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LEDSimulator Technology: A Research Tool for Colour and Texture

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Abstract

This paper describes LEDSimulator, a system that exhibits the impact of texture on colour appearance and serves as a colour communication tool for supply chain management. LEDSimulator is capable of accurately displaying coloured textures, achieving successful colour reproduction between media, and expediting the production cycle. The key technologies that accomplish this are introduced here, including: 1) visual colour matching on textures, 2) projector characterization modeling using the conventional and an advanced reduced LUT approach, and 3) a model to achieve metameric cross-media reproduction.

Introduction to LEDSimulator

Hardware

LEDSimulator serves as a visual communication tool within the supply chain for the surface colour industries [1]. It is equipped with a viewing cabinet and two spectral tunable multiple-LED lighting systems, as depicted in Figures 1a and 1b, respectively. The viewing cabinet (LEDView) provides standard viewing conditions used in typical colour laboratories. LEDView is capable of accurately simulating CIE standard illuminants such as CIE D65\D50, A, and F11. Two light panels (LEDPanels) are attached to the back of LEDView forming a display system where up to six channels from the LEDPanels illuminate a white substrate. This enables an object (or virtual sample) viewed through the aperture in the back of the LEDView to faithfully present not only the colour but also the texture of a desired product. A dark chamber isolates the space around the LEDPanels to prevent interference from ambient lighting. The display system is based on the colour mixing theories of additive (mixing coloured lights) and subtractive (reflective colours from surfaces) colour. The system can reproduce a large gamut of colours on a wide range of substrates.

***Figure 1**. System appearance*

Colour management workflow

Figure 2 shows a simplified colour management workflow including four stages. The data input (Step 1) and output (Step 4) include CIELAB coordinates [2] and reflectance data (400-700 nm with a 10 nm interval). These are first transformed to XYZ values under a set of particular illuminant/observer conditions. At the same time, LEDView adopts an illuminant at a specified illuminance (e.g., 500 lux) for observation. Step 2 obtains the corresponding XYZ values under the desired illuminant via a CIE chromatic adaptation transform such as CIECAT16 [3] to transform data between different illuminants. Users can continuously adjust colour via the colour selection software “ColorWay” (see Figure 3) until a satisfactory virtual colour is achieved. The final colour is stored in terms of CIELAB for communication in the supply chain.

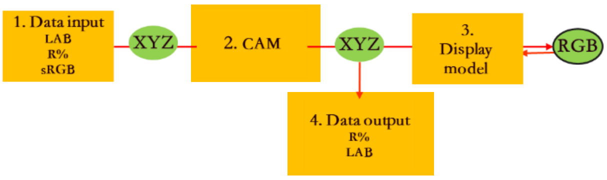


***Figure 2.** Colour management workflow*

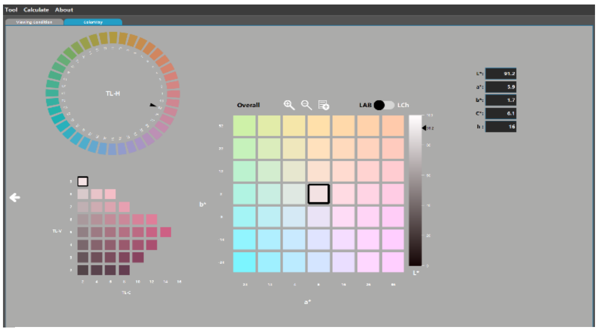
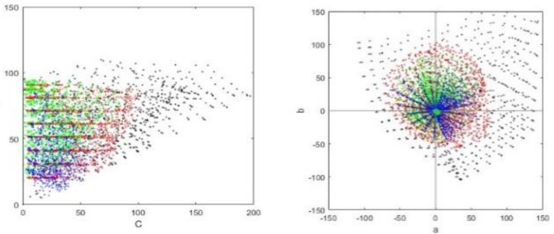


***Figure 3.** “ColorWay” interface for colour manipulation of a virtual*

Step 3 involves a characterization model that converts XYZ to LEDPanel's RGB values (three channels are used here). The conventional look-up-table (LUT) model [4] is used to display virtual colours, with a 11x11x11 LUT having equal intervals in L* space for each channel. Figures 4a and 4b display the 729 colours used in the LUT of the display in a*b* and L*Cab* planes (with black dots), showing that the samples from Munsell [5], NCS [6], and DIN [7] atlases are well within the boundary of the visual assessments on texture.



*a. L*C* plane* *b. a*b*plane*

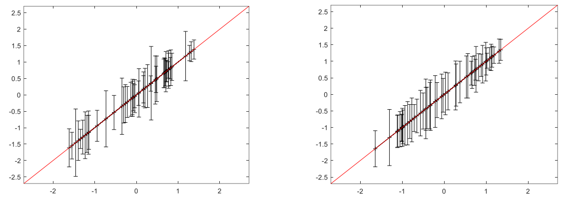
***Figure 4.** The colour gamut (black dots) of the virtual display in a) L*C_{ab}* and b) a*b* planes. The red, green, and blue dots represent the data in Munsell, NCS and DIN atlas, respectively.*

Method

A psychophysical experiment was conducted to assess the visual perception of 50 textures in the LEDView cabinet. Physical texture samples were displayed in the dark chamber and placed side by side against the 7cm aperture (FOV=5°) on the back wall of LEDView, illuminated by a D65-500 lx light source (0/45). Twenty normal colour vision observers participated (10 males and 10 females, aged 20 – 27) and were asked to evaluate 50 undyed samples for which five samples were duplicated to examine the intra-observer variability . Four perceptions were evaluated: roughness, randomness, contrast, and thickness of the textures in a 4-categorical scale of -2 (the least intensity) to +2 (the strongest intensity).

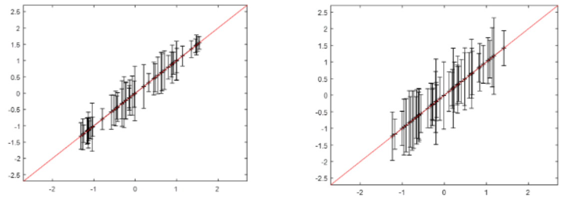
Result

Figure 5 plots the average and standard deviation of visual results against the average results.



a. Roughness

b. Randomness



c. Contrast

d. Thickness

Figure 5. *Average scores for each sample evaluation and corresponding error bars representing the standard deviation of scores among subjects.*

Correlation analysis was performed on the experimental results. All four scales fell into a single category and agreed well with each other, having a mean correlation coefficient of 0.81 between all pairs of perceptions (except 0.60 between randomness and thickness perceptions). Finally, five substrates were selected to represent approximately equal steps of Roughness, thus forming a standard texture set for each LEDSimulator system.

Projector characterization using both a conventional LUT and an advanced reduced LUT approach

Projector characterization using LUT

The LEDSimulator colour display can be considered as a non-imaging LED projector that applies a Look-Up-Table (LUT) characterization model. This was designed to overcome severe crosstalk between the multiple-LED channels used in the system, as shown in Figure 6, for which the GOG [8] and polynomial models [9] could not achieve the required colour accuracy in early system designs.

The initial LUT approach involved uniformly sampling the output values of the three channels at 11x11x11 points acquired by a JETI-Specbos 1211 spectroradiometer and then implementing a cube interpolation to compute the XYZ values.

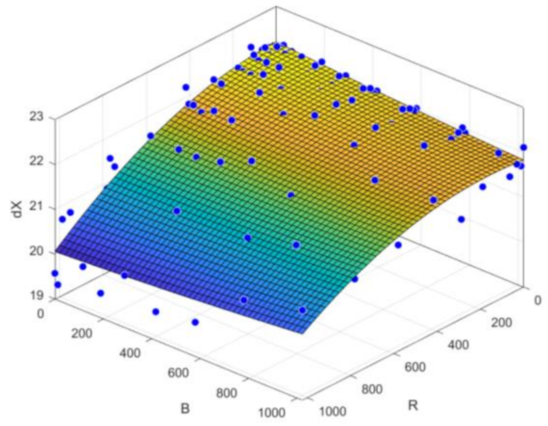


Figure 6. *The delta X for different R and B as the G channel increases from 0 to 1023, In the absence of crosstalk, the image would have been a plane*

However, the method did not perform well in dark regions. Increasing the sampling frequency was determined to be impractical since an 11-step LUT could take as long as 40 minutes to measure colours. Therefore, a point sampling method that is more uniform on the L* scale (although uneven on the channel output values) was eventually adopted. Figure 7 shows the comparison of two sampling methods.

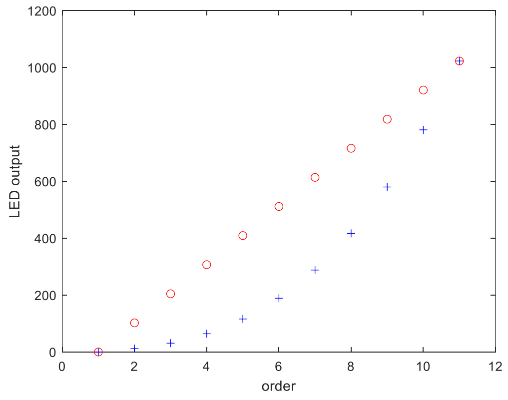


Figure 7. *A comparison of two sampling methods. The blue crosses represent non-uniform sampling and the red circles represent uniform sampling.*

The colour accuracy of LEDSimulator, i.e., the colour difference between 55 test colors measured using a JETI-Specbos 1211 spectroradiometer and those predicted by each model, has been extensively tested. In recent tests of six LEDSimulator systems, colour accuracy achieved an average of 0.40 (CIEDE00) [10]. A typical test result is summarized in Figure 8.

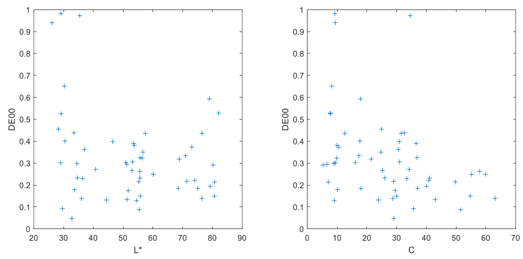


Figure 8. *Accuracy test result (CIEDE00 against L* and C*)*

An advanced reduced LUT approach

Method

Although the aforementioned LUT calibration method achieved high accuracy, it required a spectroradiometer and over 40 minutes for measurements. Unfortunately, replacing substrates without calibration could result in colour differences as high as 12.00 (CIEDE00), making substrate replacement time-consuming and requiring sophisticated equipment. This further required the use of limited, pre-set substrate materials, whose LUTs could be stored in the system.

A new model was developed to compute a new LUT for new substrates rather than performing many tedious measurements (11x11x11 colours). Users simply measure the target reflectance of the substrate to build the database. The built-in spectral data for each channel can be used to calculate the linear stacking LUT. Then an attenuation matrix calculated by the built-in LUT is used to simulate the influence of channel interaction and the LUT of the new substrate is obtained.

The calculation process is given below:

Step 1: To work out the 3 channels × 11 unequal intensity levels of the target substrate

$$\mathrm{SPD_T} = \mathrm{SPD_R} * \frac{\mathrm{R\%_T}}{\mathrm{R\%_R}} \tag{1}$$

where descriptors T and R represent target and reference respectively; SPD and R% are spectral power distribution and spectral reflectance of each sample, respectively.

Step 2: To compute SPD to XYZ

$$XYZ = CMF * SPD \tag{2}$$

where he CIE1964 10°.standard colorimetric observer (CMF) is used to establish the LUT, i.e.

Step 3: To compute the attenuation coefficient matrix

$$\begin{aligned} \mathrm{A_X} &= \frac{(\mathrm{X_{RGBr}})}{(\mathrm{X_{Rr}} + \mathrm{X_{Gr}} + \mathrm{X_{Br}})} \\ \mathrm{A_Y} &= \frac{(\mathrm{Y_{RGBr}})}{(\mathrm{Y_{Rr}} + \mathrm{Y_{Gr}} + \mathrm{Y_{Br}})} \\ \mathrm{A_Z} &= \frac{(\mathrm{X_{RGBr}})}{(\mathrm{Z_{Rr}} + \mathrm{Z_{Gr}} + \mathrm{Z_{Br}})} \end{aligned} \tag{3}$$

where $\boldsymbol{A_X}$ for attenuation coefficient of X, $\mathbf{X_{Rr}}$ for X of a particular R when G and B are equal to 0, $\boldsymbol{X_{RGBr}}$ for X of particular R, G, B that X_{Rr}, X_{Gr}, X_{Br} take, subscript, *r,* for reference LUT

Step 4: To calculate the simulated LUT

$$\begin{aligned} X_{RGBt} &= (X_{Rt} + X_{Gt} + X_{Bt})^* A_X \\ Y_{RGBt} &= (Y_{Rt} + Y_{Gt} + Y_{Bt})^* A_Y \\ Z_{RGBt} &= (Z_{Rt} + Z_{Gt} + Z_{Bt})^* A_Z \end{aligned} \tag{4}$$

where subscript, *t,* for target LUT

Result

The accuracy test described above was used to validate the performance of the algorithm. The average CIEDE2000 colour difference for the eight substrates' accuracy was 0.48 compared to 3.50 using the original LUT and 0.42 using the specially established LUT. The time to build a new LUT was also greatly reduced without performing the previously required LUT measurements (11x11x11).

There are two other primary colour calibration algorithms for display: the GOG model and the polynomial model. The GOG model adjusts the gamma, offset, and gain of each colour channel to achieve accurate colours. This involves modifying the transfer characteristics of the display to match the standard colour space. The gamma adjustment is typically done by applying a power function to the input signal, while the offset and gain adjustments are performed by adding or multiplying a constant value to each colour channel.

The polynomial model, on the other hand, uses a mathematical equation, typically a polynomial function, to map the input signal to the output colour space. This method involves fitting a curve to the measured display response to achieve the desired colour accuracy.

Table 1 shows the performance of the reduced LUT model together with other models on LEDSimulator when a new substrate is applied.

Table 1 Performance comparison of multiple models

	Number of measurements	Time (minutes)	Accuracy (DE00)
GOG model	33 (Spectroradiometer)	1	2.67
Polynomial model (11 levels)	33 (Spectroradiometer)	1	2.37
LUT model	1331 (Spectroradiometer)	40	0.42
Reduced LUT model	1 (Reflectance spectrophotometer)	1	0.48

A model for metameric cross-media reproduction

Finally, a colour matching experiment was carried out matching virtual samples to physical samples in order to establish the baseline performance of a group of observers using LEDSimulator to match colours. Note that when using LEDSimulator to compare samples viewed in the light cabinet to colours projected by LEDPanels onto a white substrate,

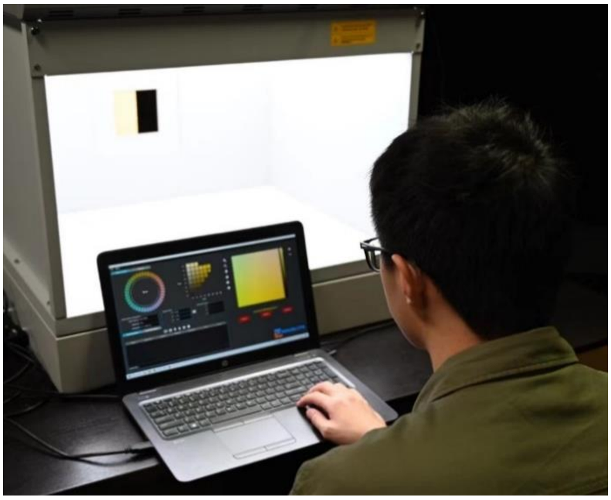


Figure 9. *A subject is performing a colour matching experiment*

metamerism occurs 1) between the difference of spectral characteristics due to viewing distance and 2) between distances of viewing of the two media under evaluation. This results in observers perceiving the two colours differently, even though the XYZ values are the same, as confirmed with a spectroradiometer.

Method

A colour matching experiment was developed to identify colour matching variation between observers and to build a correction matrix to adjust the LEDSimulator data to those of mean visual colour matching data. The experimental settings were as follows: 10 experienced subjects (six males and four females, aged 21 – 27, with normal colour vision, and majoring in colour science), performed colour matching by adjusting the projected light in the system to match 60 physical colour samples viewed in a D65-500 lx light source. The colour system used for matching is "ColorWay". Subjects adjusted CIELCh first, and, when close in neutral colours, the CIELAB colour system was applied to improve matching speed and accuracy.

Result

The colours included in the colour matching experiment were converted to CIELAB values and the results were used to evaluate the inter-observer agreement. It was found the typical variation from a group of 10 observers was 2.81 CIEDE2000. This value was divided by the physical measurement results obtained with a spectrophotometer to create a correction matrix. When applied, an input value can be inversely calculated with this matrix to obtain a colour more similar to the result of the human eye. The correction matrix reduces the colour difference (CIEDE2000) caused by metamerism from 2.13 to 0.85 in theory and significantly improves visual consistency.

Conclusion

LEDSimulator is a colour communication tool equipped with two spectral tunable multiple-LED lighting systems and a viewing cabinet. It can accurately simulate different illuminants and present both the colour and texture of a desired product accurately. LEDSimulator's colour management workflow involves four stages based on CIE Colorimetry, including data input and output, such as spectral reflectance function, XYZ, and CIELAB.

In the visual evaluation experiment on texture, 20 participants evaluated 50 samples using standard lighting conditions under a D65-500 lx light source environment. The four ratings of roughness, randomness, contrast, and thickness of the textures were scored on a scale of -2 to +2. The ratings from the four perceptions were found to be highly correlated. The results were used to select five standard substrates for the system.

In the projector characterization modeling, two LUT approaches were compared; the conventional 11x11x11 LUT and an advanced reduced LUT. The results showed that the advanced reduced LUT approach achieved a similar colour accuracy by using only one reflectance curve, thus reducing the computational complexity and calibration time.

Colour matching experiments on LEDSimulator verified a method to correct cross-device metamerism and revealed a system to achieve cross-media colour science research.

LEDSimulator can also be a valuable tool to study the total appearance by scaling colour, texture, gloss and translucency perceptions. Both the soft and hard metrologies can be used to quantify their specifications. For the imaging industry, an image database can be established by projecting coloured lights on a variety of textures to evaluate the image quality of cameras. Additionally, designers can build colour palettes specific to a variety of fabrics with specific textures.

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