Modeling of Luminance Transition Curve of Transparent Plastics on Transparent OLED Displays

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Abstract

Transparent displays have received attention as next-generation displays. In this paper, a new method to estimate the luminance transition curve of the black-and-white patch located behind the transparent plastics is presented. The luminance transition curve can provide the information on the blurriness of the transparent displays. In addition, it can be utilized to simulate the perceived images on the transparent display. Experimental results indicate that the proposed method accurately estimates the luminance transition curve of the black-and-white patch.

1. Introduction

Transparent displays allow observers to see the visual information on displays overlaid with the object or scenery behind the displays. For this reason, transparent displays have received attention as next-generation displays. They can be utilized for various applications such as shop-windows, door of the refrigerator or automobile displays. They can be manufactured based on the liquid crystal display (LCD) or organic light emitting diode (OLED) technologies [1]-[5]. The visual information on transparent displays is generated by the light emission on the OLED displays and by the light transmission on the LCD displays. Therefore, transparent LCD displays require sufficiently bright background. However, this is not the case for transparent OLED displays because they are self-luminous.

If transparent displays can operate in the translucent or opaque modes, their use will be further extended. Transparent plastics that control the transmission of incident lights can provide flexibility in operating mode of transparent OLED displays [6]-[7]. When attached to the back of transparent OLED displays, they can partially block the transmission of the incident lights from background to improve the perceived contrast in the displayed images. The performance of transparent plastics is often characterized by the luminous transmittance factor and haze [8]-[9]. The transmittance factor is the ratio of the luminous flux transmitted through a transparent plastic. The haze of transparent plastic is defined as the ratio of the transmitted light that is scattered so that its direction deviates more than 0.044 rad or 2.5° from the direction of the incident light [9]. The haze of transparent plastic affects the perceived sharpness of the objects in background.

This paper presents a new method to estimate the luminance transition curve of the black-and-white patch located behind the transparent plastics. The black-and-white patch is regarded as an object located behind the transparent plastics. Due to the haze of the transparent plastics, the black-and-white patch would appear blurred. In the proposed method, using a measured luminance transition curve of the black-and-white patch under a fixed value of the haze, the luminance transition curves for different values of the haze are estimated. It is based on the empirical assumption that the luminance level of the diffused light at a given direction is proportional to the value of haze. The proposed method can be extended to the imaging chain of the transparent OLED displays and transparent plastics by incorporating the haze and transmittance factor of the OLED displays. In addition, the luminance transition curve can provide the information on the blurriness of the transparent displays. In addition, it can be utilized to simulate the perceived images on the transparent display.

In Section 2, the proposed method to estimate the luminance transition curves of the black-and-white patch is described. In Section 3, verification of the empirical assumption is presented. In addition, experimental results are discussed. Finally, Section 4 concludes this paper.

2. Proposed Method to Estimate Luminance Transition Curves

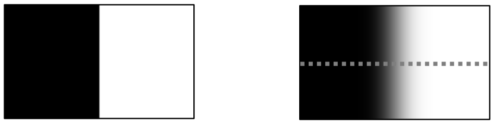
There are two major factors affecting the blurriness of the transmitted images through transparent displays. They are the haze and the distance to the objects in the background. As the value of haze increases, the blurriness in the transmitted image is increased. The light reflected from the objects in background is omni-directionally diffused [10]. For this reason, when the distance between the transparent plastic and the objects in background decreases, the transmitted image appears less blurred.

Suppose that a black-and-white patch depicted in Figure 1 (a) is an object located behind the transparent plastic. Figure 1 (b) represents an example of the transmitted image of the black-and-white patch. Figure 1 (c) illustrates the luminance transition curve of the horizontal line marked in Figure 1 (b). In Figure 1 (c), the horizontal axis denotes the horizontal position in the black-and-white patch and the vertical axis represents the normalized value of the luminance at each location. In addition, the staircase line in Figure 1 (c) represents an ideal luminance without blurriness.

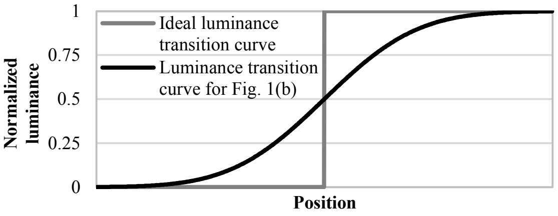
As a first step to estimate the luminance transition curves, two luminance transition curves are measured for two different values of the haze, haze=h_a and h_b (h_a<h_b), using the two-dimensional spectroradiometer from the transmitted images of the black-and-white patch displayed on a monitor. The measurements are made in a dark room to avoid flare effect. The black-and-white patch is displayed on a monitor because its wide dynamic range allows to measure small changes in luminance. The measured values of luminance are normalized to be in the range of 0 and 1. The measured luminance transition curves are utilized as the ground truth data to interpolate the luminance transition curves for different values of the haze.

The proposed method to estimate the luminance transition curves is based on the empirical assumption that the luminance level of the diffused light at a given direction is proportional to the value of the haze of the transparent plastics. This assumption can be explained using the examples depicted in Figure 2. Figure 2 (a) and (b) illustrate the luminance transition curves for haze=h_a and h_b (h_a<h_b), respectively. In Figure 2 (a) and (b), the luminance measured on the black side of the patch is owing to the diffused light from the white side of the patch. Figure 2 (c) depicts portions of two luminance transition curves on the black side of the patch. Let $l(k, h_i, d_j)$ represents the luminance transition curve with the value of haze h_i and the background distance d_j. In addition, k in $l(k, h_i, d_j)$ denotes horizontal location. The empirical assumption is then expressed as Equation (1).

$$\frac{l(k_1,h_a,d_j)}{l(k_1,h_b,d_j)}=\frac{l(k_2,h_a,d_j)}{l(k_2,h_b,d_j)}=\frac{h_a}{h_b} \qquad (1)$$

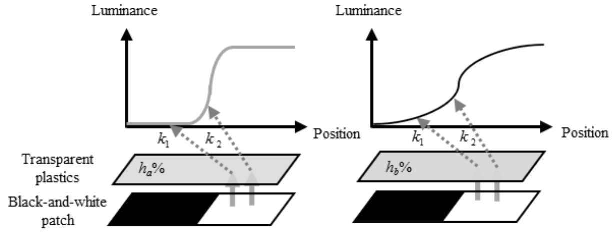


(a) Object in background (b) Transmitted image

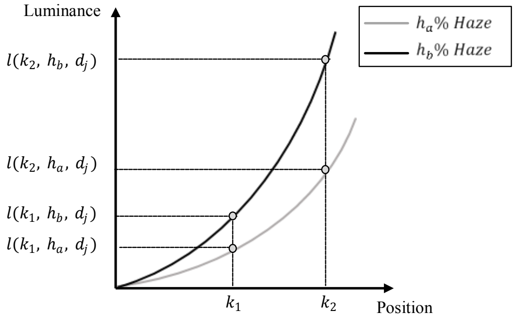


(c) Luminance transition curves

Figure 1. An example of luminance transition curve



(a) Luminance transition curve for h_a% haze (b) Luminance transition curve for h_b% haze



(c) Portions of luminance transition curves in the black side of the patch for h_a and h_b

Figure 2. Examples of luminance transition curves for different hazes

This assumption is utilized to interpolate the luminance transition curves for different values of the haze. For brevity's sake, the luminance transition curve $l(k, h_i, d_j)$ is denoted by a $1 \times$ M vector, $\mathbf{L}_{h_i,d_j} = \; l(1, h_i, d_j), l(2, h_i, d_j), \ldots, l(2, h_i, d_j)]$. Suppose that the luminance transition curves for the value of haze 0 and 100, $\mathbf{L}_{0,d_j}$ and $\mathbf{L}_{100,d_j}$ are available. When the value of haze is 100, the incident lights are completely diffused. On the contrary, there is no diffusion of the incident light when the value of the haze is 0. Based on the aforementioned assumption, the luminance transition curve for an arbitrary haze value of $h_x = x$ can be interpolated using $\mathbf{L}_{0,d_j}$ and $\mathbf{L}_{100,d_j}$by the following Equation (2).

$$\mathbf{L}_{h_x,d_j}=\begin{bmatrix}\frac{(100-x)}{100} & \frac{x}{100}\end{bmatrix}\begin{bmatrix}\mathbf{L}_{0,d_j}\\ \mathbf{L}_{100,d_j}\end{bmatrix} \qquad (2)$$

Using Equation (2), the relationship between the measured luminance transition curves and the luminance transition curves for h=0 and 100 is derived as the following equation.

$$\begin{bmatrix}\mathbf{L}_{h_a,d_j}\\ \mathbf{L}_{h_b,d_j}\end{bmatrix}=\begin{bmatrix}\frac{(100-h_a)}{100} & \frac{h_a}{100}\\ \frac{(100-h_b)}{100} & \frac{h_b}{100}\end{bmatrix}\begin{bmatrix}\mathbf{L}_{0,d_j}\\ \mathbf{L}_{100,d_j}\end{bmatrix} \qquad (3)$$

By combining Equations (2) and (3), $\mathbf{L}_{h_x,d_j}$ can be obtained by Equation (4) using the measured luminance transition curves.

$$\mathbf{L}_{h_x,d_j}=\begin{bmatrix}\frac{h_x-h_b}{h_a-h_b} & \frac{h_a-h_x}{h_a-h_b}\end{bmatrix}\begin{bmatrix}\mathbf{L}_{h_a,d_j}\\ \mathbf{L}_{h_b,d_j}\end{bmatrix} \qquad (4)$$

Using Equation (4), the luminance transition curves for different values of the haze are calculated. This procedure is graphically illustrated in Figure 3.

3. Experimental Results

In order to evaluate the performance of the proposed method, the fifteen luminance transition curves were measured from the black-and-white patch in Figure 1 (a). The values of the haze were 7, 80, and 99%. The background distance were 10, 20, 30, 40 and 50 cm. The fifteen luminance transition curves were utilized as the ground truth data to verify the performance of the proposed method. It should be noted that only two luminance transition curves are required for the estimation of the luminance transition curves for different values of the haze.

3.1 Verification of the Empirical Assumption

In this paper, it is empirically assumed that the luminance level of the diffused light at a given direction is proportional to the value of the haze of the transparent plastics as in Equation (1). Figure 4 illustrates the measured luminance transition curves on the black side of the patch when the background distance is 50 cm. In the horizontal axis, k_1 ~ k_5 denote the positions of the measurement. Table 1 lists the ratio of the values of haze and luminance. The first column lists the ratios of the values of haze. The ratios of the luminance at each location are averaged over the five different background distances of the ground truth data. In addition, the ratios at the k_1 ~ k_5 locations are averaged and listed at the last

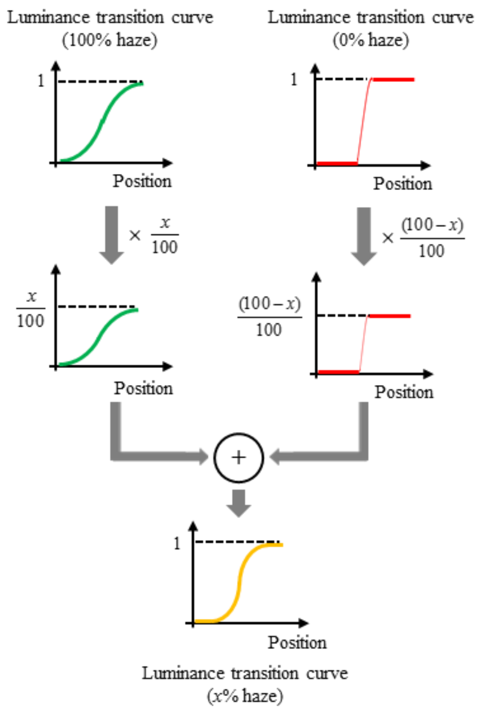


Figure 3. Graphical explanation of the proposed estimation method

column. It can be noticed that the averaged ratios of luminance appear quite flat over the five locations even though there are some differences between the ratios of haze and luminance.

3.2 Performance of Estimation of the Luminance Transition Curves

In the proposed method, the luminance transition curves are estimated for different values of the haze using Equation (4). The objective of this experiment was to evaluate the accuracy of the interpolation of the luminance transition curves. Among the ground truth data with three different haze values, two of them were utilized as training samples to estimate the luminance transition curves of the remaining one. For example, among the three luminance transition curves with the background distance=10, $\{\mathbf{L}_{7,10}$, $\mathbf{L}_{80,10}$ and $\mathbf{L}_{99,10}\}$, $\mathbf{L}_{7,10}$ and $\mathbf{L}_{99,10}$ were utilized to interpolate $\mathbf{L}_{80,10}$. Suppose that $\hat{\mathbf{L}}_{80,10}$ or $\hat{l}(k, 80,10)$, $k = 1,2 \dots \mathrm{M}$ denotes the estimated luminance transition curve. The average error between the estimated and measured luminance transition curves was calculated by (5).

$$error = \frac{1}{M}\sum_{k=1}^{M}|\hat{l}(k,80,10)-l(k,80,10)| \qquad (5)$$

Figure 5 presents a diagram to summarize this procedure. Figure 6 illustrates the graphs of the measured curve $\mathbf{L}_{80,10}$ in the dotted line and the estimated curve $\hat{\mathbf{L}}_{80,10}$ in the solid line. Two curves appear almost the same. Table 2 lists the averaged error of the estimation of the luminance transition curves. Because the luminance transition curves were normalized to be in the range of 0 and 1, the numbers in Table 2 can be regarded as the percentage value. The results in Table 2 indicate that the proposed estimation method of the luminance transition curves yields high degree of accuracy. In addition, the training values of the haze should be sufficiently apart to increase the accuracy of the interpolation.

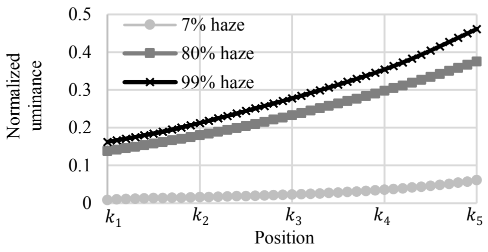


Figure 4. Measured luminance transition curves on the black side of the patch (d=50 cm)

Table 1. The average ratio of luminance

Ratio of haze (h_a / h_b)	Averaged ratio at position k_i					Average over positions
	k_1	k_2	k_3	k_4	k_5	
80/99(=0.808)	0.812	0.810	0.809	0.817	0.817	0.813
7/80(=0.088)	0.093	0.099	0.097	0.099	0.108	0.099
7/99(=0.071)	0.076	0.080	0.079	0.081	0.088	0.081

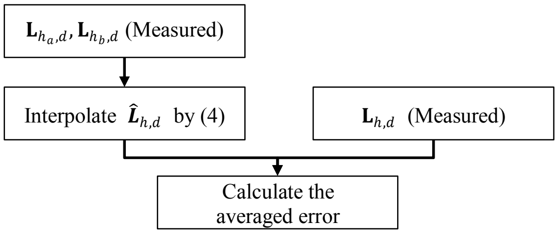


Figure 5. Flowchart of the evaluation of accuracy of the interpolation of luminance transition curve

3.3 Simulation of the Transmitted images

The proposed method can be utilized for simulation of the transmitted images through the transparent plastics. It can be assumed that the luminance transition curve represents the results of convolution of the step function representing the ideal transition curve in Figure 1 (c) and the blur kernel. Suppose that the blurriness in the transmitted image is modeled by a Gaussian blur kernel. The standard deviation to specify the Gaussian blur kernel can be determined using an iterative process by minimizing the following criterion.

$$\sigma_{h_x,d_j} = \arg\min_{\sigma}(\| \mathbf{L}_{\sigma} - \mathbf{L}_{h_x,d_j} \|) \qquad (6)$$

where $\mathbf{L}_{\mathrm{h_x,d_j}}$ represents the luminance transition curve estimated by the proposed method and $\mathbf{L}_{\sigma}$ denotes the luminance transition curve generated by convolving the step function in Figure 1 (c) with the Gaussian blur kernel specified by the standard deviation σ. In addition, $||\cdot||$ denotes the vector norm operation.

In other words, the Gaussian blur kernel can be determined from the estimated luminance transition curve using Equation (6). By applying the calculated Gaussian kernel to a background image, the transmitted image through the transparent plastics can be simulated. Figure 7 illustrates the examples of simulation based on the aforementioned procedure. Figure 7 (a) represents examples of

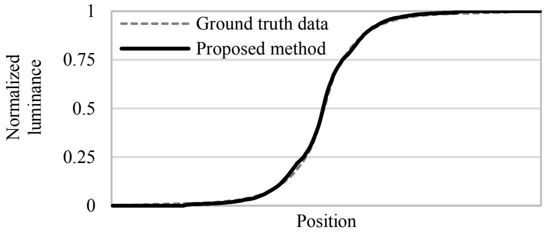


Figure 6. Comparison of the measured and estimated luminance transition curve, $\mathbf{L}_{80,10}$ *and* $\hat{\mathbf{L}}_{80,10}$

Table 2. Averaged error for the interpolation of the luminance transition curves

Training samples	Testing sample	Background distance (cm)					Average
		10	20	30	40	50	
$\mathbf{L}_{80,d}$, $\mathbf{L}_{99,d}$	$\hat{\mathbf{L}}_{7,d}$	1.18	2.77	1.87	3.01	2.24	2.22
$\mathbf{L}_{7,d}$, $\mathbf{L}_{99,d}$	$\hat{\mathbf{L}}_{80,d}$	0.87	1.97	1.70	1.36	2.27	1.64
$\mathbf{L}_{7,d}$, $\mathbf{L}_{80,d}$	$\hat{\mathbf{L}}_{99,d}$	0.62	1.13	2.51	1.93	2.72	1.78

background scenery. Figure 7 (b) and (c) represent the results of the simulations for the different values of the haze and background distances.

4. Conclusion

Transparent displays allow observers to see the visual information on displays overlaid with the object or scenery behind the displays. For this reason, transparent displays have received attention as next-generation displays. If transparent displays can operate in the translucent or opaque modes, their use will be further extended. Transparent plastics that control the transmission of incident lights can provide flexibility in operating mode of transparent OLED displays. This paper presents a new method to estimate the luminance transition curve of the black-and-white patch located behind the transparent plastics. The black-and-white patch is regarded as an object located behind the transparent plastics. Based on the empirical assumption that the luminance level of the diffused light at a given direction is proportional to the value of haze, the luminance transition curves for different values of the haze are estimated. The proposed method can be extended to the imaging chain of the transparent OLED displays and transparent plastics by incorporating the haze and transmittance factor of the OLED displays. Experimental results indicate that the proposed method accurately estimates the luminance transition curve of the black-and-white patch.

Acknowledgement

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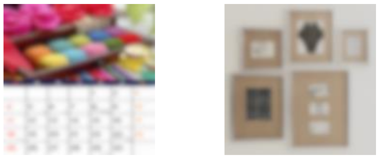
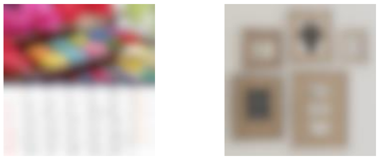
(a) Background images



(b) Results of simulation for h_i = 7% and b_j = 10 cm



(c) Results of simulation for h_i = 80% and b_j = 10 cm

Figure 7. Examples of simulation of the perceived images

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