Physical-based Photon Mapping Technique for LED Back-light Lighting Simulator

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Abstract

With the increasing popularity of LCD displays due to lower prices and larger sizes, backlights with an RGB LED source are slowly replacing CCFL-type backlights, as an RGB LED has a wider color gamut, higher luminance, and lower power consumption. However, even though light modules with an array of individual LEDs can uniformly cover the entire backlight area, this does not ensure chromaticity and luminance uniformity over the backlight panel, thereby stressing the need for a lighting simulation of the backlight. Accordingly, this paper proposes an effective lighting simulator that is able to predict the chromaticity and luminance distribution of an LCD backlight panel, especially an LED-type backlight. A photon mapping technique based on Monte Carlo ray tracing is utilized for tracing photons and visualization of the photon map. Plus, for a more accurate prediction, along with the spectral characteristics of the LED source and panel sheets, the more complex optical characteristics depending on the wavelength and incident angle of the photon are also modeled.

1. Introduction

The image quality of LCD displays essentially depends on quality of the backlight unit (BLU), and the key issues that determine the quality of the BLU include the luminance intensity of the panel surface, reference white color reproducibility, and luminance and chrominance uniformity. This has produced a lot of research on high luminance with low power and white color reproducibility, resulting in the recent trend of LED backlighting, which employs LED devices as the LCD backlight source instead of CCFL.[1-2] LEDs provide long life with considerable more brightness and a low power consumption, plus the mixture of red, green, and blue LED allows flexible control of the reference whites. However, even though all LEDs have the same colors with uniformly positioned arrays on the back side of the BLU, it is difficult to create a uniform luminance distribution and reference white on the panel surface due to the specific characteristics of each LED, such as the spectral power distribution, total luminance, and spatial emission property.[3] Accordingly, the main purpose of this study was to develop a very useful simulation algorithm that can predict the chromaticity and luminance distribution of the final backlight panel surface for any LED array and BLU sheet model. In addition to using a photon mapping algorithm based on the Monte Carlo ray tracing method[1], the spectral characteristics of the LED and optical sheets are also considered to trace a light ray with any spectrum. Plus, a simple method is proposed to generate non-uniform random photons satisfying the spatial emission profile of an LED. Both the spectral-based characteristics and the non-uniform emission profiles are converted to a roulette table for effective fitting and reducing the computational cost. The final photon map of the target surface is then converted to CIEXYZ tristimulus value for each area according to the pixel size. The proposed method was evaluated along with a commercial software tool using a virtual back-light unit and the performances compared in terms of the luminance, CIE x value, and CIE y value prediction.

2. Photon mapping technique for rendering

Photon mapping is the process of emitting photons from light sources and tracing them through a model, as shown in Figure 1.[4]

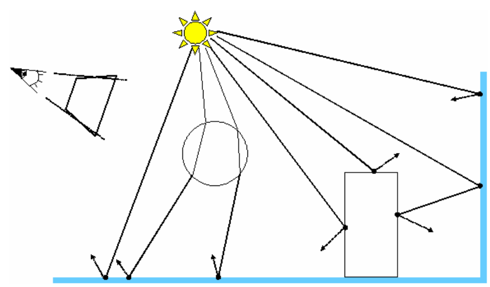


Figure 1. *Ray tracing process for photon mapping technique.*

When a photon hits an object surface or defined target surface, the information on the photon, including its geometric parameters and luminance value, is stored as a point in a global data structure, a photon map. Finally, the photon map is rendered for any view point using a simple ray tracing method or visualization of the radiance for any target surface.

2.1 Photon emission

The first step in photon mapping is the creation of the photons from light sources and the emission of the photons in a three-dimensional model. The light sources can be typical point lights, area light sources, or other complex lights. In general, photons include three pieces of information, its position, direction, and power. The position and direction of a photon can be arbitrary or selected based on a weighted probability, while the power of the light source is divided among all the emitted photons.

2.2 Photon tracing

When a photon is emitted, its path is traced in a model, and the tracing process is the similar to general ray tracing. A photon can be intersected with objects and reflected, transmitted recursively, or absorbed, and the decision of reflection, transmission, or absorption is performed by a probabilistic sampling technique known as Russian Roulette based on the material parameters of the surface

2.3 Photon storing

When the photon being traced meets the target surface or a diffuse surface, the tracing process is stopped and the photon's information stored in a global data structure. The photon map is thus points set in three-dimensional space and used for image rendering. The number of photons near an arbitrary position in the photon map represents the incoming flux to that small region. The map structure needs to allow the density of photons around an arbitrary position to be easily estimated in a map with millions of photons, and this is solved using a kd-tree or Voronoi diagram.[4] Fig. 2 shows the construction of a photon map and the concept of radiance estimation.

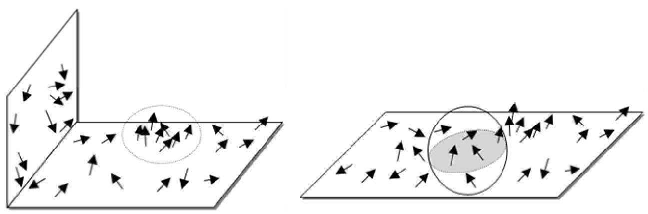


Figure 2. *Construction of photon map and estimating radiance information.*

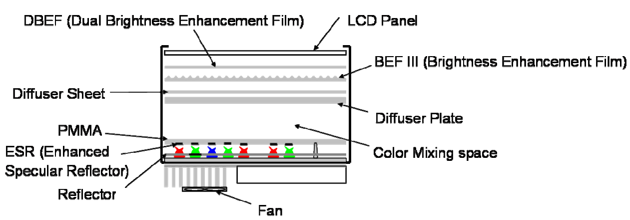


Figure 3. *LCD back-light structure using LED light devices.*

3. Implementation of physical-based photon mapping

The purpose of this study was to develop an effective simulation algorithm to predict the chromaticity and luminance distribution of a lamp-lit LCD backlight panel with arbitrary LED arrays and sheet structures, as shown in figure 3. Thus, based on the physical characteristics of an LED, the Monte Carlo method was extended to consider both the emission distribution and the spectral power distribution of an LED device during the photon emission process, and model the spectral reflectance and transmittance properties of the inner sheets.

3.1 Photon emission according to spectral power and emission profile of LED

The LED light source used for an LCD back-light has its own spectral power distribution and non-uniform emission properties along with all directions. Figure 4 shows the relative spectral power distribution and emission profile of the LED used in the current simulation.

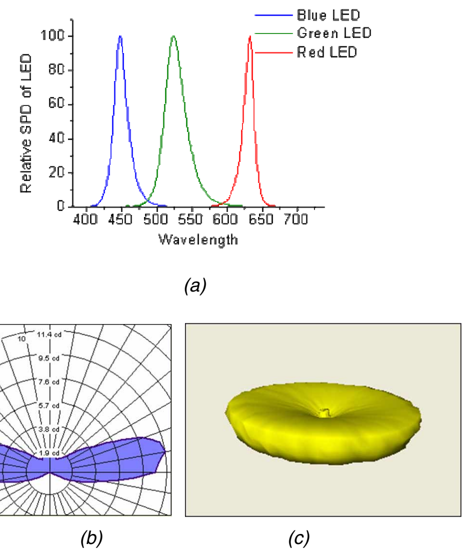


Figure 4. *Relative spectral power distribution and emission profile of LED (a) spectral power distribution of red, green, and blue LED (b) emission profile of red LED (c) 3-D emission profile of red LED.*

This study introduces an effective technique to generate non-uniform random photons so that the wavelength distribution and initial directions of all the photons created by the Monte Carlo method satisfy both the real spectral distribution and the emission profile of the LED. The procedure of photon creation is shown in figure 5. The cumulative sum of the relative spectral power distribution is calculated first. Next, it is preferable to make a roulette table large enough to allocate sufficient bins proportional to the energy of each wavelength. The specific wavelength value is then stored in each table bin, where the number of bins storing the same wavelength value is proportional to the energy of each wavelength. In the present simulation, the size of the roulette table was $\sum Energy_{each\ wavelength} \times 10$ based on experimentation.

$$N_{b(\Delta)}(\lambda) = \frac{E(\lambda)}{Energy_{tatal}} \times S_{LT}, \tag{1}$$

where $N_{b(\Delta)}(\lambda)$, S_{LT}, and $E(\lambda)$ are the number of bins for each wavelength value, the total number of bins for the roulette table, and the energy level of each wavelength. The same method is also used to create another roulette table for the emission profile. A randomly generated photon contains three properties: wavelength, direction, and energy, where the wavelength and direction are defined by the above two roulette tables, and the energy is determined by dividing the total flux of the LED by the total number of photons generated. Figures 6 (a) and (b) show the spectral power distribution of the red LED and emission profile, respectively. Photon generation experiments were performed using 50,000 random selections from the roulette table for the wavelength and direction, and the resultant histogram of the process is shown in figures 6 (c) and (d). The results confirmed that the proposed roulette-based non-uniform photon creation matched well with the original physical characteristics of the LED.

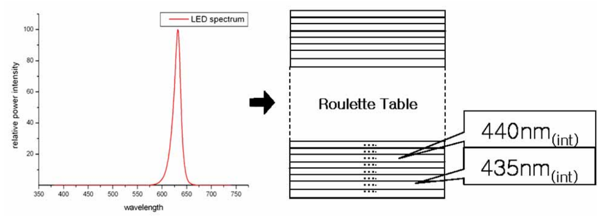


Figure 5. *Creation of roulette table according to spectral power distribution (a) spectral power distribution of red LED (b) roulette table and stored wavelength values.*

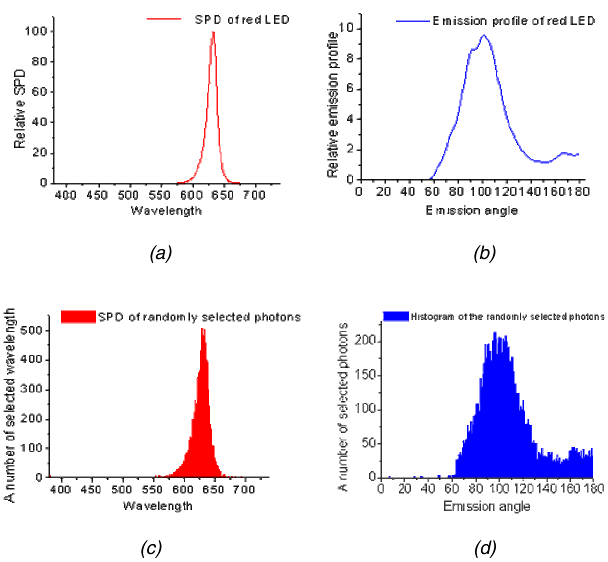


Figure 6. *Generation of nonuniform random photons of (a) spectral power distribution and (b)emission profile, and the (c), (d) resultant histogram of (a) and (b), respectively.*

3.2 Photon tracing based on physical characteristic of sheets

The sheet hit by a photon has a slightly different refection coefficient, transmittance, and absorption according to the incident angle of the photon to the intersection surface, rather than the wavelength of the photon. Yet, if the photon is reflected or transmitted, the type of optical interaction, such as diffuse, specular, or Gaussian diffuse, will depend on both the wavelength and the incident angle of the photon. Thus, to increase the accuracy of the simulation, the optical characteristics of the sheets were modeled with regard to the wavelength and incident angle. Consequently, if a photon hits a sheet, a uniformly distributed random variable $\xi \in [0,1]$ is used, resulting in the following decision.[4]

$$
\begin{aligned}
& I \in [0, k_r], && \textit{reflection} \\
& I \in [k_r, k_r + k_t], && \textit{transmission} \\
& I \in [k_r + k_t, 1], && \textit{absorption}
\end{aligned}
\qquad (2)
$$

Thereafter, the next direction of the photon can be three types of reflection or transmission: perfect diffuse, Gaussian diffuse, or specular, as shown in figure 7. Thus, the decision on the final direction is also made using the same uniformly random variable according to the property profile described in figure 8.

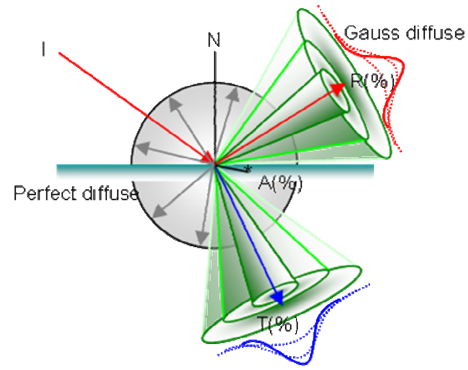


Figure 7. *Types of reflection or transmission.*

	λ (mn)	300				550			
I(°)		R(%)	T(%)	A(%)	FWHM	R(%)	T(%)	A(%)	FWHM
0	Spec	5	22	5		0	18	10	
	Lamb	0	5	0		0	9	0	
	Gauss	0	63	0		0	63	0	
	Gauss Angle				20				20
45	Spec	5	20	5		0	18	10	
	Lamb	0	11	0		0	9	0	
	Gauss	0	63	0		0	63	0	
	Gauss Angle				20				20
90	Spec	5	28	5		0	18	10	
	Lamb	0	9	0		0	9	0	
	Gauss	0	63	0		0	63	0	
	Gauss Angle				20				20

Figure 8. *Optical property profile of sheet according to wavelength.*

In the case of a Gaussian diffuse reflection or transmission, the random direction with the Gaussian probability is calculated using the following equations (3) and (4) according to the Full Width at Half Maximum (FWHM) determined by the property profile of the sheet.

$$I = I_0 \times e^{-\left(\theta/a\right)^2} \qquad (3)$$

$$a = FWHM_{Gaussian} \Big/ \left(2 \times \sqrt{(\ln(2)}\right) \qquad (4)$$

Since the area visualized by the simulation is the outer panel of the back-light unit, when a traced photon hits the final target sheet on a pre-defined recursion level, the tracing process stops and the photon is stored as a two-dimensional coordinate of the panel, that is, in a photon map based on the proposed algorithm.

3.3 Visualization of photon map

The photon map resulting from all the traced photons can be used for realistic image visualization. The real size of the unit grid area of the sheet for the image pixels is calculated by dividing the image resolution by the size of the target sheet, as shown in figure 9. Thus, to calculate the tristimulus values for reproduction, the spectral power distribution is shaped by gathering the radiances cumulated in each unit grid area, then the spectral power distribution is converted into a tristimulus value using equation (5).[5]

$$X = \sum_{\lambda=380}^{740} S(\lambda)\bar{x}(\lambda)\Delta\lambda$$
$$Y = \sum_{\lambda=380}^{740} S(\lambda)\bar{y}(\lambda)\Delta\lambda \quad (5)$$
$$Z = \sum_{\lambda=380}^{740} S(\lambda)\bar{z}(\lambda)\Delta\lambda$$

where $S(\lambda)$ represents the spectral power distribution gathered in a unit grid space, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the color-matching functions for the XYZ primaries, respectively. Next, the tristimulus value is converted into a linearized RGB value using a sRGB transformation matrix with D65 reference white, as shown in equation (6).[6]

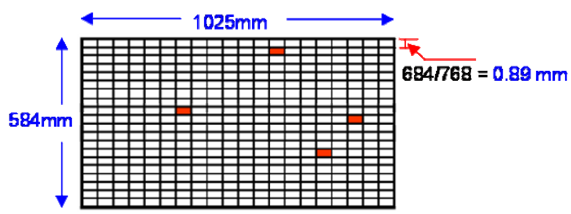


Figure 9. Unit grid space of photon map for visualization.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{D65} \quad (6)$$

$$\begin{aligned} &\text{If } R, G, B \le 0.0031308 \\ &\quad R'_{sRGB} = 12.92 \times R \\ &\quad G'_{sRGB} = 12.92 \times G \\ &\quad B'_{sRGB} = 12.92 \times B \\ &\text{else if } R, G, B > 0.0031308 \\ &\quad R'_{sRGB} = 1.055 \times R^{(1.0/2.4)} - 0.055 \\ &\quad G'_{sRGB} = 1.055 \times G^{(1.0/2.4)} - 0.055 \\ &\quad B'_{sRGB} = 1.055 \times B^{(1.0/2.4)} - 0.055 \end{aligned} \quad (7)$$

Thereafter, the linearized RGB value is converted into a nonlinear sR'G'B' value using equation (7), and finally converted into an 8-bit RGB value for display.[6]

$$\begin{aligned} R_{8bit} &= round(255.0 \times R'_{sRGB}) \\ G_{8bit} &= round(255.0 \times G'_{sRGB}) \\ B_{8bit} &= round(255.0 \times B'_{sRGB}) \end{aligned} \quad (8)$$

4. Rendering simulation and results

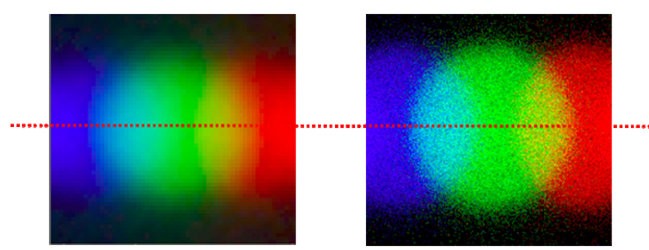
Lighting simulations using the proposed physical-based photon mapping method were performed for the outward panel of a particular back-light unit. The proposed method was also evaluated in comparison with a high-priced commercial software tool for same back-light unit model. Table 1 shows the comparative results for a virtual back-light unit consisting of an LED and diffuse sheet. Fig. 10 shows the simulation results for another virtual back-light unit, as listed in table 2, and figure 11 shows a comparison profile of the Lumens, CIE x, and CIE y value for the dotted line in figure 10. The proposed physical-based photon mapping method rendered a similar light distribution for the back-light unit to that produced by the well-known commercial software tool.

Table 1. Comparative results of final outward light flux for same BLU model.

INPUT			Speos			KNU		
Led	Flux(mW)	Wp	Lumen	Ciex	Ciey	Lumen	Ciex	Ciey
Red	0.2	630	42.2617	0.691	0.309	42.29973	0.6928	0.3071
Red	0.2	635	35.4	0.701	0.299	35.41381	0.7005	0.2994
Red	0.2	640	29.1284	0.71	0.29	29.22125	0.7069	0.293
Green	0.2	524	104.25	0.184	0.735	104.45873	0.1888	0.732
Green	0.2	530	113.142	0.221	0.729	113.17048	0.2257	0.7239
Blue	0.2	448	6.5034	0.153	0.025	6.50051	0.1535	0.0242
Blue	0.2	452	7.8075	0.149	0.031	7.78255	0.1496	0.0294

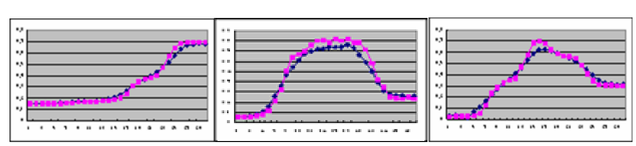
Table 2. Simulation parameters for virtual back-light unit model.

LED	Reflector(BLU)	Diffuse sheet	detect
Red (1) Green (1) Blue (1)	Size 60*60*30(mm)	Size 648*148*2(mm) Height 26(mm)	Height 30(mm)
Angular data(150-180)	Absorption ratio 5%, Specular reflection 95%	Absorption ratio 8%, Transmission (Lambertian 64%, Gaussian 28%, FWHM 35)	



(a) (b)

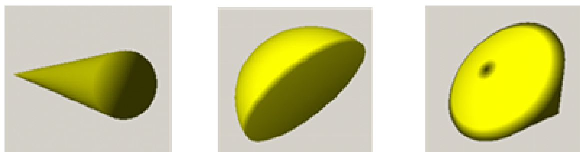
Figure 10. Simulation results for virtual BLU model (a) commercial software (b) proposed photon mapping algorithm.



(a) (b) (c)

Figure 11. Profile of dotted line shown in figure 10: (a) Lumens, (b) cie x value, and (c) cie y value.

Figure 12 shows the three types of LED radiation angular data, while figure 13 shows the lighting simulated results for the back-light unit with 130 LEDs for each type of radiation angular. In the simulations, 100,000 rays were generated per LED, making a total of 13,000,000 rays. The time required for the entire rendering was 18 minutes with a Pen.4 2.8GHz computer.



(a) (b) (c)

Figure 12. *LED radiation angular data used for back-light (a) 170°- 180°(b) 120°- 180°(c) 90°- 180°.*

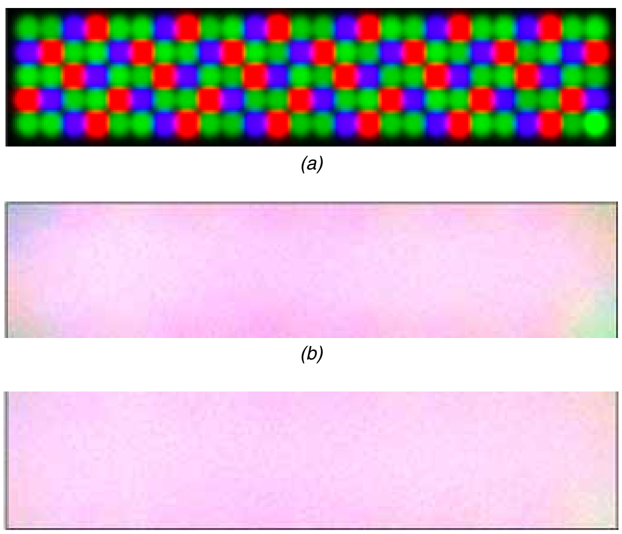


Figure 13. *Back-light simulation for 130 LEDs: (a) for radiation angular range of 170°- 180°, (b) radiation angular range of 120°- 180°, and (c) radiation angular range of 90°- 180.*

Based on the experimental results, the proposed physical-based tone mapping algorithm could be effectively used in the pre-simulation of a particular back-light unit model for analysis and design.

5. Conclusion

With the advent of LED devices as a new light source for back-light units, the uniformity problem of chromaticity and luminance has become an important issue for the display industry, highlighting the need for a lighting simulation of the backlight. Therefore, this study proposed an effective lighting simulator that is able to predict the chromaticity and luminance distribution of a LCD backlight panel using a physical-based tone mapping algorithm. First, a well-designed photon generation considering the spectral power distribution and radiation property is introduced. Plus, the physical characteristics of the sheets are accurately modeled not only in terms of their optical reflection, transmission, and absorption according to the wavelength, but also according to the incident angle. To reduce the computational cost, a roulette table process is implemented for non-uniform stochastic sampling. As a result, the proposed photon mapping method can accurately simulate the physical interaction of the light photons in a three-dimensional back-light unit model. It is expected that the proposed algorithm can be effectively used in the pre-simulation stage of arbitrarily structured back-light units.

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