Tristimulus Colorimetry for Video Display Units

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Abstract

A microprocessor controlled tristimulus colorimeter with "notebook" computer data recording and manipulation enables accurate chromaticity measurements. Importance of exact colorimetric mapping of the Video Display Units (VDUs) prompted the development of CCD camera-tristimulus filter colorimeters. Characterization of CCDs for spectral response and pixel to pixel uniformity precedes the filter design. The paper will show attainable accuracy; discusses problems arising from pixel to pixel variation of spectral responsivity and its partial correction by matrix transformation of the tristimulus values.

Introduction

In the past few attempts were made for developing instruments for imaging colorimetry. One of the most recent tries was focused on measuring color prints. This approach utilized a CCD camera mounted side by side to a tristimulus colorimeter available commercially[1] to measure average chromaticity values on the depicted surface area. In this technique only average spectral response corrections were applied at each pixel to perform as a tristimulus colorimeter. Since the geometry and sensing areas of the two instruments are very different, this may lead to considerable error for color determination of the measured surface. An other method utilized the known spectral response of each pixel with using 3 colored filters; calculations where then applied for determining the chromaticity of a measured object; the results again were not yielding very accurate data .[2]

A new approach was introduced for enabling simple measurement technique of light sources where chromaticity is changing from one spot to another; information can be obtained across an area sensed by the CCD camera for luminance and chromaticity point by point. We concentrated particularly on color displays with differing luminance and chromaticity characteristics. The same approach can be used for other applications as well where surface characteristics vary. In this case the system has to be augmented with a stable source of radiation with known spatial distribution and corresponding spectrally to that of a CIE standard illuminant.

In designing a CCD tristimulus colorimeter the following steps have to be followed: first a thorough spectral sensitivity measurement of large number of pixels need to be performed to determine the uniformity across the surface of the camera; from the many spectral sensitivity curves an average can be derived. In order to measure color coordinates accurately with the system, three different filters have to be fitted to the average of the spectral response to achieve the CIE tristimulus type responses. Finally, to determine the usefulness of the system, it is possible to calculate the color differences obtained with the filters across the camera with respect to the "real" color obtainable with a high precision single channel imaging colorimeter looking at the same homogeniously illuminated surface. The color differences should be evaluated for those light sources whose spectral power distributions would be most likely evaluated with the CCD colorimeter. For these a pixel to pixel matrix correction can be applied, increasing the measurement accuracy considerably.[3]

2. Instrument design

The complete measuring setup consists of two parts:

A. Imaging single channel tristimulus colorimeter and
B. A CCD image sensor colorimeter.

2.1 Imaging single channel tristimulus colorimeter

The input optics of the imaging single channel tristimulus colorimeter are shown on Fig.1. The scene to be measured is focused by the telescope objective **1** onto a mirror in the middle of a glass cube, which is then focused by objective **3** onto diaphragm **4**. Behind the diaphragm is a set of glass filters (**5**) that corrects the spectral responsivity of the Si photo element (**6**) to match the CIE x (λ), y (λ), and z (λ) color matching functions.

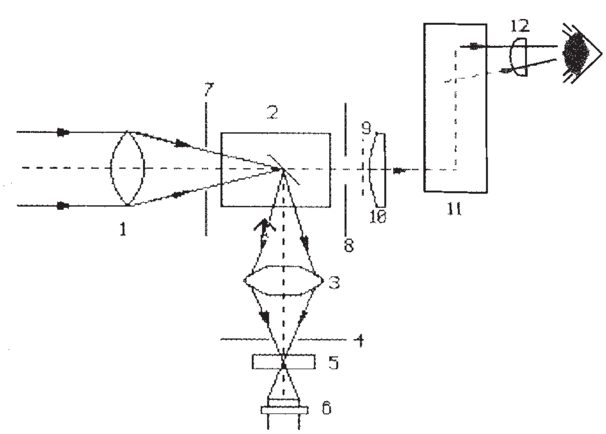

Figure 1. Single channel colorimeter input optics

The objects consisting of elements **8** to **12** focus the image emerging from the partial mirror **2** into the observer's eye to be able to see the exact measurement location. A micropocessor controlled current-voltage transducer, signal amplifier and analog-to-digital transducer are directly mounted on the optical unit. The digital output is fed to a notebook computer that is utilized as a read-out display, to program the unit, to process the signal and compute the colorimetric parameters as well.

2.2 CCD colorimeter

In case of the CCD colorimeter the main problem lies in the proper colorimetric filtering of the camera. As it would be desirable to obtain better filtering then is available on commercial CCD cameras a technique was chosen where the total CCD camera surface is filtered. Individual variations in pixel spectral responsivity can be corrected only by electronic correction in this case; the method is described in section 3.

To obtain the best possible filter match to the CIE color matching functions first the spectral responsivity of a relatively high number of pixels had to be determined. Previous experiments showed that the spectral responsivity varies slightly from pixel to pixel by a continouos manner as a function of location; this function can be estimated from the large number of pixels tested.

Our investigation concentrated on a CCD camera made by Micam - HRS,[4] they were matched with two different sets of filters, with $f_1' < 1.5$ % for $\bar{y}$ and $\bar{z}$ filters, and $f_1' < 3$ % for $\bar{x}$ filters. (see definition of f_1' in App.1.) The pixels evaluated were chosen as shown on the map in Fig. 2.

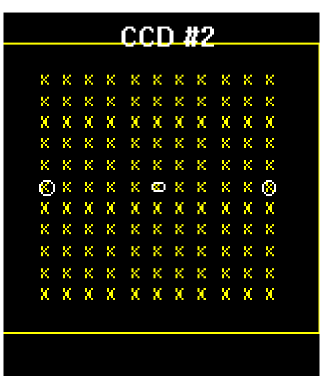

Figure 2. Map of measured pixels

Average spectral response curve of the pixels of our chosen CCD camera is presented in Fig. 3; All spectral response curves where normalized to the maximum value. The spectral response measurements were carried out using a Cary 14 type spectrophotometer modified for automatic data acquisition .

Accurate determination of the spectral response variation across the two-dimensional surface area of the CCD camera was needed for the "correction" matrix for obtaining the correct chromaticity coordinates and luminance value for each pixel location. Variations in sensitivity values from one end of the camera area to the other are shown on Fig. 4 at four different wavelengths.

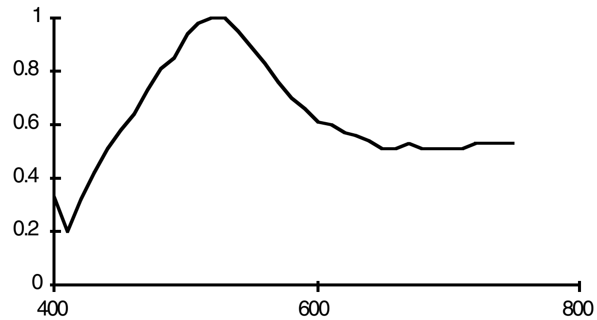

Figure 3. Average spectral sensitivity of the CCD

Filter-matching of CCD camera has posed new problems not generally found in the case of single photocell filter matching. The colorimetric filters were produced by adding several (4 or 5) layers of different colored glasses with carefully controlled thicknesses.

With the given spectral transmission characteristics of the glass layers it is possible to add them together with certain thickness of each over the detector to obtain the required response curves. However for very good fit, expressed as low f_1' number , in the case of the $\bar{x}$ filters the total transmissivity of the glass layers might be too small to achieve the required magnitude of the signal level.

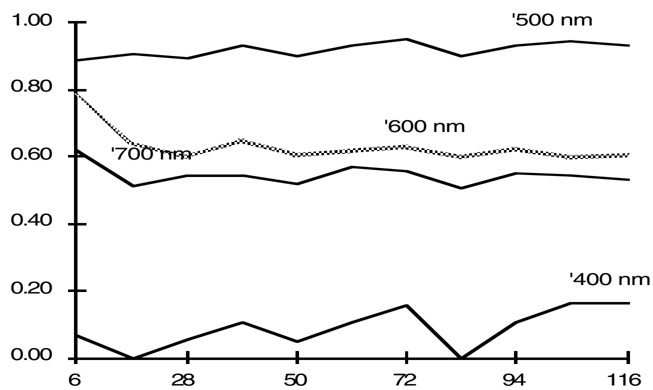

Figure 4. Relative sensitivity change across the CCD

It is necessary to maintain the diameter of the filter larger then the camera diameter in order to allow other optical components to be installed between the camera and filter if required. This arrangement poses further restrictions on the thickness uniformity for all filters across a large area. Loss of filters during manufacturing due to high numbers of breakage is unavoidable in most cases.

Fig. 5 in App. 2 shows the set of filter-CCD average combination response curves obtained by very good matching and for comparison with less perfect matching for an other CCD camera recently investigated.[4]

3. Electronic Correction of Tristimulus Values

Colorimetry can be interpreted as the mapping of a vector from an n dimensional spectral power distribution space into a 3-dimensional color space.[3] In this vector space the tristimulus value calculation can be expresssed as

$$T_{i1} = \int P_\lambda \bar{t}_i(\lambda) d\lambda$$

where T_i stands for X,Y, and Z tristimulus values and $\bar{t}_i$ stands for $\bar{x}, \bar{y}$, and $\bar{z}$ color matching functions and can be written in the form of a scalar multiplication

$$T_i = \bar{P} * \bar{t}_i \qquad \bar{P}* \text{ here is } P_\lambda \text{ vector.}$$

The color measuring subspace is determined by the color-percepting qualities of the human eye; its basic vectors can be vectors describing human visual qualities, e.g. the CIE color matching functions or any other three independent vectors in this subspace. In this case the measurement results can be transformed from one system of basic vectors to that of another. If however the vectors given by the spectral responsivities of the filtered detectors are not within the chosen subspace, the measurement results cannot be transformed explicitely. One can seek in this case a "best" transformation, e.g. by equating for the least mean square error for all the spectral power distributions in question. If there are only three types of spectral power distributions considered as is the case of a VDU (one set of phosphors or LCD + filters + backlight power distribution) then the matrix transformation can be exact.

We have determined—by the help of the precision single channel imaging colorimeter—for the given set of pixel-to-pixel spectral distributions the correction matrices, built them into the evaluation program of the imaging colorimeter and used the colorimeter for evaluating LCD displays.

4. Results

Measurement results with our imaging colorimeter were compared to results obtained by spectroradiometric measurements on the same display colors.

Spectral response curves obtained with the filters matched to the CCD have resembled the CIE tristimulus functions with very good approximation. In App. 2. Fig. 4 represents $\bar{x}$ and $\bar{y}$ curves together with the CIE tristimulus functions. In App. 3. Fig. 5 shows the spectral power dis-tributions of the R, G, and B settings for a liquid crystal display.

Table 1. lists the values for the chromaticity coordinates of the R, G, B, settings of the display by spectrophotometric method and with the imaging colorimeter without the matrix correction.

CIE chromaticity coordinates	B	G	R
	spectophotometric		
x	0.144	0.225	0.690
y	0.092	0.694	0.310
z	0.763	0.081	0.000
	CCD colorimeter		
	B	G	R
x	0.149	0.216	0.685
y	0.085	0.697	0.313
z	0.765	0.087	0.001

Table 1. CIE chromaticity coordinates for blue, green, and red LCD filters

Table 2. lists the variation of chroma difference compared to the "CIE chromaticity" as calculated from spectrophotometric measurements and "average chromaticity" (calibrated with the single channel colorimeter), expressed as

$$\Delta E = \left[(\Delta L*)^2 + (\Delta u*)^2 + (\Delta v*)^2 \right]^{1/2}$$

Δ E(SPR-AVE)	0.015	0.004	0.008
Δ E(#1-AVE)	0.064	0.023	0.024
Δ E(#59-AVE)	0.070	0.023	0.023
Δ E(116-AVE)	0.070	0.023	0.025

SPR: SPECTROPHOTOMETRIC

Table 2. CIELUV chroma diffe

for the R, G, B type spectral power distribution measurement. We calculated ΔE between three pixels from both sides and the center area of the CCD and the average value for both type of cameras as well as shown on Tab. 2.

5. Conclusions

Using a high precision single channel colorimeter for calibration of the specially designed tristimulus imaging colorimeter it is possible to measure chromaticity coordinates with reasonable accuracy; chroma-differences ΔE of $< 0.01 - 0.1$ can be achieved as compared to the "absolute" measurement results obtained by spectrophotometry. The many advantages of the instrument allowing instantaneous readings in spatial distribution of luminance and chromaticity across the display area of many different VDUs is of great value to the manufacturers and users. By applying in-situ pixel to pixel matrix correction the colorimetric error for any chosen set of three primary spectral power distrib-utions can be made negligible.

Appendix

1. Definition of f_1 function[5]

$$f_1 = \frac{\int \left| s_x(\lambda)_{rel} - s_T(\lambda)_{rel} \right| d\lambda}{\int s_T(\lambda)_{rel} d\lambda}$$

where $s_x(\lambda)_{rel} = s(\lambda)_{rel} \times \dfrac{\int S(\lambda)_A \times s_T(\lambda)_{rel}}{\int S(\lambda)_A \times s(\lambda)_{rel} d\lambda}$

and $s_T(\lambda)_{rel}$ is the target spectral responsivity

$S(\lambda)_A$ is the spectral distribution of Standard Illuminant A

$s(\lambda)_{rel}$ is the relative spectral responsivity of the detector

2. CCD camera + Tristimulus filter spectral sensitivities

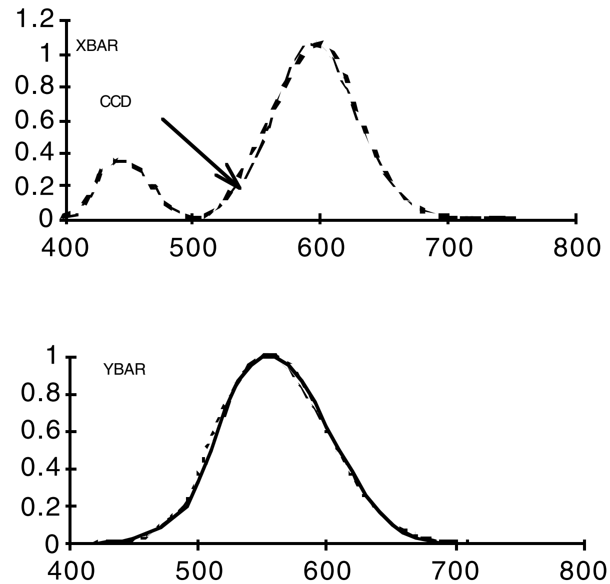

Figure 5. $\bar{x}$ and $\bar{y}$ sensitivities and CIE tristimulus functions

3. LCD R, G, B, filter spectral power distributions

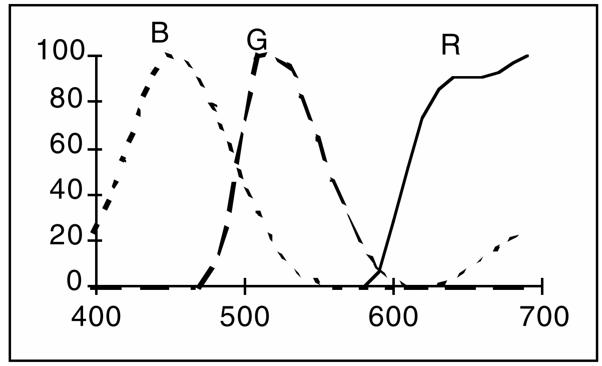

Figure 6 B, G, R spectral power distribution for LCD displays

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