Enhancing Angular-Dependent Color Performance of TFT-LCDs by Transmittance Scaling

Wei-Chung Cheng, National Chiao Tung University, Department of Photonics and Display Institute, Hsinchu, Taiwan

Abstract

This paper presents an algorithm for minimizing color shift of a liquid crystal display (LCD). In a normally white, twisted nematic-type LCD, the angular-dependent color shift is inversely proportional to its panel transmittance. By increasing the panel transmittance and decreasing the backlight intensity simultaneously, we can reduce the angular-dependent color shift and power consumption at the same time. In this study, first, we characterized the angular-dependent luminance reduction and color shift of a 19" TFT-LCD. Second, we conducted experiments to characterize the human factors of viewing angle variation. Since dynamic range also decreases as the viewing direction increases, tone re-mapping is required. We conducted psychophysical experiments to study the interaction between perceived contrast and brightness of pictorial images. Based on the experimental results, we proposed an algorithm that scales the transmittance of red, green, and blue channels independently subject to image distortion constraints. We implemented the proposed algorithm by prototyping an RGB LED-backlit LCD monitor and driving modules to demonstrate the concept.

Introduction

Color issues are challenging circuit designers with the rising demand for high-quality multimedia applications. One of the driving forces is the blooming flat panel TV market plus the emerging high-definition TV broadcasting. In the next decade, the existing billions of CRT-based TVs are expected to be replaced by flat panel displays such as liquid crystal display (LCD), plasma (PDP), projector, etc. Among these display technologies, the LCD has had the highest market growth in the past years thanks to its form factor, cost, lifetime, power consumption, and color performance. Although the "LCD monitors" (as office appliance for computer output devices) had great success, the "LCD-TV" (as home appliance for entertainment) suffers from the inherent weakness of liquid crystals – color shift. Color shift degrades the image quality and detains purchase decision of consumers.

A TFT-LCD monitor, as shown in Fig. 1, consists of two major components: TFT-LCD panel and backlight module. Each subpixel on the panel can be considered as a voltage-controlled light valve. The light valve modulates the amount of light emitted from the backlight to the red, green, or blue color filter. The TFT-LCD panel transmits light for a bright subpixel and blocks light for a dark subpixel. In other words, in a transmissive display, the desired luminance is obtained by absorbing unwanted light [1].

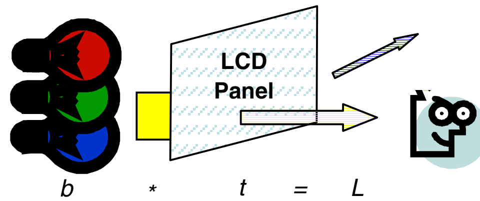

***Figure 1**. Backlight, transmittance, luminance, and light leakage.*

The LCD color shift, caused by the retardation variance of the liquid crystals, is dependent on a number of variables including transmittance, chroma, and viewing angle. For twisted nematic (TN) LCDs, the refraction ratio of liquid crystals depends on the applied voltage (function of graylevel) and wavelength (red, green, or blue subpixel). The LCD color shifts as the graylevel (brightness) or/and the chroma (hue) changes. As the grayscale decreases, the liquid crystals cannot polarize the light effectively. Light starts to disperse into off-axial directions and flatten/widen its spectral distribution, called *light leakage*. The leaked light trespasses the color filters of the adjacent subpixels and generates unwanted color components, which decrease the color saturation and alters the hue, i.e., resulting in color shift (cf. Fig. 2).

***Figure 2**. Left: Luminance/contrast degrades and color shifts as viewing direction increases from 0° to 30° and 60° on a 19" TFT-LCD. Right: The backlight of a green subpixel leaks into its adjacent red and blue color filter and causes color shift.*

Light leakage-induced color shift can be corrected by the LCD controller after carefully characterization followed by compensation for the normal viewing angle (perpendicular to the display surface). However, the LCD color also shifts as the viewing angle changes. This off-axial color shift, called *angular-dependent color shift*, cannot be corrected by tuning the LCD controller solely [1].

To cope with angular-dependent color shift, a number of different approaches have been proposed. Optically, the color shift can be reduced by design optimization of optical films and polarizers. Inside a pixel, the multiple-domain vertical alignment (MVA) design can widen the acceptable viewing angle. Similar solutions include patterned vertical alignment (PVA), advanced super view (ASV), and in-plane switching (IPS) modes [2].

However, very few driving-based approaches have been proposed. Marcu *et al.* proposed a method of compensating for the color shift at different locations [3]. Li *et al.* proposed an idea of dynamically compensating for the color shift according to the viewer's position [4]. These two approaches reduce the color shift based on the viewer's position.

Color Shift Characterization

To measure the angular-dependent color shift for all viewing directions requires a sophisticated instrument. A *ConoScope*™ (autronic-MELCHERS GmbH) can measure the luminance and chromaticity from all possible angles within a hemisphere. Figure 3 shows the luminance measurement results on three different graylevels 75, 135, and 195 of a 19" TN-type TFT-LCD monitor (Viewsonic VX912). The panel was driven by an nVidia GeForce 6600-based 256MB graphics card in a WinTel computer. The luminance and chromaticity of every angle was simultaneously measured and recorded. The measurement sessions were repeated every 15 graylevels from 0 to 255. The upper three contour charts show the distributions of luminance variation. The horizontal cross-sectional distributions (along the 9-to-3-o'clock plane) are shown in the lower three charts. From the charts we observe that the angular-dependent luminance reduction also depends on the graylevel.

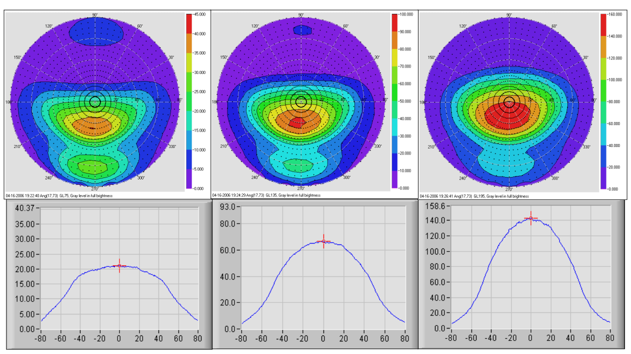

Figure 3. *Luminance vs. viewing direction measured by a ConoScope for on graylevel 75, 135, and 195 (from left to right). The upper and lower charts show the luminance distributions in a hemisphere and on the 9-to-3-o'clock plane, respectively.*

Figure 4 shows the angular chromaticity differences on different graylevels. On graylevel 255, the chromaticity difference is very small near 0° but increases quickly with viewing direction. On the other hand, graylevel 135 has the biggest chromaticity difference near 0° but decreases quickly with viewing direction.

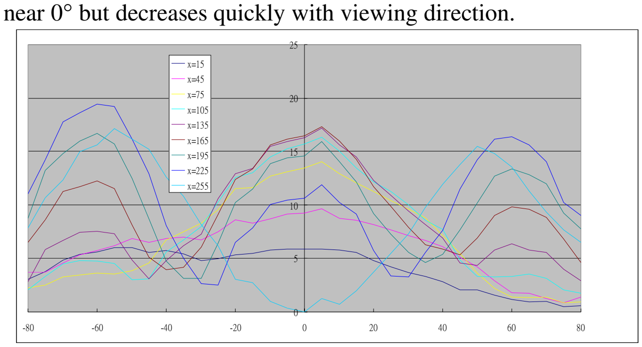

Figure 4. *Angular chromaticity difference on the 9-to-3-o'clock plane on different graylevels.*

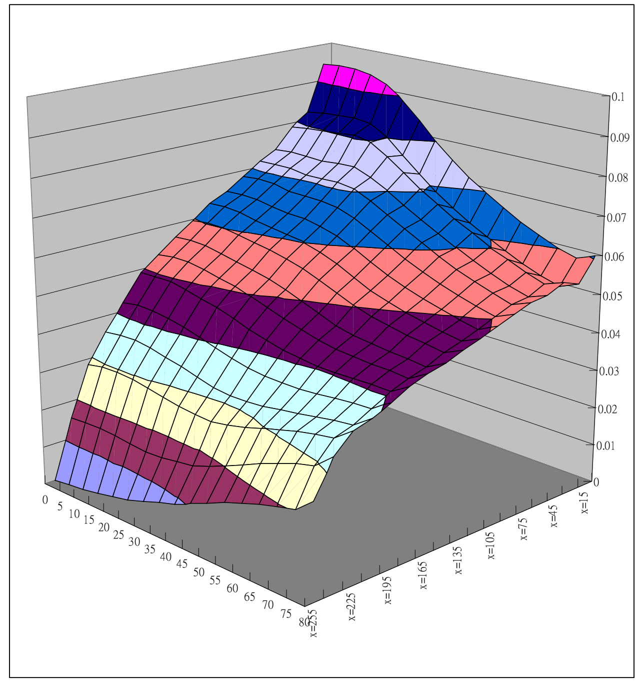

Figure 5. *Angular chromaticity difference on the 9-to-3-o'clock plane on different graylevels.*

We calculated the average chromaticity difference within a solid angle. The results are shown in Fig. 5 as a function of both solid-angle and graylevel. For each solid-angle, the chromaticity difference decreases monotonically with graylevel. For example, the average chromaticity difference of the 30° solid-angle can be modeled by a cubic function of normalized graylevel:

$$\Delta E = -0.2303x^3 + 0.3145x^2 - 0.1846x + 0.1032.$$

Viewing Direction Variation

We conducted two experiments to study the human factors of viewing direction variation in desktop and mobile applications.

The first experiment was for desktop applications. We recorded the subject's face movement while he was performing pre-defined tasks. A 19" TFT-LCD was placed 20" in front of the subject. A reflective glass was placed between the LCD and the subject at 45°. A camcorder was set at the same optical distance to record the subject's face such that the eye positions can be traced. A grid was placed behind the subject for determining his eye position (cf. Fig. 6a). The subject was asked to play a computer game. A sample of the eye tracing during game-playing is shown in Fig. 7. The time course of viewing directions is shown in Fig 8.

Although more experiments are to be conducted to collect data from more subjects on different tasks, our preliminary findings show that the viewing direction variation can be modeled by a Gaussian distribution (cf. Fig. 6b). In other words, the viewing direction is not always centered.

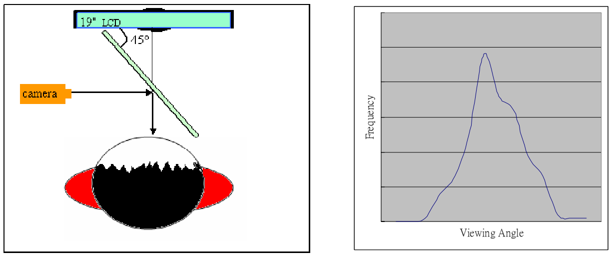

***Figure 6**. (a) Setup for videotaping observer's viewing direction variation. (b) Near-Gaussian distribution of viewing angles.*

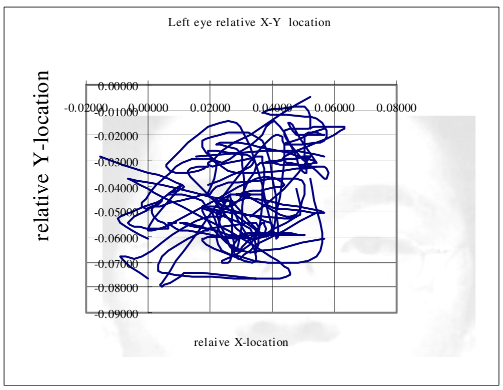

***Figure 7**. Trace of face movement during a game-playing task.*

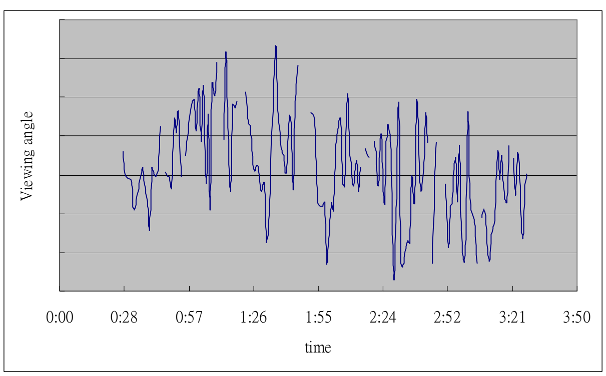

***Figure 8**. Time course of viewing angles of Fig. 7. Its histogram is shown in Fig. 6b.*

The second experiment was for mobile applications. We crafted a simple device to capture the subject's viewing directions during operating a PDA (HP iPaq 6500), which features cell phone and camera. We mounted a camera on the PDA to photograph the subject's eye position. The captured video was then analyzed off-line to calculate the viewing directions. In front of the camera lens, we put a piece of transparency with grid on it such that we were able to figure the coordinates of the subject's eye positions.

The first task was cell phone application. The subject was asked to make a phone call by punching the virtual buttons on the LCD/touch screen with a stylus in his right hand. The trace of viewing directions is shown in Fig. 9. First, when the subject was looking at the display from viewing direction (-10°,-10°) in Cartesian coordinate while dialing the number, the PDA was tilted up-right toward the stylus in his right hand. After dialing, the PDA was raised to ear level and the viewing direction went off chart.

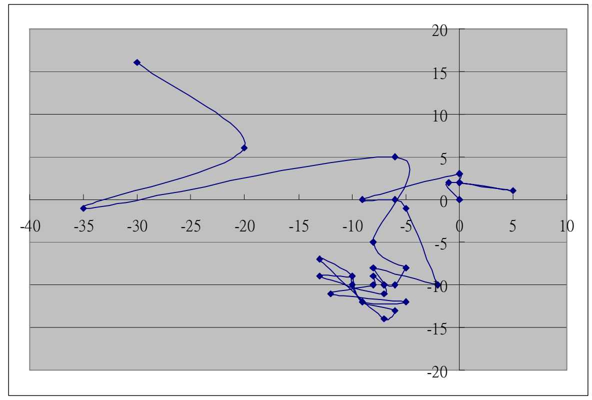

***Figure 9**. Time course of viewing directions during making a phone call with a PDA.*

The second task was camera application. The subject looked at the PDA from (0°, 0°) and taped the touch screen to activate the camera. Then the subject rotated the PDA 90° clockwise to examine the virtual viewfinder on the display (-12°,-10°). Then the subject adjusted the PDA position to compose the image (-25°,-8°). Finally the subject pressed a button to release the shutter followed by returning to the original position (-5°,-3°) to review the captured image.

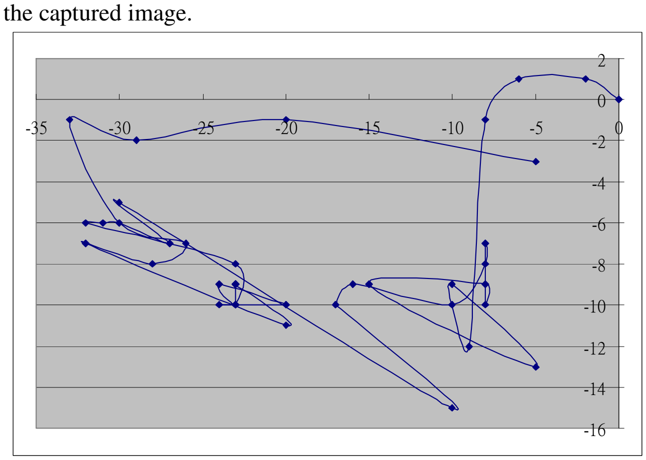

***Figure 10**. Time course of viewing directions during making a phone call with a PDA.*

Based on the experimental results, the viewing direction is not always centered, especially in mobile applications. However, most existing optimization methods and characterizing standards for LCDs focus on normal viewing direction only.

Brightness vs. Contrast

Since dynamic range also decreases as the viewing direction increases, tone re-mapping is required to reproduce decent image quality. We conducted psychophysical experiments to explore new approaches to tone mapping for reduced dynamic range [5].

Psychophysical experiments were conducted with thirty-seven subjects, who were asked to match reduced brightness with increased apparent contrast of complex stimuli. The goal is to establish the relation between perceived brightness and apparent contrast of natural images. Our objective is to answer the following question: When the brightness of an image is reduced, can we compensate for it by increasing its contrast?

The experiments were conducted in a light-proof darkroom, in which the measurable illumination is less than 0.03 lx. A set of six identical LED lights were installed for controlling the surround illumination. Each LED light contains three channels -- red, green, and blue. The luminance and chromaticity of the six LED lights can be controlled freely. The surround illumination was projected on a white screen as the field of view. A pair of identical transmissive 19" TFT-LCD monitors (Viewsonic VX912) was used to display the test images. They were driven by the same computer, and color-corrected by a GretagMacBeth Eye-One XT spectrophotometer.

The psychophysical experiments were performed for three different levels of surround – 0%, 50%, and 100% of the full luminance of the monitors (R/G/B=255/255/255). The original softcopy was displayed by the left-hand-side monitor with 100% of backlighting. The contrast-adjusted softcopy was displayed by the right-hand-side monitor with 70% of backlighting. Thirty-seven subjects were enlisted. Most of them were Asian male, aged from 22 to 28, and have normal vision after lens correction. The subjects were screened by a simple Ishihara Color Deficiency Test, and two of them were excluded as a result.

The experiment started with a 30 seconds period for the subject to adapt to the surround illumination while the monitors displayed gray fields of the same luminance. The subject was asked to match the original softcopy with the contrast-adjusted one. Fechner's *method of limits* was used. A series of differently contrast-enhanced images in ascending/descending order was displayed sequentially. The subject had to decide if the point of isoluminance was reached. The corresponding contrast adjustment at the point of isoluminance was recorded for analysis. The experiments were repeated for three times with surround at 0%, 50%, and 100%.

Figure 11 shows the experimental data as subject count vs. contrast adjustment in the ascending and descending trials for dark surround. The top/bottom curve represents the descending/ascending data. Each point indicates the number of subjects who agreed on the same isoluminant point. Both ascending and descending distributions are near Gaussian with a mean value around 120% contrast-adjustment. It indicates that most subjects agreed on this point of isoluminance. The mean of the ascending trial is greater than that of the descending trial. The reason is the persistence of visual perception, which is common in experiments using the method of limits.

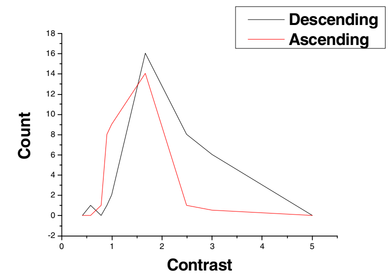

Figure 11*. Subject tally vs. isoluminant contrast scale.*

Transmittance Scaling

The concept of *transmittance scaling* is simply dimming the backlight to conserve power consumption while increasing the panel transmittance to preserve the same luminance. Transmittance scaling is by far the most effective technique for reducing power consumption in a transmissive display. To compensate for the visual quality loss due to reduced luminance, proper image enhancement is necessary. Choi *et al.* proposed a technique that increases the pixel values (t) to recover the original luminance (L) [6].

$$\begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix} = (\alpha \cdot b_W) \cdot \begin{bmatrix} t_R / \alpha \\ t_G / \alpha \\ t_B / \alpha \end{bmatrix} \tag{1}$$

where α is the dimming factor, say 80%. Equ 1 implies that when the backlight is dimmed to 80%, the panel transmittance has to be multiplied by 1/0.8, for example. However, when t/α is greater than unity, the original luminance can not be recovered and image distortion occurs. Choi's algorithm can preserve the luminance of the dark regions, but the bright regions will be over-saturated.

Since preserving the original luminance is not always possible, finding a proper alternative transformation of luminance, $L^*=f(L)$, is the key of transmittance scaling algorithms. Cheng *et al.* proposed an algorithm to compensate for the luminance loss by increasing the contrast [7]. In our work, we used a modified version of Cheng's algorithm. The following linear transformation was used

$$L^* = \begin{cases} 0, & L < gl \\ c(L - gl), & gl \le L \le gu \\ \alpha \cdot b_W, & gu < L \end{cases} \tag{2}$$

$$c = \frac{b_L}{gu - gl}$$

where b_L is the percentage of luminance measured from the viewing direction of interest. The gl and gu are constants generated by the optimization algorithm.

We define image quality as

$$F_C = \sum_{gl}^{gu} f_c(x) \cdot PDF(x), \tag{3}$$

where

$$f_c(x) = \begin{cases} 0, & 0 \le x < gl \\ c, & gl \le x \le gu, \quad 0 \le c \le 1 \\ 0, & gu < x \le 1 \end{cases} \tag{4}$$

and $PDF(x)$ is the probability density function of pixel value x. The power consumption is a function of b_L

$$P(b_L). \tag{5}$$

The objective function is to find the optimal gl and gu that minimize Equ. 5 subject to the given image quality constraint F_C and the attenuated maximum luminance in the given viewing direction b_L.

Prototype System

The proposed system is depicted in Fig. 12. It incorporates a camera, which is a common accessory of portable computers, cell phones, and PDA, along with the face detection software. The user's viewing direction can be obtained once the face location is recognized. The gamma curve can then be adjusted at run-time based on pre-calculated lookup table, which is derived from characterization data from a ConoScope. In our prototype, we used a custom made FPGA board to intercept and manipulate the video signals.

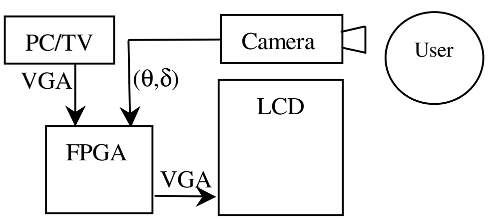

***Figure 12**. Block diagram of the proposed system.*

A notebook PC (Sony Vaio TX650) and a webcam (Logitech QuickCam Notebook Pro) were used to detect the user's face position. A number of free, open-source algorithms and implementations of face detection are available from the Internet. We used Sebastien Marcel's Torch3 vision library (http://www.idiap.ch/~marcel).

We built a prototype backlight module by replacing the two side-lit CCFL backlights with custom made RGB LED backlights for a 19" LCD monitor. Our prototype LED backlights uses top-emitting LED chips. Each LED chip houses four LEDs – one red, two green in series, and one blue (cf. Fig. 13). The three colors were driven separately such that the output chromaticity can be adjusted. Each LED backlight consists of 24 LED chips, wired as 4 parallel sets of 6 serial chips. Each channel is driven by a dedicated current mirror driver on a custom designed PCB. The driving current is controlled by a pulse-width modulation signal [8].

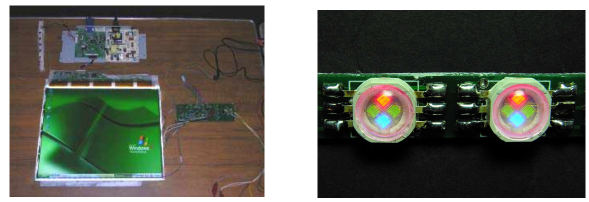

***Figure 13**. Exposed side-lit LED backlights on top and bottom with the driver board (left). An LED chip consists of one red, two green, and one blue LEDs (right), whose spectra are spikier than CCFL's (top).*

Precise characterization of the luminance-to-graylevel relation is the basis of backlight scaling. In the video subsystem of a computer, the luminance-to-graylevel relation can be altered by a number of hardware/software components. First, the color manager in the operating system may modify it by changing the lookup table. Second, the analog video interface such as the VGA connection may attenuate the signal strength. Third, the gamma setting inside the display may modify the mapping again. The other factors such as manufacturing variation and aging of the display cannot be overlooked, either.

In our prototype, the luminance-to-graylevel was characterized and modeled by

$$L(x) = 100.21x^2 + 5.5603x - 0.3411. \tag{6}$$

where x is the normalized graylevel (digital count divided by 255).

To preserve the luminance of x after the backlight dimmed to b, we need to find x' which satisfies

$$b \cdot L(x') = L(x). \tag{7}$$

The mapping between x and x' can be established by consolidating Equ. 6 and 7.

We applied the proposed algorithm to four benchmark images from Corbis™. The simulation results are shown in Table 1. When the color difference constraint of $2\Delta E$ was given, the power savings range from 30% to 40%.

Table 1: Optimal solutions to $2\Delta E$ at 0°

Image	b_R	b_G	b_B	*Power savings*	*Color shift reduction*
veggie	*0.8392*	*0.7412*	*0.5333*	*41.71%*	*16.24%*
dinner	*0.8000*	*0.7725*	*0.7765*	*32.52%*	*9.05%*
wake-boarder	*0.8314*	*0.7686*	*0.8000*	*31.12%*	*7.94%*
pyramid	*0.7765*	*0.7765*	*0.8235*	*30.99%*	*8.45%*

Figure 14 shows luminance vs. digital count of our target LCD when viewed at 0°, 30°, and 45°. The maximum luminance with pixel value 255 decreases from 250.6 nits to 194.83 and 127.03 when viewed at 30° and 45°, respectively. Without proper backlight scaling algorithm, the backlight intensity needs to be increased to 128% and 197% to preserve the original luminance. If we apply a backlight scaling algorithm, then the visual performance can be enhanced with the reduced dynamic range.

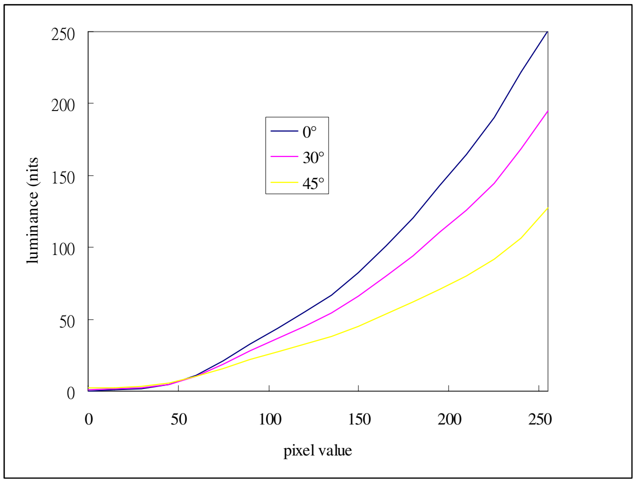

Figure 14. *Luminance vs. digital count at 0°, 30°, and 45°.*

Conclusion

We have measured and characterized the angular-dependent color shift of an LCD. We have also conducted experiments to characterize the human factors of viewing direction variation. Psychophysical experiments have been conducted to study the interaction between perceived contrast and brightness of pictorial images. We have proposed an algorithm and prototyped an RGB LED-backlit LCD monitor to demonstrate the concept.

Acknowledgements

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Author Biography

Wei-Chung Cheng received his Ph.D. from Electrical Engineering-Systems, University of Southern California, Los Angeles, California in 2003. He joined the faculty of Department of Photonics and Display Institute, National Chiao Tung University, Hsinchu, Taiwan as an assistant professor in 2005. His research team, the Perception-Oriented Design Lab (http://color.di.nctu.edu.tw), sponsored by the major LCD panel manufacturers in Taiwan, focuses on color-related problems in LCD design. His research interests include color engineering and power minimization for the video sub-system.