Development of a perceptual colorimeter based on a conventional CCD camera with more than three color channels

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ABSTRACT

In order to improve the precision of colorimeters based on a digital image capture device, we increased the number of acquisition channels by using a supplementary filter placed in front of the color camera and taking two images of the scene: one without the filter (3 RGB channels) and one with the filter (3 different UVW channels). We selected a wide-band cyan filter that increases the transmission of spectral zones common to the three pseudo-color matching functions of the CCD camera and the spectral transmission of the channel with the lowest sensitivity. This six-channel color measurement instrument shows an improvement in the precision level compared with a conventional three-channel system, obtaining a better Vora factor (greater than 0.96), color quality factor (greater than 0.95) and color reproduction index (greater than 96%). From the colorimetric values obtained with the six-channel system we developed a perceptual colorimeter by applying different color appearance models (ATD, Hunt'91, CIELAB, LLAB, Hunt'94 and CIECAM02). The results obtained with the colorimeter developed showed a good performance for the perceptual parameters in comparison with a conventional telespectroradiometer, especially when Hunt'94 and CIECAM02 models were applied.

1. INTRODUCTION

An optoelectronic digital image capture device cannot be used directly as an instrument for color measurement. Recently, we developed a complete system for characterizing image capture systems in order to convert them into a useful color measuring instrument, that is, an absolute tristimulus colorimeter[1,2,3]. The main stages for characterizing a digital image capture device as an instrument for color measurement are spectral and spatial characterization and color transformation from the RGB device dependent space to a device independent space such as CIE-XYZ.

When a digital image capture device with a CCD-RGB sensor is used as a colorimeter, it shows good results in terms of repeatability, although its precision when measuring tristimulus values is usually limited, i.e. there are deviations between the predicted values and the real values[2]. To improve this precision, a possibility might be to increase the number of image acquisition channels by means of a filter and to take two images of the scene: one without the filter and one with the filter.

From the colorimetric values obtained in a universal space of color representation such as CIE-XYZ, it is possible to develop a perceptual colorimeter by applying different color appearance models[4] to the XYZ tristimulus values obtained.

In this work we had two different aims. The first was to study the improvement in the precision of the color measurements obtained by using a supplementary filter placed in front of the RGB-CCD camera and comparing the results obtained using only three channels (RGB colorimeter) or the six channels obtained when the filter is used (RGBUVW colorimeter). The second aim was to convert the RGBUVW colorimeter developed into a perceptual colorimeter by applying different color appearance models, and to evaluate their performance.

2. METHOD

The image capture device used consists of a conventional 3CCD-RGB camera (Sony DXP-930P) with a zoom lens (Sony VCL-614WEA) and a frame grabber (Matrox MVP-AT 850). We performed the spectral and colorimetric characterization of the image digitalization system considered according to the method developed in a previous work[1,2]. Spectral characterization was obtained experimentally by measuring the optoelectronic conversion spectral functions that relate the digital response of the optoelectronic sensor to the spectral exposure level (OECSF). The OECSFs were fitted mathematically by sigmoid functions defined by four parameters. Firstly, the spectral characterization was performed using the CCD-RGB camera. We therefore obtained three OECSFs for each wavelength. From these OECSFs it is possible to obtain the pseudo-color matching functions of the image capture device ($\mathbf{T}_{\mathbf{RGB}}$). Taking into account the shape of the pseudo-color matching functions, an optimization process was carried out by simulation in order to choose a filter that improved the performance of the instrument in terms of colorimetric results. From this process, we deduced that wide-band filters that permit a greater transmission of spectral zones common to the three pseudo-color matching functions and may increase the spectral transmission of the channel with the lowest sensitivity were the most suitable for this purpose. According to this, we chose a cyan filter with a high mean spectral transmittance (Figure 1). Performing the spectral characterization with the supplementary filter in front of the CCD camera again, we obtained three more OECSFs for each wavelength. In total we had six OECSFs, which were used to obtain the pseudo-color matching functions for the RGBUVW colorimeter ($\mathbf{T}_{\mathbf{RGBUVW}}$).

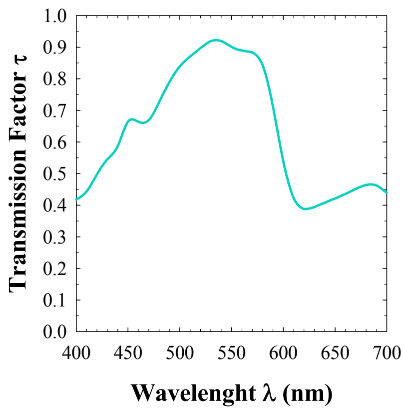

Figure 1: Spectral transmission factor of the filter used

The colorimetric characterization consists in transforming the RGBUVW digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions. Thus, in the first stage, a gray balance was applied over the raw RGBUVW digital data to convert them into RGBUVW relative colorimetric values. From these values, we obtained the basic colorimetric profile (**M**)—i.e. the 3x6 matrix that corresponds to the best linear combination of the pseudo-color matching functions in order to match the CIE-1931 XYZ color matching functions—by using the maximum ignorance by least-square regression method[5]. In the second stage, an algorithm of luminance adaptation was inserted into the basic colorimetric profile in order to determine 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. Finally, by capturing a sample of colors such as the ColorChecker chart under different light sources and comparing the estimated XYZ data obtained with the colorimetric characterization performed and the XYZ data (in cd/m^2) measured using a telespectroradiometer (Photo Research PR-650), we found that a linear correction had to be performed due to the mismatch of the color matching functions of the camera.

The performance of RGB and RGBUVW colorimeters is analyzed in two ways. The first procedure is based on the algebraic properties of the colorimetry and consists in quantifying the distance between the vector subspaces corresponding to the $\mathbf{T}_{\mathbf{RGBUVW}}$ and $\mathbf{T}_{\mathbf{XYZ}}$ color matching functions (Vora quality factor q_v) or quantifying the common volume between these vector subspaces (quality factor CQF)[6,7]. The second procedure consists in measuring different samples using the imaging sensor system and a conventional telespectroradiometer and comparing different parameters such as color differences or color reproduction indices[8] .

Using the CIE-XYZ values obtained with the RGBUVW colorimeter, we applied different color appearance models[4], specifically ATD, Hunt'91, CIELAB, LLAB, Hunt'94 and CIECAM02[9]. In order to analyze the performance of the proposed system as a perceptual colorimeter, we compared the perceptual data obtained from a group of samples using this system and those obtained from tristimulus values measured by a telespectroradiometer, obtaining the confidence value (CV) as follows:

$$CV = 100\frac{\left(\frac{1}{n}\sum_{i=1}^{n}(V_i - P_i)^2\right)^{1/2}}{\frac{1}{n}\sum_{i=1}^{n}V_i} \qquad (1)$$

where V_i are the perceptual data obtained from the RGBUVW colorimeter, P_i are the perceptual data obtained from the telespectroradiometer measurements and n is the number of samples considered.

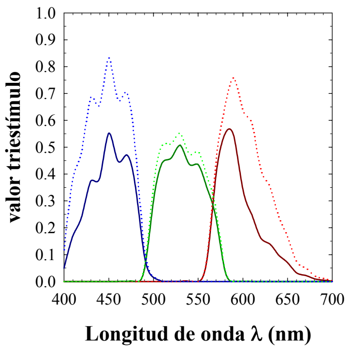

Figure 2: Pseudo-color matching functions for the RGB (dashed lines) UVW (solid lines) colorimeter.

3. RESULTS

Figure 2 shows the pseudo-color matching functions corresponding to the RGBUVW colorimeter. It was found that the pseudo-color matching functions corresponding to the UVW and the RGB channels were related by the filter transmittance.

The basic colorimetric profile is given by

$$\mathbf{M} = \mathbf{T_{XYZ}}^{\mathbf{t}} \cdot \mathbf{T_{RGBUVW}} \cdot (\mathbf{T_{RGBUVW}}^{\mathbf{t}} \cdot \mathbf{T_{RGBUVW}})^{-1} = \begin{bmatrix} 2.144 & -5.1312 & 0.3017 & -0.8930 & 6.2127 & 0.1049 \\ 0.4342 & -8.4864 & -0.4620 & 0.9454 & 11.2592 & 0.8740 \\ 0.0787 & 6.4999 & 0.1050 & -0.1578 & -7.0897 & 3.0938 \end{bmatrix}$$

Using the algebraic-based procedure we obtained a Vora quality factor q_v of 0.9258 for the RGB and 0.9630 for the RGBUVW colorimeter. The results obtained for the color quality factor (CQF) were 0.9361 and 0.9530. This means an increase of 4 and 1.8%.

The measurement of color differences between the colorimeters developed and a conventional telespectroradiometer can be used to evaluate the improvement of the precision of the digital colorimeter when the number of channels is increased. Table 1 shows the results corresponding to L*, a*, b*, C_{ab}*, H_{ab}* and the color difference formula CIE-94. Increasing the number of channels leads to a considerable improvement in the precision of the colorimetric values measured.

Table 1. Mean values of the CIELAB parameter differences and color differences using the CIE-94 formula obtained when a set of samples are measured using the RGB or the RGBUVW colorimeters and a telespectroradiometer.

	$\lvert\Delta L^*\rvert$	$\lvert\Delta a^*\rvert$	$\lvert\Delta b^*\rvert$	$\lvert\Delta C_{ab}^*\rvert$	$\lvert\Delta H_{ab}^*\rvert$	ΔE_{94}
RGB Colorimeter	4.32	6.00	8.80	10.37	3.87	6.59
RGBUVW Colorimeter	1.36	5.41	5.67	6.18	2.74	5.02

Another test for checking the improvement in the precision of the colorimeter that we performed is to calculate the color reproduction index (CRI)[8], based on a weighted average of the absolute deviations of lightness (Q), colorfulness (M) and hue (H) when a color appearance model is used. To calculate the CRI we considered the Hunt'91 model for non-related colors (Table 2). The CRI was higher for the RGBUVW colorimeter than for the RGB colorimeter. The combined indexes IcQ, IcM and IcH were also higher for the RGBUVW colorimeter than for the RGB colorimeter, which means that the dispersion in the results is lower.

Finally, in order to analyze the performance of the colorimeter developed as a perceptual colorimeter, the Confidence Value (CV) obtained when different color appearance models are applied is shown in Table 3. In general, the RGBUVW colorimeter shows a better performance when the Hunt'94 or CIECAM02 models are considered. Comparing the perceptual parameters, the colorimeter shows the best performance for the lightness or brightness parameter.

Table 2. Values of the combined indexes IcQ, IcM, IcH and the Color Reproduction Index (CRI) obtained when a set of samples were measured using the RGB or the RGBUVW colorimeters and a telespectroradiometer.

	IcQ	IcM	IcH	CRI
RGB Colorimeter	97.64	95.49	94.99	95.78
RGBUVW Colorimeter	99.27	97.11	95.79	96.99

Table 3. Confidence Value (CV) for the appearance parameters of lightness or brightness, colorfulness and hue obtained when a set of samples were measured using the RGBUVW colorimeter and a telespectroradiometer, and different color appearance models were applied.

CV	ATD	Hunt'91	CIE-LCH	LLAB	Hunt'94	CIECAM02
Lightness/Brightness	3.60	2.20	2.96	4.49	2.69	4.29
Colorfulness	7.89	10.57	21.42	13.99	3.50	6.28
Hue	88.72	9.55	16.70	16.28	2.83	3.59

4. CONCLUSIONS

The results show an improvement in the performance of the colorimeters developed with respect to the precision level when the number of channels is increased, as a better Vora factor (greater than 0.96), color quality factor (greater than 0.95) and color reproduction index (greater than 96%) are obtained.

The comparison between the results of perceptual variables corresponding to the different color appearance models obtained with the RGBUVW colorimeter and those obtained from measurements carried out with a telespectroradiometer show that the lowest deviations are obtained by applying the Hunt'94 and CIECAM02 models. Furthermore, deviations obtained in most of the analyzed models are small, which allow us to conclude that the system developed shows a good behavior as a perceptual colorimeter.

Acknowledgements

This research was supported by the Spanish Ministry of Science and Technology (Ministerio de Ciencia y Tecnología) by means of grants PDI2002-00118 and PIR1995-0587-OP. Meritxell Vilaseca and Marta de Lasarte would like to thank the government of Catalonia (Generalitat) for the PhD grants they have received.

References

1. F.M. Martínez-Verdú, J. Pujol, P. Capilla, "Calculation of the color matching functions of digital cameras from their complete spectral sensitivities", J. Imaging Sci. Technol. 46, 15-25 (2002).
2. F.M. Martínez-Verdú, J. Pujol, P. Capilla, "Characterization of a digital camera as an absolute tristimulus colorimeter", J. Imaging Sci. Technol. 47, 279-295 (2003).
3. M. de Lasarte, M. Vilaseca, J. Pujol, M. Arjona, F.M. Martínez-Verdú, D. De Fez and V. Viqueira, "Influence of Technology, Color Architecture and Bit-depth of Optoelectronic Imaging Sensors used as Color Measurement Instruments", in Proceedings of the AIC '04 (2004).
4. M.D. Fairchild, "Color appearance models" (Addison-Wesley, Reading, Massachusetts, 1998).
5. G.D. Finlayson, M.S. Drew, "Constrained least-squares regression in colour spaces", J. Electron. Imaging, 6, 484-493 (1997).
6. P.L. Vora, H.J. Trussell, "Measure of goodness of a set of color-scanning filters", Journal of the Optical Society of America A, 10, 1499-1508 (1993).
7. G. Sharma, H.J. Trussell, "Figures of merit for color scanners", IEEE Trans. Image Process., 7, 129-133 (1997).
8. R.W.G. Hunt, "The Reproduction of Color" (Fountain Press, England, 1995).
9. N. Moroney, M.D. Fairchild, R.W.G. Hunt, C. Li, M.R. Luo and T. Newman, "The CIECAM02 color appearance model", in Proceedings of Tenth Color Imaging Conference: Color Science Systems and Applications (Society for Imaging Science and Technology, Springfield, Va., 2004), 23-27.