A High-Speed Imaging Colorimeter LumiCol 1900 for Display Measurements

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Abstract

We present a novel high-speed imaging colorimeter especially designed for test applications and requirements typically found in display measurement. It combines the benefits of a red-green-blue (RGB) complementary metal oxide semiconductor sensor (CMOS) camera and a high accuracy spot colorimeter. Using the colorimeter as reference for the camera enables precise characterizations of the whole display area with respect to luminance and chromaticity.

This device has potential for substantial time- and cost-savings, because it measures faster than conventional imaging colorimeter. It combines the functionality of two measurement devices into a single body and may reduce the number of test stations in production lines.

1 Background

As display technologies improve, comprehensive characterizations of all optical display properties like contrast, gamma-curve, flicker, uniformity of luminance and color become increasingly important. This is not only true for R&D in laboratory, but in particular also for quality control, two dimensional inspections and adjustments in production lines. A number of different measurement devices like spectrometers, imaging colorimeters and conventional charge coupled device image sensor (CCD) cameras are used in order to realize the versatile measurements and test applications. Slowing down the tact times should be avoided because it leads to cost increase in production lines.

Fig. 1 shows an example of uniformity measurement of an organic light-emitting diode (OLED) display in accordance with the Information Display Measurements Standard (IDMS)[1]. The display shown in Fig. 1 has 9 windows located on black background. Spectra were measured with the Konica Minolta CS-2000 spectroradiometer. Fig. 2 shows the spectra of the three windows (T/R, M/C and B/L). In Fig. 1, from B/L to T/R, it is observed that the colors of the areas gradually shift toward blue. Also as shown in Fig. 2, the *Le* values in 530 nm and 620 nm are decreasing respectively. From these figures, we can clearly observe a non-uniformity. Therefore, correcting the non-uniformity of displays is an important application in production lines. By using LumiCol 1900, non-uniformity can be measured by a single measurement, and the tact time of non-uniformity adjustment can be significantly reduced.

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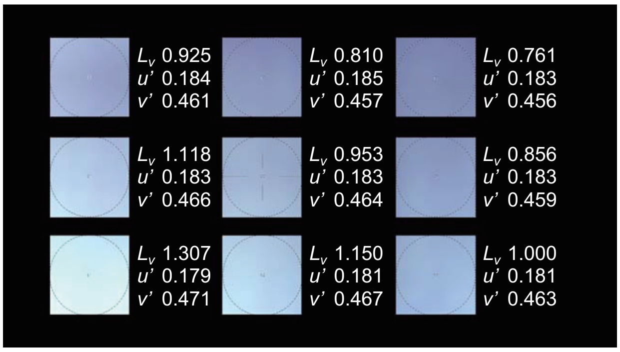

Fig. 1 Example of uniformity inspection. View of OLED displays. Each display image is at RGB output signal level [19/19/19]. Where Lv denotes luminance value, and *u'* and *v'* denote color coordinates.

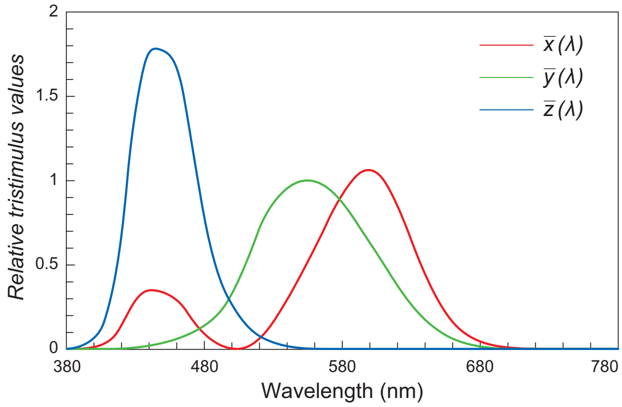

Fig. 3 CIE1931 XYZ color matching functions.

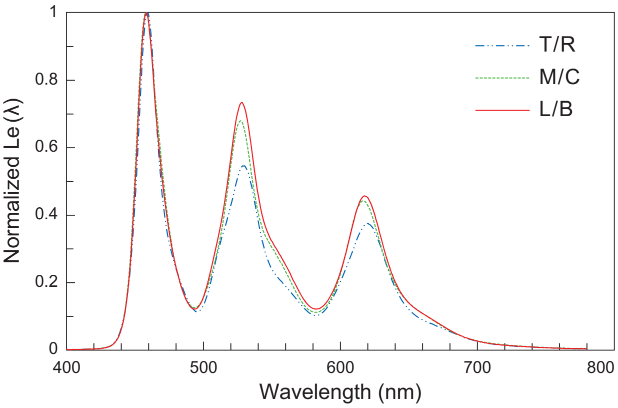

Fig. 2 Spectra of an OLED display at RGB output signal level [19/19/19] at different display positions. B/L marks the bottom left of the nine windows in Fig. 1. M/C refers to the middle center and T/R to the top right measurement spot, respectively. *Le* denotes light emission quantity.

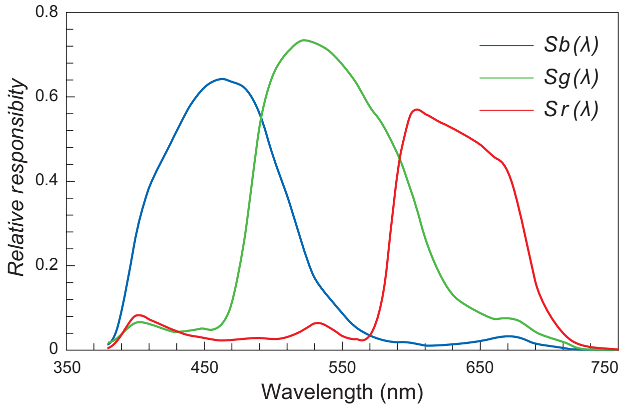

Fig. 4 RGB camera spectral responsivity.

2 Prior Technology

Conventional imaging colorimeters using a tristimulus filter wheel combine several sequential exposures. Exposures with all filters, which are typically four to six, cause a significant delay due to the mechanical movement of the wheel. The other method is to use an RGB camera. RGB cameras using a Bayer pattern can measure all color values at once. However, there are large differences in spectral transmittance between RGB filters and tristimulus XYZ filters. Fig. 3 shows the CIE1931 color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ which are equivalent to human eye's sensitivity. Fig. 4 shows the RGB spectral responsivities of the camera. To compensate the difference, RGB values obtained from the camera are calibrated to match the tristimulus values from a reference spectrometer, by using a display with typical spectrum as a calibration source and measuring different colors on the display screen. When a display with the different spectrum is measured, however, the difference of the spectrum of displays results in a measurement error.

3 Measuring Principle

We solved these problems by a real-time correction method. The real-time correction is to convert RGB values into tristimulus values by using simultaneous measurement of a built-in colorimeter.

LumiCol 1900 combines a fast and precise XYZ sensor with an RGB CMOS camera. We embed a modified spot-colorimeter[2)] as the reference XYZ sensor. The built-in XYZ sensor acquires X, Y and Z values while the camera using a Bayer pattern measures the RGB values, simultaneously. Thus, typical production requirements, such as high speed, high accuracy, low maintenance effort, and cost efficiency can be fulfilled. The special design and calibration procedure of LumiCol 1900 thereby transfers high accuracy measurement values of the spot colorimeter to the 2D image of the camera. Thanks to the combination of a camera and a spot colorimeter, many different measurement tasks typically found in a production environment can be covered with the single device. At the same time, the measurement speed of LumiCol 1900 is extremely high.

In contrast, a conventional filter-wheel imaging colorimeter such as Instrument Systems LumiCam

1300[3] requires several sequential exposures, one for every color filter, causes a significant delay causedue to by the change of the filters. Table 1 compares measurement speeds of LumiCol 1900[4] and LumiCam 1300.

Table 1 Performance of measurement speed.

Luminance	LumiCol 1900 Spot XYZ + RGB camera	LumiCam 1300 XYZ Filter Wheel + B/W Camera
100 cd/m^2	0.5 sec.	6 sec.
1 cd/m^2	1.5 sec.	not described

Fig. 5 shows a schematic of LumiCol 1900. A beam splitter allows for simultaneous measurements of camera and colorimeter. Fig. 5 (b) shows a camera's field of view by the blue rectangle area and the measurement area of the colorimeter by the green circular area. The colorimeter serves as reference for real-time correction during each measurement.

The acquisition of the XYZ values by LumiCol 1900 consists of two steps: transformation from RGB to XYZ and real-time correction. In the first step, RGB data acquired by the camera is transformed into tristimulus value (X', Y', Z') by the following equation:

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} & m_{02} \\ m_{10} & m_{11} & m_{12} \\ m_{20} & m_{21} & m_{22} \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

where m_{00}, m_{01}, $\cdots$, m_{22} are coefficients of the transformation matrix. The transformation matrix is calculated during the calibration at the factory, using a spectrometer and a typical display as a calibration source with different colors on the display screen. When color number i is displayed, CIE tristimulus values XYZ measured by the spectrometer are given by the following equations:

$$X_i = \int \bar{x}(\lambda)\, Le_i(\lambda)\, d\lambda$$
$$Y_i = \int \bar{y}(\lambda)\, Le_i(\lambda)\, d\lambda \quad (2)$$
$$Z_i = \int \bar{z}(\lambda)\, Le_i(\lambda)\, d\lambda$$

where X_i, Y_i, Z_i are tristimulus values of color number i. These values are precisely measured with the spectrometer. On the other hand, the *RGB* values of the camera are given by the following equations:

$$R_i = \int Sr(\lambda)\, Le_i(\lambda)\, d\lambda$$
$$G_i = \int Sg(\lambda)\, Le_i(\lambda)\, d\lambda \quad (3)$$
$$B_i = \int Sb(\lambda)\, Le_i(\lambda)\, d\lambda$$

Given a set of (X_i, Y_i, Z_i) and (R_i, G_i, B_i), the transformation matrix is found in a way that a deviation between (X_i, Y_i, Z_i) and (X'_i, Y'_i, Z'_i) is minimized in the XYZ color space.

As mentioned, a certain amount of error may still remain because the spectrum of customer's device-under-test (DUT) is likely to be different from the spectrum of the display used for the factory calibration. In the real-time correction, the XYZ sensor is used to correct the tristimulus values after application of the transformation matrix, i.e. in the CIE 1931 color space. This is performed by comparing the measurement results of the XYZ sensor and the approximated tristimulus values over the camera pixels within the area of the colorimeter spot (the green area in Fig. 5 (b)). The three independent parameters (scaling factors) of the diagonal 3×3 matrix can thus simply be found by dividing each of the second tristimulus values by the values from the XYZ sensor. Finally, this correction is applied to all pixels in the entire camera's field, as explained above, so as to obtain the corrected tristimulus values.

$$\begin{bmatrix} X'' \\ Y'' \\ Z'' \end{bmatrix} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{bmatrix} \cdot \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \quad (4)$$

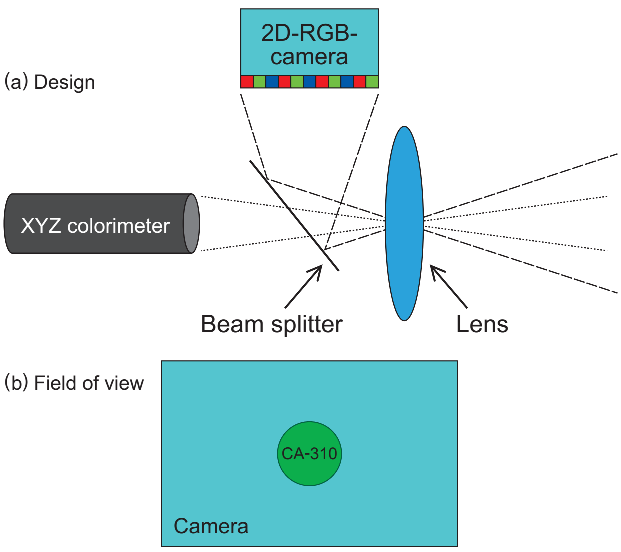

Fig. 5 Design and field of view of LumiCol 1900.

As a result, a high accuracy of the colorimeter measurement is achieved over camera's entire field of view. This real-time correction for the camera measurements works best with displays showing uniform color pattern, and can be used with any uniform DUT in principle.

4 Measurement Performance

The measurement performance resulting from the above-described principle can be demonstrated by the accuracy of the colorimeter with respect to a reference instrument and by means of the response non-uniformity (*RNU*). Moreover, the high measurement speed and time-saving potential are briefly highlighted.

Accuracy of luminance measurements

Fig. 6 shows the accuracy of LumiCol 1900 colorimeter measurements with respect to luminance L_v and the color coordinates *u*' and *v*', respectively, determined for four different devices (with 100 measurements on average). The measurements were performed on a display showing white images with two different luminance levels, 1 and 100 cd/m^2. The measurements of the built-in XYZ sensor were compared to the measurement of a high-end spectroradiometer. In addition, the results of measurements using an optional low-luminance mode (LLM) are shown. In the LLM, averaged dc-calibrations are performed prior to each measurement.

The sum of the mean value and the threefold standard deviation ($ave + 3\sigma$) of the luminance measurement (Fig. 6 (a)) of the colorimeter with respect to a spectroradiometer are 0.90% and 0.77% for L_v=100 cd/m^2 (circles) and L_v=1 cd/m^2 (triangles), respectively.

For the color coordinates *u*' (Fig. 6 (b)) and *v*' (Fig. 6 (c)), the deviations are given as absolute values. At a luminance level of L_v = 100 cd/m^2 (circles), the comparison between built-in colorimeter and spectroradiometer reveals mean deviations of 0.0004 for *u*' and 0.0018 for *v*'. For L_v = 1 cd/m^2 (triangles), the mean deviations are 0.0022 for *u*' and 0.0054 for *v*'. The low luminance mode, represented by diamonds, reduces the deviations for measurements at L_v = 1 cd/m^2 to 0.0007 for *u*' and 0.0022 for *v*'.

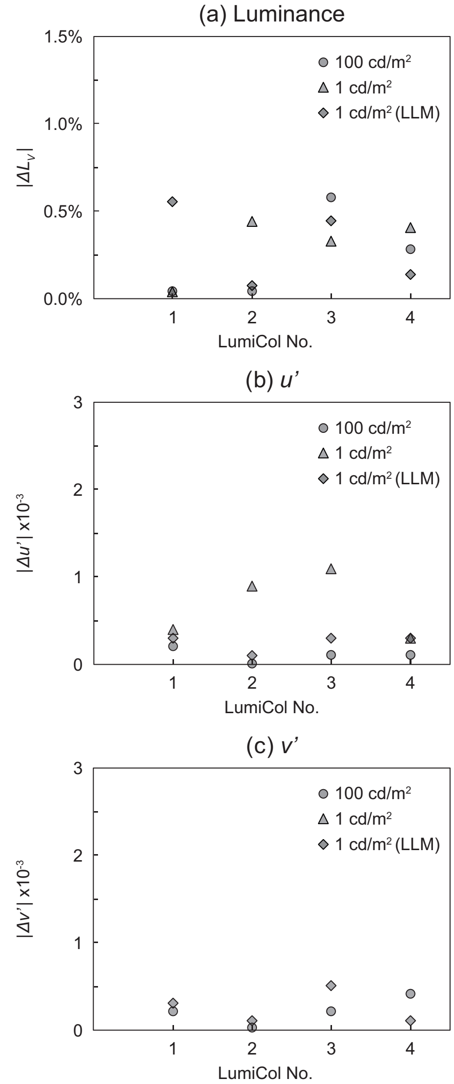

Fig. 6 Measurement accuracy of LumiCol 1900 (for white).
The deviations from spectroradiometer measurements with respect to luminance and chromaticity were determined on a display showing white images of different luminance levels (circles: 100 cd/m^2; triangles: 1 cd/m^2). In addition, the deviations for measurements in the LLM are shown (diamonds: 1 cd/m^2).

Accuracy of color measurements

Fig. 7 shows the accuracy, again using a high-end spectroradiometer as reference instrument, for measurements on a DUT showing colored images (red [255/0/0], green [0/255/0], and blue [0/0/255] represented by colored circles, squares and triangles). Three graphs show the deviations of luminance L_v and color coordinates *u*' and *v*' (c), respectively. For luminance, the $ave + 3\sigma$ values are below 0.6 % for red and green (circles and squares) and below 0.9 % for blue (triangles). For the color coordinate *u*', the $ave + 3\sigma$ values are 0.0003, 0.0004, and 0.0008 for the colors red, green and blue, respectively (same symbols as in Fig. 7 (a)). In Fig. 7 (c), the accuracy for the color coordinate *v*' is shown. Here, the $ave + 3\sigma$ values are 0.0009, 0.0008, and 0.0012 for red, green, and blue, respectively.

In sum, it was shown that the accuracy of the novel measurement device for luminance and color measurements on a display of arbitrary uniform content is within the range of state-of-the-art imaging colorimeters based on the filter wheel technology.

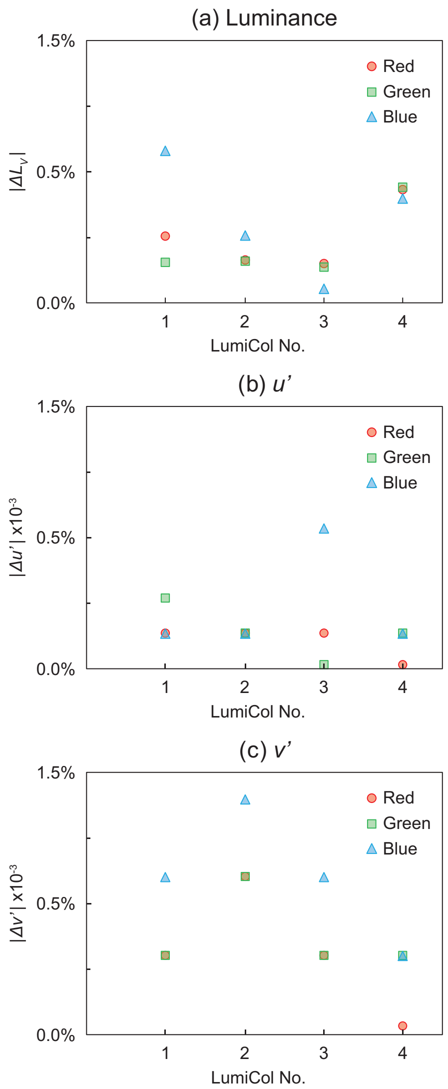

Fig. 7 Measurement accuracy of LumiCol 1900 (for color).
The deviations from spectroradiometer measurements with respect to luminance and chromaticity were determined on a display showing colored images (red, green, and blue represented by circles, squares and triangles respectively).

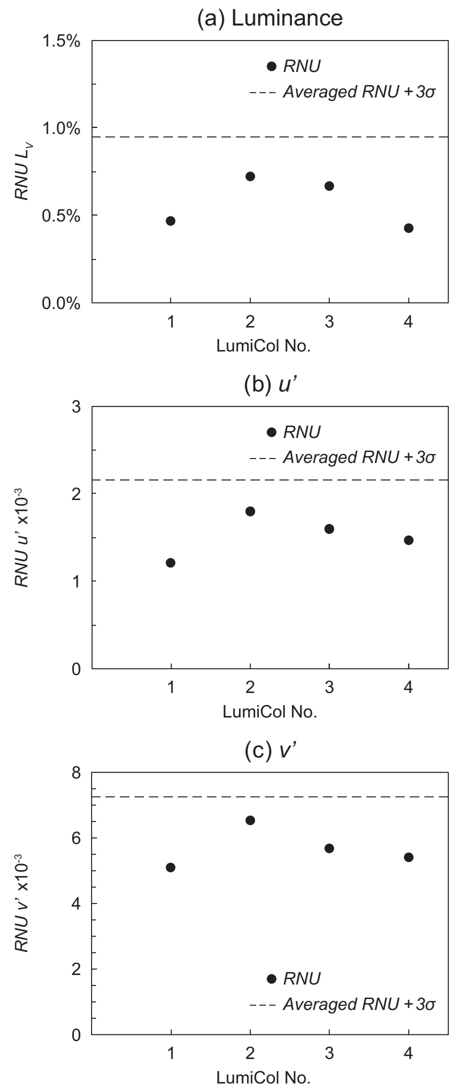

Fig. 8 Response non-uniformity of four different LumiCol 1900 devices determined from measurements on a uniform light source with a luminance level of 100 cd/m^2 (represented by symbols).
The *RNU*s were determined for the quantities luminance (a) and color coordinates *u'* and *v'*. The dashed lines mark the *ave* + *3σ* values.

Response non-uniformity (RNU)

The response non-uniformity is a measure for the accuracy of the pixel-wise two-dimensional measurement. The results of the evaluation below show how a conventional RGB CMOS camera can be utilized for high-accuracy color measurements in the CIE 1931 XYZ color space. This is achieved by the specific calibration procedure applied to, i.e. flat field correction, color calibration, and color fine-correction to the reference sensor.

The response non-uniformity in Fig. 8 was determined from measurements of four different LumiCol 1900 devices on a uniform light source (L_v = 100 cd/m^2). For the evaluation of the *RNU*, an 8×8 binning was applied to the XYZ images, resulting in a resolution of 240x150 pixels. After binning, the XYZ-image was transformed into (L_v, *u*', *v*'). For each channel (L_v, *u*', *v*'), the mean value was calculated. For chromaticity (*u*', *v*'), the response non-uniformity is defined as the largest deviation from the mean value within the binned image. For luminance L_v, the *RNU* is defined as the largest deviation from the mean value divided by the mean value of the binned image.

Figs. 8 (a)-(c) show the results. For luminance measurements, the *RNUs*, determined for four different devices, are all below 0.8 % (symbols in Fig. 8 (a)). Adding the standard deviation *3σ* to the mean value sums up to around 0.95 % (dashed line). Figs.8 (b) and (c) show the corresponding values for the color coordinates *u*' and *v*'. The maximum value of Δ*u*' and Δ*v*' is 0.0065. The *ave* + *3σ* values are 0.0022 for *u*' and 0.0073 for *v*'.

5 Conclusion

This report presents a novel approach to imaging colorimetry focusing on the typical needs and requirements of testing and adjusting in display production environments. The basic principle for LumiCol 1900 is the usage of a spot colorimeter as reference for 2D measurement. On the one hand, the built-in XYZ sensor enables to determine a transformation matrix during the calibration procedure, converting the RGB values of the camera pixels into the CIE 1931 XYZ tristimulus values; the colorimeter is used for a real-time correction during each measurement to improve the accuracy of the camera measurement.

The resulting accuracy of the LumiCol 1900 for luminance and color measurements on displays is within the accuracy range of state-of-the-art imaging colorimeters based on the filter-wheel technology. It was shown that this is also true for uniformity of the RGB CMOS camera by RNU. Moreover, LumiCol 1900 measures significantly faster because all color values are captured with a single exposure. The chromaticity response of non-uniformity by the pixel-wise two-dimensional measurement is below 0.0065. The imaging colorimeter measures ten times faster than the conventional filter-wheel imaging colorimeter.

LumiCol1900 has been developed in a short period of time by a complementary combination of Instrument Systems' imaging colorimeter technology and Konica Minolta's XYZ sensor technology.

6 References

1) Information Display Measurements Standard V1.03aa. chapter 8.1.2 Sampled Vantage Point Uniformity
2) Konica Minolta Holdings, Inc. CA-310 catalogue http://www.konicaminolta.com/instruments/download/catalog/display/pdf/ca310_catalog_eng.pdf
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