Color Characterization of an LC Projection System Using Multiple-regression Matrix and Look-Up-Table with Interpolation

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Abstract :

A forward model of an LC projector is studied to predict its colorimetric attribution. To identify color characteristics of the projector, 729 colors were measured in a dark room. The forward model was built using three methods: (1) a 3×11 multiple-polynomial regression matrix, (2) a 3-dimensional(3-D) look-up table(LUT) with cubic interpolation, and (3) a one dimensional(1-D) LUT with linear interpolation. In addition, 216 colors were also measured to evaluate the prediction accuracy of the forward model. All methods can be used to obtain acceptable predictions of colorimetric attributions on the LC projector. When the 3×11 multiple-polynomial regression matrix was used, the average and maximum prediction differences were 2.18 and 6.68 ΔE^*_{uv}, respectively. For the 3-D LUT method, those values were 3.3 and 16.4 ΔE^*_{uv}, respectively. The results of the 1-D LUT are comparable with those of the 3-D LUT if the sampling points per channel of these two approaches are the same. If the sampling points per channel are dense enough, for example 16 points per channel, the performance of the 1-D LUT is better than that of the 3×11 multiple-polynomial regression matrix .

Keywords : color characterization, LC projector, forward model, look-up-table, cubic interpolation, multiple-polynomial regression matrix

1. INTRODUCTION

Reproducing colors correctly is very important for a color output device. Therefore, color characterizations of color output devices are necessary in order for digital signal controls to reproduce desired colors. Liquid crystal (LC) projectors have been developed by many companies to present not only video programs but also computerized information. For the above two reasons, color

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characterizations of LC projectors have become very important. In this article, a multiple-polynomial regression[1,2] method, a 3-D LUT with cubic interpolation method[3,4], and a 1-D LUT with linear interpolation were studied to characterize the color rendering properties of an LC projector.

2. BUILDING OF THE FORWARD MODEL

Building the forward model of the test projector using the multiple-polynomial regression method, 3-D LUT with cubic interpolation and 1-D LUT with linear interpolation are described as follows:

(1) Multiple-polynomial regression matrix

Multiple polynomial regression is a useful method for characterizing a color device. The method is a two-step process which consists of gray-balancing and matrix transformation. The procedure for characterizing a color device using this method is as follows:

1.1 Sample N points on each RGB channel with equal partition. Use these 3×N points to produce N×N×N possible combinations of RGB signals.

1.2 Input these signals to the test LC projector to show their colors in order and measure their tristimulus values XYZ sequentially.

1.3 Convert the RGB DAC values of the test color patches to gray-balanced RGB values. The function of this step is to convert the original RGB signal space to another space which is more similar to the CIE XYZ color space. The luminance values of RGB primary colors of 729 test patches were employed to establish the correlation according to the definition :

$$R' = Yr,\ G' = Yg,\ B' = Yb$$

where Yr, Yg, and Yb are the luminance values of RGB channels, respectively.

1.4 Use the regression technique to obtain the transfer matrix from gray-balanced RGB space to CIE XYZ space. In this project, a 3×11 regression matrix was used and its mathematical formula is expressed as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \textit{multiple - polynomial regression matrix} \end{bmatrix}_{3\times 11} \bullet \begin{bmatrix} 1 \\ R' \\ G' \\ B' \\ R'G' \\ R'B' \\ G'B' \\ R'^2 \\ G'^2 \\ B'^2 \\ R'G'B' \end{bmatrix}_{11\times 1} \qquad (1)$$

(2) 3-D LUT with cubic interpolation

3-D LUT with interpolation can characterize a color device very well no matter how complex or how nonlinear its color production mechanism is. The procedure for using this method is as follows:

2.1 Sample N points on each RGB channel with equal space. Use these 3×N points to produce N×N×N possible combinations of RGB signals.

2.2 Input these signals to the test LC projector to show their colors in order and measure their tristimulus values XYZ sequentially.

2.3 Use the measurement results to build a 3-D LUT which maps the RGB signal space to the XYZ color space.

After the LUT is built, if an RGB signal is inputted into the test LC projector, its corresponding XYZ values can be predicted using the LUT and the cubic interpolation technique.

(3) 1-D LUT with linear interpolation

1-D LUT with interpolation is a useful method for characterizing a color device if the color production mechanism of the color device is very linear. The procedure for using this method is as follows:

3.1 Sample N points on each RGB channel with equal space.

3.2 Input these signals to the test LC projector to show their colors in order and measure their tristimulus values XYZ sequentially.

3.3 Use the measurement results to build three 1-D LUTs which map the DAC signals to the XYZ color space of each channel. So, there are a total of nine 1-D LUTs for the three primary channels of the projector

After the 1-D LUTs are built, if an RGB signal is inputted into the test LC projector, its corresponding XYZ values can be predicted using the LUTs and the linear interpolation technique.

3. COLORIMETRIC EXPERIMENT

The colorimetric experiments were conducted in a dark room to characterize the LC projector and evaluate its forward model. The EPSON 3300 with maximum resolution of 640×480 pixels was chosen as a test LC projector. A total of 729 test colors which are the possible combinations of the following R, G, and B DAC values: 0, 32, 64, 96, 128, 160, 192, 224 and 255 were measured to build the forward model. During the measurements, the test samples were displayed as a 450 pixel × 450 pixel square in the middle of the panel; the rest of the screen was left black.

4. RGB PRIMARY COLORS OF THE LC PROJECTOR

Color rendering of a display depends on its RGB primary colors. Fig.1 shows the RGB primary colors of the test LC projector. The tristimulus values XYZ of each channel become saturated at the higher and lower driving levels. For this reason, the sampling points on the RGB channels should be dense enough to efficiently sample the turnaround point.

The luminance differences between the measurements and the results of the additive law of mixing colors were computed to examine the channel dependence of the projector. Fig.1 also shows the results of neutral colors obtained by the measurements and the additive law of mixing colors. The figure reveals that luminance differences between measurements and the additive law of the neutral colors are very small. In fact, the average luminance difference of the 729 colors is less than 3 % showing that the channel dependence of the test projector is small.

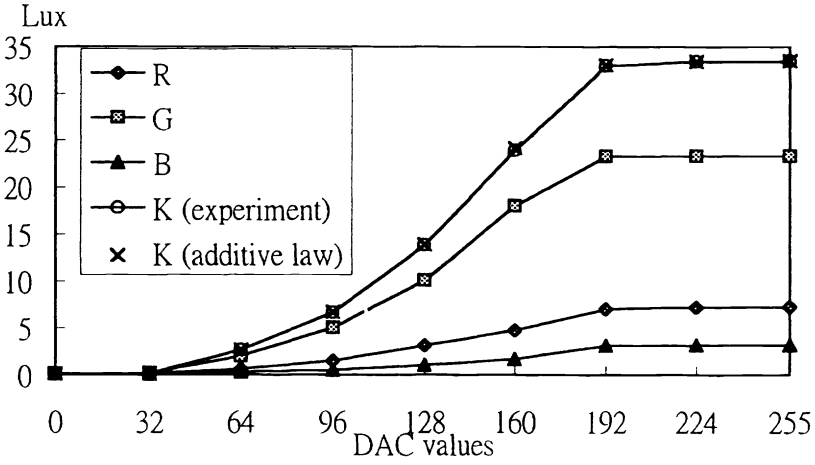

Fig.1 Tristimulus values XYZ of RGB channels. Test device : EPSON

5. EVALUATION OF THE FORWARD MODEL

After building the forward model of the LC projector, RGB DAC values of an additional 216 colors were then input to the test projector to be measured. And XYZ values of these DAC values were also predicted by the forward models. The differences between the measurement and prediction results can be used to evaluate the accuracy of the forward models. For an accurate forward model, XYZ values predicted by the forward models will be the same as the measurement results. The DAC values of the 216 colors are the possible combinations of the following R, G, and B DAC values: 0, 51, 102, 153, 204, and 255.

Average and maximum color difference (ΔE^*_{uv}) among prediction and measurement values are the parameters for evaluating the accuracy of the color characterization model. The performance of the multiple-polynomial regression method and the 3-D with cubic interpolation are discussed first. Fig.2(a) shows the average ΔE^*_{uv}, maximum ΔE^*_{uv}, and the standard deviations(STD) of the 216 test colors for the test projector. For the multiple-polynomial regression method, average ΔE^*_{uv}, maximum ΔE^*_{uv}, and STD are 2.18, 6.68, and 1.19 ΔE^*_{uv}, respectively. ΔE^*_{uv} distribution shown in Fig.2(b) is the other parameter to evaluate the accuracy of the model. The more colors with prediction differences of less than 1 or 2ΔE*, the better the model works. The percentages of samples whose colorimetric attribution prediction differences are less than 1 and 2 ΔE^*_{uv} as determined by the multiple-polynomial regression method are about 13.4% and 52.3%, respectively. Colorimetric attribution of 97.2% test samples can be predicted within 5 ΔE*. As shown in Figs.2(a) and 2(b), these values are significantly better than those obtained using the 3-D LUT with cubic interpolation method. The average ΔE^*_{uv}, maximum ΔE^*_{uv}, and STD are 3.3, 16.4, and 2.53 ΔE^*_{uv}, respectively. There are only 40.3% of the color samples for which colorimetric attribution can be predicted within accuracy of 2 ΔE^*_{uv} using the 3-D LUT approach.

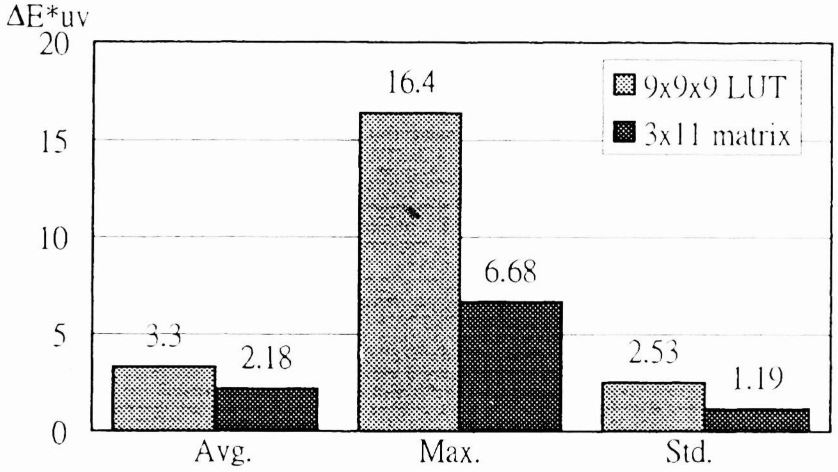

Fig.2(a) Average ΔE*, maximum ΔE*, and standard deviation of the 216 colors predicted using the multiple-polynomial regression and 3-D LUT methods.

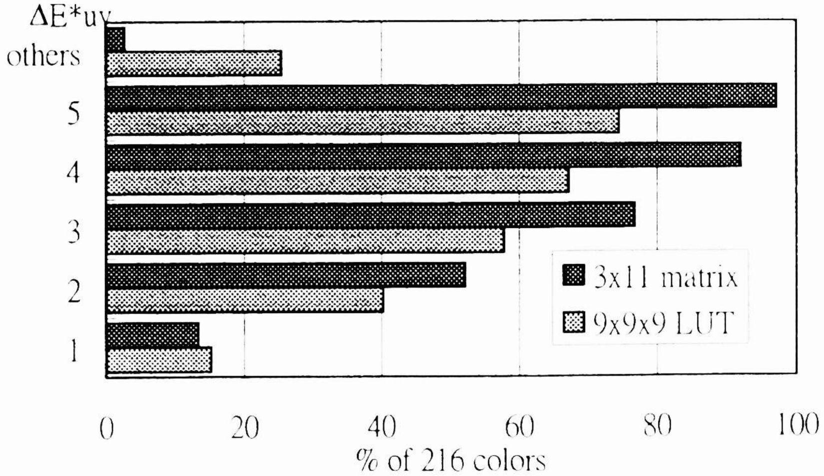

Fig.2(b) ΔE* distribution of the 216 colors predicted using the multiple-polynomial regression and 3-D LUT methods.

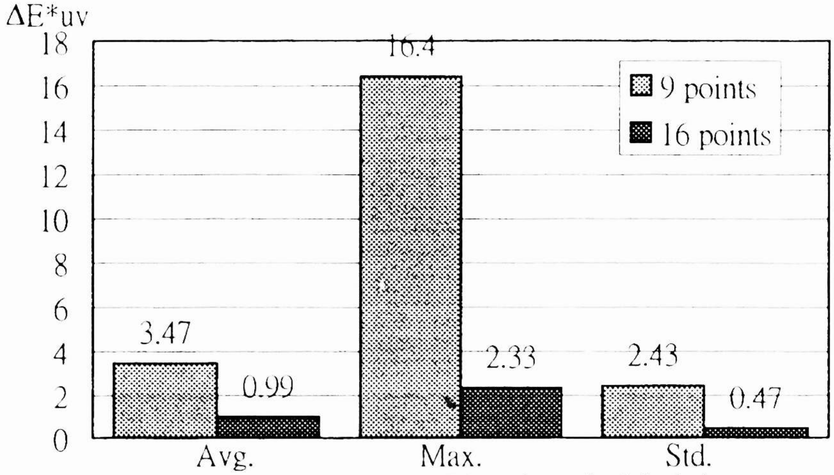

Fig.3(a) Average ΔE*, maximum ΔE*, and standard deviation of 1-D forward model v.s. the number of sampling points.

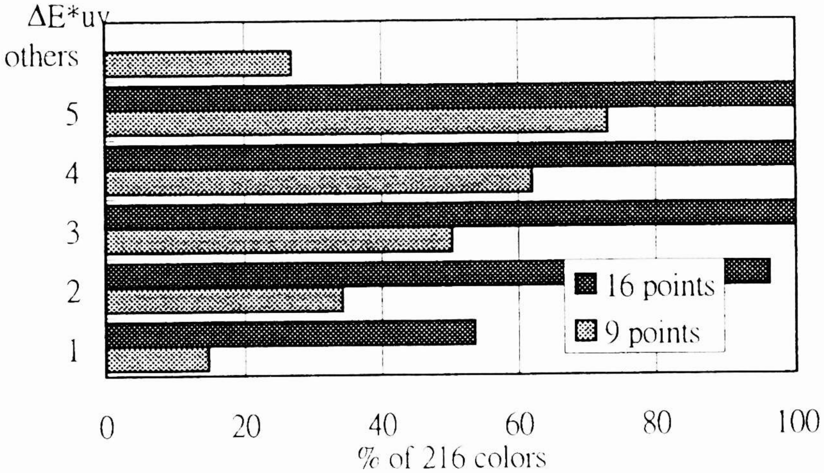

Fig.3(b) ΔE* distribution of 216 color predictions by the 1-D forward model v.s. the number of sampling points.

The reason that the LUT achieved the worst results is that the sampling points of each channel were not dense enough. The cubic interpolation is a 3-D linear interpolation, so values between the nine measurement grid points of each channel are approximated by straight lines. In other words, luminance-voltage curves of the projector are approximated as nine segments which are quite different from the properties of LCD. Because the sampling points of each channel are not dense enough, it can be expected that 1-D LUT with linear interpolation is not a good approach if there are only nine sampling points on each channel. Figs.3(a) and 3(b) reveal the results. The average ΔE^*_{uv}, maximum ΔE^*_{uv}, and STD are 3.47, 16.37, and 2.43 ΔE^*_{uv}, respectively. The results are comparable with those of the 3-D LUT approach because the channel interactions of the projector are small enough. The 3-D LUT approach can not obtain obvious improvement over that of the 1-D LUT in these conditions.

The performance of the 1-D and 3-D LUT approaches can be improved significantly by increasing the number of sampling points on each channel. Sixteen sampling points whose DAC values were chosen from 0 to 255 with increments of 17 DAC values were also measured to build the 1-D LUT forward model. The performance is also shown in Figs.3(a) and 3(b). The average ΔE^*_{uv}, maximum ΔE^*_{uv}, and STD in this condition are improved to be 0.99, 2.33, and 0.47 ΔE^*_{uv}, respectively. The percentages of samples with colorimetric attribution prediction differences of less than 1 and 2 ΔE^*_{uv} are also improved from 14.8% and 34.3% to 53.7% and 96.3%, respectively. These results are adequate, so the $16\times16\times16$ 3-D LUT method is not necessary.

6. CONCLUSIONS

In our work, it can be concluded that the multiple-polynomial regression method can obtain acceptable results. If the channel interactions of the projector are small enough, the 1-D LUTs works more effectively than the 3-D LUT approach because it requires fewer color measurements. For both LUT approaches, nine sampling points for each channel are insufficient for achieving acceptable results. Sixteen sampling points per channel are proper.

Numerically, the colorimetric attributions of 52.3% and 96.3% of the signals of the projector can be predicted to within 2 ΔE^*_{uv} difference from the actual values by the multiple-polynomial regression method and the 1-D LUT method(16 sampling points per channel), respectively. The average and maximum differences are 2.18 and 6.68 ΔE^*_{uv} using the multiple-polynomial regression method, and 0.99 and 2.33 ΔE^*_{uv} using the 1-D LUT approach. Our studies reveal that the colorimetric prediction accuracy of both methods are acceptable and that the 1-D LUT method will more accurately predict projector colors if the channel interactions of the projector are small enough.

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