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Effect of choosing a different number of linearization samples on display characterization

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Abstract

The most common and popular display used with desktop personal computers and workstations is the flat-panel LCD, primarily because of low-power consumption. These devices present challenges in terms of color fidelity because of channel interaction and non-constancy of channel chromaticities. Therefore, the development of models to establish accurate color characterization is still a research problem. The main purpose of color characterization of a device is to define the transformation between RGB (the device color space) and CIEXYZ or CIELAB (reference color space) [1]. There are three different common characterization models which have been widely used in the literature for device characterization: GOG, PLCC and PLVC. All three models require the use of measured samples to characterise the non-linear response of the display. The objective of this research was to determine the effect of varying the number of linearization samples on the characterization performances for a set of 20 displays. For small numbers of linearization samples the GOG model frequently gave the best performance. However, performance using PLVC and PLCC improved markedly as the number of linearization samples increased. Improvement gains when using more than about 18 linearization samples were modest. For 18 or more linearization samples the best performance was usually obtained using PLVC although for some displays PLCC gave better performance.

Introduction

Flat-panel (LCD and LED) displays become popular as the devices based on these technologies are light, small, have lower power consumption as well as offering a greater luminance, great sharpness, higher contrast ratio and better spatial uniformity than the old CRT display technologies. It is essential to have an accurate color rendering and understand the relationship between digital input values and output colors. In order to control the colorimetric characterization of a color display precisely, different methods have been used for characterization. The GOG model which has been a popular choice used for the old CRT displays technology is also used for characterization of LCD/LED displays which effectively exhibit a gamma-like response because of manufacturers desire for them to behave more like a CRT display. The PLCC and PLVC models which are based on interpolation are also used for the display characterization in this study. The GOG and PLCC methods are two-stage methods where linearization is followed by a linear (matrix) transform. The work in this paper is part of a wider project to explore characterization methods for modern display technology and to assess the effect of using different numbers of linearization samples with different characterization models such as GOG, PLCC and PLVC.

Review of conventional display characterization models

There are two steps in the characterization process based on the physical model [2, 3], linearization and transformation of the linearized values into the $CIEXYZ$ tristimulus values.The GOG and PLCC methods are two-stage methods where linearization is followed by a linear (matrix) transform (Equation 1), in contrast, the PLVC does not use the matrix transformation.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

where RGB are the linearised and normalised (in the range 0 to 1) values.

GOG model:

The relationship between luminance L and normalised value $d/(2^N-1)$ is generalised to yield:

$$L = (ad/(2^N-1)+b)^\gamma \tag{2}$$

where the a and b are the coefficients as the system gain and offset respectively. This generalised relationship is known as the gain-offset-gamma or GOG model [4].

PLCC model:

The Interpolation method (PLCC) is based on a functional approximation by applying a linear interpolation between measurements [5], followed by a colorimetric transformation between the chromaticity matrix and the luminance responses of primaries. In this study, simple linear interpolation is used. Imagine a series of N values of R and N corresponding values of R'. The interpolated linear value y for any non-linear value x is given by the Equation 3.

$$y = R_i' + \frac{x-R_i}{R_j-R_i}(R_j'-R_i') \tag{3}$$

where $R_i < x < R_j$. Clearly, some additional consideration needs to be taken if $x = R_1$ or $x = R_N$ and either $x < R_1$ or $x > R_N$. In addition the value of y is constrained to be $0 <= y <= 1$.

PLVC model:

The Piecewise Linear model assuming Variation in Chromaticity (PLVC) uses Equation 4 to obtain the XYZ values;

$$X(d_r(i), d_g(j), d_b(l))$$
$$= [X(d_r(i)) - X_k] + [X(d_g(j)) - X_k] + [X(d_b(l)) - X_k] + X_k$$

$$Y(d_r(i), d_g(j), d_b(l))$$
$$= [Y(d_r(i)) - Y_k] + [Y(d_g(j)) - Y_k] + [Y(d_b(l)) - Y_k] + Y_k$$

$$Z(d_r(i), d_g(j), d_b(l))$$
$$= [Z(d_r(i)) - Z_k] + [Z(d_g(j)) - Z_k] + [Z(d_b(l)) - Z_k] + Z_k$$

The X_k, Y_k and Z_k are obtained by accurate measurement of the black level for each device. The $X(d_r(i))$, $X(d_g(j))$, $X(d_b(l))$, $Y(d_r(i))$, $Y(d_g(j))$, $Y(d_b(l))$ and $Z(d_r(i))$, $Z(d_g(j))$, $Z(d_b(l))$ are all obtained by one dimensional linear interpolation with the measurement of a color ramp along each primary. The GOG and PLCC methods are two-stage methods where linearization is followed by a linear (matrix) transform. The difference between GOG and PLCC is simply in how the linearization is performed. The GOG model fits the tone reproduction curve with a parametric model; the PLCC uses interpolation between known points to 'fit' the data (PLVC also uses interpolation but does not separate the linearization stage from the color transform stage in the way that PLCC does). In this study, the starting point was to convert nonlinear *RGB* to linear *RGB* since the aim is to convert from *RGB* to XYZ. In contrast, if users wanted to go from XYZ to *RGB* (which is probably more common in practice) then this would be done by mathematical inversion for the GOG model whereas for the PLCC model a separate interpolation would be required.

Experimental

A tele-spectroradiometer (TSR) Minolta CS-2000 (Measuring angle: 1°, Accuracy: Luminance: ±2%, x: ±0.0015, y:±0.001, Repeatability: Luminance: ±0.15%, xy: ±0.002 for standard light source A) was used to measure stimuli displayed on the display in a dark room. The display and the tele-spectroradiometer were warmed up for at least one hour before any measurements taken place. The stimuli were displayed on the full screen of the display and there were a total of 789 (3x255 color linearization samples and 24 samples of the Macbeth ColorChecker). The 2° CIE observer was used to measure $CIEXYZ$ values for various stimuli defined by Macbeth ColorChecker chart sample set and the 256 step of the color-ramps for each channel (768 in total). The color-ramps were used to characterise the tone reproduction curve using either the GOG, PLCC and PLVC model. The main characteristic of this data set is that the samples are very chromatic. 20 different LCDs were used and are simply named A, B, C, ..., S and T. Table 1 shows some specification of these displays.

It is possible to obtain these corresponding sets of linear and non-linear values in two ways; either using the grey-ramp values or using the color-ramps. In this paper, the color-ramps linearization data set have been chosen to describe. The 256 color-ramp values were subsampled to generate 7 sets of training data with 256, 129, 66, 34, 18, 10 and 6 samples. In all cases, the extreme values were always present (0 to 255) and the other values were uniformly spaced between them. For each display, the Yxy values were measured for the color channels at each of the 256 steps

Table 1: Age, Luminance of black level (cd/m^2), chromaticity of white point and gamut size specification of each display.

Display	Age	Luminance of black level cd/m^2	White point		Gamut size
			x	y	
A	2015	0.28	0.31	0.29	0.1210
B	2016	0.35	0.31	0.32	0.1199
C	2006	0.18	0.32	0.35	0.1173
D	2015	0.23	0.32	0.34	0.1169
E	2007	0.23	0.34	0.36	0.1162
F	2015	0.23	0.33	0.35	0.1159
G	2013	0.32	0.32	0.32	0.1146
H	2012	0.15	0.32	0.33	0.1146
I	2014	0.16	0.34	0.35	0.1140
J	2012	0.21	0.30	0.30	0.1140
K	2014	0.22	0.30	0.33	0.1137
L	2013	0.32	0.32	0.33	0.1134
M	2011	0.34	0.32	0.33	0.1129
N	2010	0.33	0.32	0.33	0.1128
O	2012	0.19	0.31	0.33	0.1118
P	2008	0.30	0.33	0.34	0.1106
Q	2009	4.57	0.34	0.36	0.1080
R	2012	6.20	0.34	0.36	0.1035
S	2011	0.28	0.34	0.35	0.1002
T	2013	0.37	0.31	0.33	0.0950

(in order to implement the models) and also for the Macbeth set of samples. Performance for all 20 displays were evaluated using median ΔE^*_{00} primarily on the Macbeth set of samples and is presented in this section for seven different sub-sampling regimes (N = 6, 10, 18, 34, 66, 129 and 256), this allows a comparison between the GOG, PLCC and the PLVC model.

Fig. 1 shows the approach was used to evaluate performance. In this approach, the samples used for the characterization process and the test samples were all displayed and measured once for each display devices individually. This means that the test samples were defined in terms of *RGB* values. The XYZ values of the displayed samples were measured and are considered to be the ground truth. The characterization process was then used to convert display *RGB* values to $CIEXYZ$ values and the color difference between the predicted XYZ values and the ground-truth measured XYZ values was used as a measure of performance. characterization performance was therefore evaluated in terms of ΔE^*_{00} values between measured and predicted XYZ values. Fig. 1 illustrates the comparison between the predicted XYZ and the measured XYZ. For characterization in typical ambient or office situations, it may be more important to include a black correction. As it noted from previous studies, black-subtraction, in general, is necessary and causes the chromaticity to be constant [6, 7, 8].

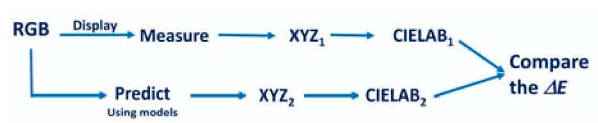

Figure 1: The RGB conversion procedure and comparisation between the predicted XYZ and measured XYZ.

Results and Disscution

Table 2 and 3 shows the median ΔE^*_{00} for the Macbeth set of samples (averaged over all Macbeth samples) for $N = 256$ and $N = 6$ (the number of linearization samples) respectively from which it is evident that the performance of the GOG model is a little better for values of $N = 6$ in most of the displays.

Fig. 3 illustrates the effect of using a different number of linearization samples with Macbeth sample sets using the GOG, PLCC and PLVC model. There is little difference in performance when using 256 (ΔE^*_{00}=1.69) or 6 (ΔE^*_{00}=1.63) linearization samples for the GOG model. However, GOG performs better using 6 linearization samples. Display *A*, *B*, *G*, *I*, *J*, *K*, *L*, *N* and *O* give a better performance using GOG model with 6 linearization samples. The PLCC model is always the best choice for display *P*, *Q* and *R*, no matter how many linearization samples are used. Display *C*, *D*, *E*, *F* and *S* give a better performance using PLVC model irrespective of the number of linearization samples. In summary, there is a trade-off point of about 18 samples when using the PLVC and PLCC models after which little further improvement is found.

Table 2: The median color differences (ΔE^*_{00}) for $N = 256$ linearization samples using different models.

N=256			
Display	GOG	PLCC	PLVC
A	0.72	0.51	0.46
B	0.64	0.64	0.76
C	3.15	1.49	0.69
D	2.63	1.45	0.45
E	2.91	1.90	1.11
F	2.88	1.85	0.79
G	1.06	1.06	0.95
H	1.57	1.21	1.09
I	1.09	0.80	0.55
J	1.50	1.36	0.89
K	0.69	0.58	1.20
L	0.62	0.62	0.90
M	1.22	0.75	0.71
N	1.01	0.65	0.76
O	1.17	0.25	0.47
P	2.13	0.40	0.49
Q	0.83	0.67	1.73
R	1.75	1.13	2.46
S	3.76	2.63	2.40
T	2.57	2.39	2.31

Table 3: The median color differences (ΔE^*_{00}) for $N = 6$ linearization samples using different models.

N=6			
Display	GOG	PLCC	PLVC
A	0.70	1.20	1.06
B	0.59	0.59	1.19
C	1.70	1.80	1.67
D	2.61	1.98	1.34
E	2.76	2.40	1.71
F	2.72	2.30	1.63
G	1.08	1.62	1.88
H	1.56	1.27	1.40
I	1.08	1.53	1.38
J	1.38	2.00	1.55
K	0.71	1.09	1.76
L	0.70	1.17	1.40
M	1.12	1.11	1.28
N	0.89	1.36	1.93
O	0.88	1.26	1.55
P	1.92	1.04	1.32
Q	0.82	0.75	2.21
R	1.71	1.32	2.84
S	5.01	2.41	2.27
T	2.60	2.33	2.24

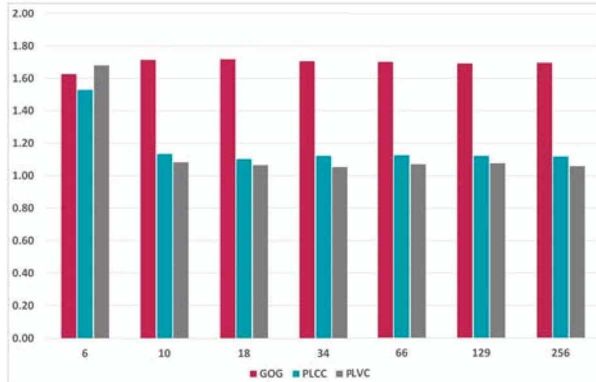

Figure 2: The median ΔE^*_{00} using different models, averaged over 20 displays, as a function of *N* (the number of linearization samples.

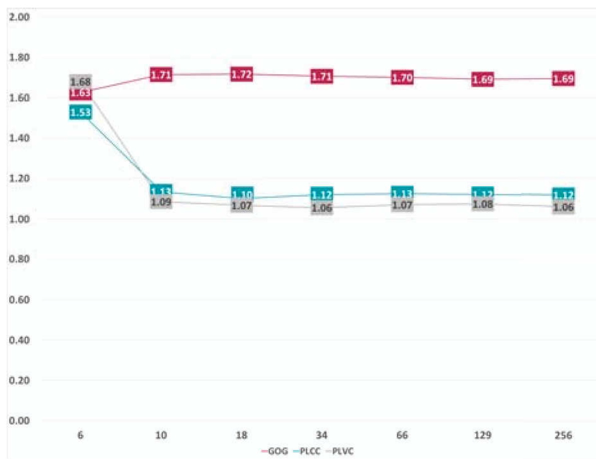

Figure 3: The median ΔE^*_{00} averaged over 20 displays as a function of *N* (the number of linearization samples.

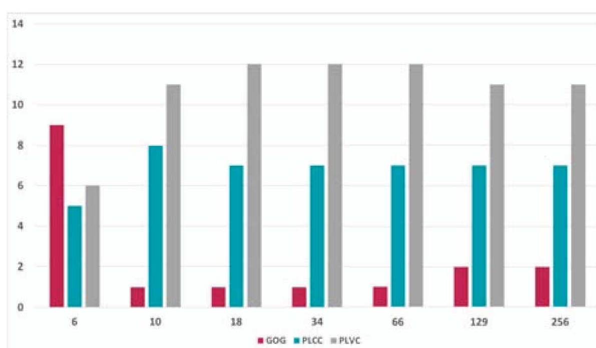

Figure 4: Performance of each model prior to choosing the different number of linearization samples in all 20 display devices.

Table. 4 shows the best performance of models in terms of the ΔE^*_{00} with choosing the different number of linearization samples in each display. It is evident that in 9 different displays, the GOG has got a better performance with having less than 10 linearization samples among the 20 LCD displays. Fig. 4 also illustrates that the PLVC is superior to the PLCC and GOG in

Table 4: Effect of choosing the different number of linearization samples on performance of each model in all 20 display devices.

	6	10	18	34	66	129	256
A	GOG	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
B	GOG	PLVC	GOG	GOG	GOG	GOG	GOG
C	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
D	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
E	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
F	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
G	GOG	PLCC	PLVC	PLVC	PLVC	PLVC	PLVC
H	PLCC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
I	GOG	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
J	GOG	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
K	GOG	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
L	GOG	GOG	PLCC	PLCC	PLCC	GOG	GOG
M	PLCC	PLCC	PLCC	PLCC	PLVC	PLVC	PLVC
N	GOG	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
O	GOG	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
P	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
Q	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
R	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC	PLCC
S	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC	PLVC
T	PLVC	PLVC	PLVC	PLVC	PLCC	PLCC	PLCC

more than 11 displays when more than 10 linearization samples are present.

In summary, when all 20 displays are considered the PLVC gives the best performance and the GOG model gives the worst performance with PLCC in between the two. Whereas GOG is relatively unaffected by the number of linearization samples, this is not the case for the other two models. For PLVC and PLCC, the error decreases with increasing number of characterization samples but there is a trade-off; for beyond $N = 18$, increasing N results in only a small increase in performance. Some more complex characterization models are available in the literature but this study considered only GOG, PLCC and PLVC because these models are easily available and widely used.

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