the color matching functions and their overlapping among red, green and blue channels. The independence of the three channels for the 3 CCD color architecture is shown in its narrower and less overlapping red, green and blue color matching functions (Figure 3).



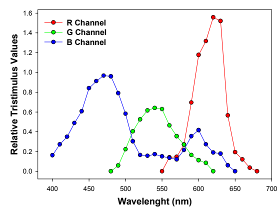
SONY DXC-390P Color, 3CCD – 8 bits
(a)



QImaging RETIGA Color, 1CCD – 12 bits
(b)



QImaging QICAM Color, 1CCD – 10 bits
(c)



PixeLINK PL-663 Color, CMOS - 8 bits
(d)

Figure 3. Color matching functions for (a) SONY DXC-390P Color, 3CCD – 8 bits, (b) QImaging RETIGA Color, 1CCD – 12 bits, (c) QImaging QICAM Color, 1CCD – 10 bits and (d) PixeLINK PL-663 Color, CMOS - 8 bits.

The performance of the different optoelectronic imaging sensors as systems for color measurement is analyzed by means of minimum, maximum and mean CIE-L*a*b* color differences, comparing color measurements obtained with these characterized devices and a telespectroradiometer using a standard color chart (ColorChecker DC Chart) (Table 1). CIE-L*a*b* color differences are expected to be improved optimizing the usable dynamic range of optoelectronic imaging sensors.

The results obtained so far indicate that optoelectronic imaging sensors with CCD technology and high bit-depth give rise to a considerably better performance as system for color measurement. The fact that the analyzed devices with different color architecture also have different bit-depth does not allow us to draw any conclusion about the most convenient color architecture, although 3 CCD color technology is expected to be preferably to 1CCD because of the linear dynamic range for each channel.

Table 1. Maximum, minimum and mean CIE-L*a*b* color differences (ΔE_{ab}) on the ColorChecker DC Chart for the optoelectronic digital image capture devices analyzed.

Devices Analyzed	Maximum ΔE_{ab}	Minimum ΔE_{ab}	Mean ΔE_{ab}
SONY DXC-390P Color, 3CCD – 8 bits	46.24	2.24	12.71
QImaging RETIGA Color, 1CCD – 12 bits	31.48	1.10	10.83
QImaging QICAM Color, 1CCD – 10 bits	47.77	1.46	10.92
PixeLINK PL-663 Color, CMOS - 8 bits	66.11	2.04	17.35

4. CONCLUSIONS

We performed a spatial and spectral characterization and the color transformation of an 8 bit CMOS camera, a 3-CCD 8 bit camera, a 1-CCD 12 bit camera and a 1-CCD 10 bit camera. The improvement in the spatial uniformity of the image sensor from a flat field of illumination obtained when the spatial characterization is applied to the raw images was similar for all the devices analyzed. The useful dynamic range of the corrected blue channel was greater for 3 CCD color devices than for 1 CCD ones, in which the dynamic range of the blue channel shows two linear parts, and hence two work regions with a useless transition region between them. Therefore, 3 CCD color architecture is recommended in order to obtain the widest linear dynamic range and the widest working range for all channels.

The minimum, maximum and mean CIE-L*a*b* color differences permits us to analyze the performance of the different optoelectronic imaging sensors as systems for color measurement. The results obtained so far indicate that optoelectronic imaging sensors with CCD technology and high bit-depth give rise to a considerably better performance as systems for color measurement.

5. ACKNOWLEDGMENTS

This research was supported by the Spanish Ministry for Science and Technology (*Ministerio de Ciencia y Tecnología*) through grant number DPI2002-00118. M. Vilaseca and M. de Lasarte would also like to thank for to the government (Generalitat) of Catalonia the PhD grants they received. We also would like to thank to the Department of Optics of the University of Granada to make our available their QImaging RETIGA Color 12 bits color camera.

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