Minimization for LED-backlit TFT-LCDs

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ABSTRACT
This paper presents an algorithm for minimizing power consumption of LED backlights in transmissive TFT-LCD monitors. The proposed algorithm reduces power consumption by scaling the luminous intensity of the red, green, and blue LED backlights independently according to the image histograms of each color channel. The algorithm consists of two phases. The first phase, chromaticity scaling, finds the optimal ratios of red, green, and blue backlights subject to a perceived color difference constraint. The second phase, luminance scaling, finds the optimal dimming factor subject to a perceived lightness difference constraint. The perceived color and lightness differences are measured by the CIELAB Color Difference Equation $2\Delta E^*_{ab}$, a standard metric for measuring color variation. Psychophysical experiments were performed with 35 observers to uncover the optimal luminance scaling function. An experimental LED backlight module was implemented and installed on a 19" side-lit TFT-LCD monitor to replace the original CCFL backlight. Within limited perceivable difference $2\Delta E^*_{ab}$, up to 76% of power consumption can be reduced for the benchmark images.

Categories and Subject Descriptors
I.4.3 [**Image Processing and Computer Vision**]: Enhancement – *grayscale manipulation.*

General Terms
Algorithms, Measurement, Design, Human Factors.

Keywords
TFT-LCD power minimization, LED backlight, chromaticity-luminance scaling, CIELAB color difference.

1. INTRODUCTION
Power consumption has become the critical issue for battery-powered electronics. In literature, researchers have found that the display consumes a major portion of the total power consumption in portable devices, and proposed related low-power techniques [1]. The liquid crystal display (LCD) has been widely used in battery-powered portable electronics such as laptop computers, personal digital assistants, cell phones, global positioning systems, etc. In these portable applications that require small-size displays, the thin-film-transistor LCD (TFT-LCD) technology is favored thanks to its superb image quality, low manufacturing cost, compact size, and low-voltage power source compared with the other display technologies including CRT, plasma, projection, organic/inorganic LED, etc.

1.1 Optical Efficiency of TFT-LCD
A TFT-LCD monitor 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, and energy is wasted in the process. The low optical efficiency of the TFT-LCD panel is the major cause of its high power consumption. Generally speaking, less than 5% of light can be delivered to the viewer, while the rest 95% is wasted in the monitor.

Conventional TFT-LCD monitors use the cold cathode fluorescent lamp (CCFL) backlight. The CCFL needs to be driven by a DC-AC inverter and requires more space. Another reason for not using the CCFL backlight is environmental, because the mercury inside conventional CCFL cannot be effectively replaced yet. The trend of TFT-LCD backlighting is toward using light emitting devices (LED). The LED can produce very narrow spectrum and thus achieve very high color saturation, which was used by the latest LCD-TV to deliver wider color gamut. The LED is driven by DC power without a DC-AC inverter, which was used by ultra-thin sub-notebook PCs and MP3 players like the Apple iPod. Despite its advantages, the current challenge of LED backlighting is its efficiency, cost, heat dissipation, variation, and stable performance.

1.2 Previous Works on Backlight Scaling
The concept of *backlight scaling* – dimming the backlight to conserve power consumption and/or to increase image quality – has been used in the display industry for years. A dynamic backlight control algorithm, for example, was proposed to increase the dynamic contrast ratio of CRTs back to 2001 [1]. Backlight scaling is by far the most effective technique for reducing power consumption in a TFT-LCD monitor. This technique scales down the backlight luminous intensity to save power consumption at the cost of reduced image luminance, which results in lower visual

quality. To compensate for the visual quality loss due to reduced luminance, proper image enhancement is necessary.

Different image enhancement algorithms for backlight scaling have been proposed in the past years. Choi *et al.* proposed a technique that increases the pixel values to recover the original luminance [2]. Choi's algorithm can preserve the luminance of the dark regions, but the bright regions will be over-saturated. The number of over-saturated pixels was chosen to evaluate the image quality loss. Cheng *et al.* proposed an algorithm to compensate for the luminance loss by increasing the contrast [3]. Although the algorithm is a compromise between preserving the brightness and preserving the contrast, it preserves the original *tonality*, i.e. the proportional difference between bright and dark regions. The relationship between brightness and contrast, however, was proposed without substantial support. Iranli *et al.* proposed using *histogram equalization*, an image processing algorithm that balances the number of pixels on each graylevel, to perform the image enhancement [4]. The minimal perceivable radiant flux from a display was calculated from the aspect of human factors by Zhong *et al.* in [5]. The authors concluded that the comfortable reading luminance is seven orders of magnitude larger than the just-perceptible threshold. However, such pure radiometric calculation is oversimplified without considering the other dominating human vision factors such as light adaptation and dark adaptation [6]. For example, for the classical just-noticeable difference (JND) data to be valid, the ambient light cannot be ignored, since the adaptation mechanism of human eyes can change visual sensitivity by five orders of magnitude.

In a nutshell, the principle of backlight scaling is to trade perceived image quality for power savings. In this paper, we employ the results and methods that were well established in vision study and color science to design our proposed backlight scaling algorithm.

1.3 Assess Visual Quality

In color science, a color space usually consists of the one-dimensional *luminance* and the two-dimensional *chromaticity*. For a color, luminance indicates its magnitude, while chromaticity indicates the ratio between red, green and blue. *Colorimetry* is the discipline of determining and specifying colors of objects by standardizing the observer, illuminator, viewing geometry, etc. Most *de facto* color spaces were defined by *CIE*, the International Commission on Illumination. The Euclidean distance between two different colors can be used to measure their *color difference*. However, CIEXYZ is not an ideal color space because the color difference is not perceived uniformly. For example, for the same color difference, a pair of blue colors is perceived more differently than green colors. A more uniform color space, *CIELAB*, was defined by the CIE. The CIELAB ΔE^*_{ab} color difference is defined by

$$\Delta E^*_{ab} = \sqrt{(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})}. \tag{1}$$

The ΔE^*_{ab} color difference is considered as a uniform metric and has been widely used and implemented in commercial colorimeters.

Three luminance-related terms are usually referred to in backlight scaling studies. *Luminance* is a physical measure defined as cd/m^2 (nits). The luminance of an object can be measured by a luminance meter or a colorimeter. *Brightness* is the attribute of a visual sensation according to which an area appears to emit more or less light. *Lightness* is the brightness of an area judged related to the brightness of a similarly illuminated area that appears to be white or highly transmitting [6]. Brightness and lightness are psychophysical terms and cannot be measured by instruments. Intuitively speaking, brightness represents the perceived luminance when there is only a single color in sight, while lightness represents the relative brightness of the color when the reference white is also present. In this paper, we use brightness to describe the perceived quantity of luminance. Brightness is not linearly proportional to luminance, but a power function by *Stevens' law* [7]. In displays, this nonlinearity is amended by gamma correction.

2. Interaction between Brightness and Contrast

In our prior work [8], we designed and conducted psychophysical experiments to establish the relationship between brightness and contrast. In this section, we summarize Cheng's algorithm and our psychophysical results.

2.1 Concurrent Brightness and Contrast scaling (CBCS)

In the CBCS algorithm proposed in [3], the affined transfer of a pixel p_L can be parameterized by

$$CBCS(gl, 0, gu, b_L) \equiv p_L^* = \begin{cases} 0, & p_L < gl \\ c(p_L - gl), & gl \le p_L \le gu, \\ b_L, & gu < p_L \end{cases} \tag{2}$$

where b_L is the backlight factor and

$$c = \frac{b_L}{gu - gl}. \tag{3}$$

The image quality is defined by

$$F_C = \sum_{gl}^{gu} f_c(x) PDF(x), \tag{4}$$

where

$$f_c(x) = \begin{cases} 0, & 0 \le x < gl \\ c, & gl \le x \le gu, \quad 0 \le c \le 1 \\ 0, & gu < x \le 1 \end{cases} \tag{5}$$

and $PDF(x)$ is the probability density function of pixel value x. The objective function of the CBCS algorithm is to find the optimal gl, gu, and b_L that maximize F_C.

2.2 Psychophysical Experiments

The psychophysical experiments were conducted in a dedicated darkroom. Two identical transmissive 19" TFT-LCD monitors (Viewsonic VX912), driven by the same computer and graphics card, were used to display the test images. Two images -- the original one and the adjusted one -- were presented to each observer at a time. The original image was displayed on the left with full backlight intensity. The adjusted image was displayed on the right with 70% of backlight intensity after the following contrast enhancement

$$p_L = MAX\{MIN\{1, (p_L - \overline{m})c + \overline{m}\}, 0\}, \tag{6}$$

$$\overline{m} = 126/255. \tag{7}$$

Totally 37 observers were enlisted as the subjects of the experiment. Most of them were Asian male aged from 22 to 28 with normal lens-corrected vision. The subjects were screened by the Ishihara Color Deficiency Tests. Two observers' data were excluded due to their vision deficiency.

We used *method of limits*, a classical psychophysical method invented by Fechner [9]. Each observer was asked to compare the original image against a series of differently contrast-enhanced images, and to find the most resemble one. The experiment has to be done in ascending order followed by in descending order such that the persistence factors, in this case the adaptation phenomena, can be analyzed. The optimal contrast enhancement picked by each observer, expressed by *c* in Equ (5), was recorded. Fig 1 shows the observer count vs. the optimal contrast enhancement for the ascending and descending trails. Both distributions are Gaussian, representing the variation in individual vision. The mean of ascending distribution is greater than that of the descending distribution, which is due to adaptation and is typical in human perceptional experiments using method of limits. The peak of the distribution is around 1.2, meaning that for the given image, most observers agree on that the optimal contrast enhancement is 1.2 when the backlight is dimmed to 70%, in which conditions the two images have the most resemblance.

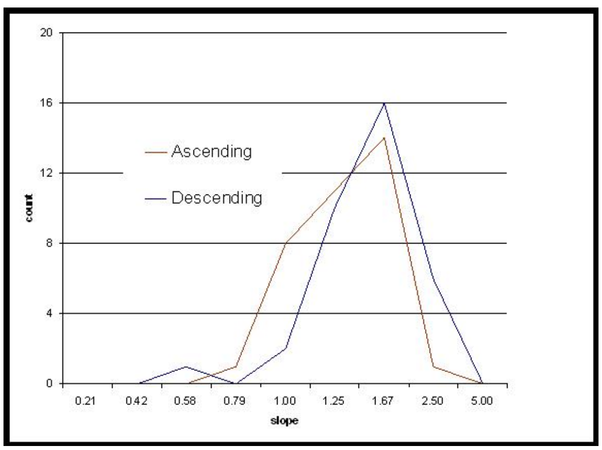

Fig 1: Observer count vs. optimal contrast. Both ascending (red) and descending (blue) experimental data are shown.

To compare our psychophysical results with CBCS, we calculated the image quality of the same image by using Equ (4). The relation between image quality and contrast enhancement is shown in Fig 2. We found high resemblance between Fig 1 and Fig 2. In other words, for the given image, our psychophysical findings are in accordance with the analytical model in [3]. Although further experiments are undergoing for more concrete conclusions, in this work we adopted the CBCS algorithm.

3. LED Backlight

Our prototype LED backlight uses top-emitting LED chips. Each LED chip houses four LEDs – one red, two green in series, and one blue. The three colors were driven separately such that the output chromaticity can be adjusted. The prototype was built on the same 19" TFT-LCD monitors, which use typical *twisted nematic* (TN) liquid crystal mode. Originally the LCD panel has two side-lit CCFL backlights on the top and bottom. We custom made two LED backlights to replace the original CCFL light source. Each LED backlight consists of 24 LED chips, wired as 4 parallel sets of 6 serial chips.

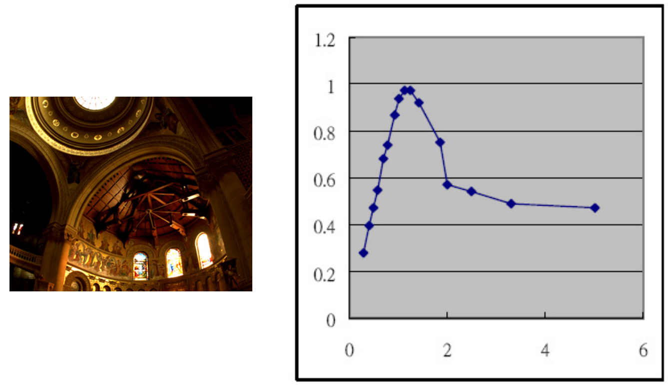

Fig 2: Image quality vs. contrast enhancement.

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.

We performed luminance and power characterization after the LED backlight was installed on the TFT-LCD panel. The colorimetric data were measured by a Konica-Minolta CS-200 chroma meter. Based on the measurement data, the luminance vs. power relation of LED can be modeled by a polynomial function as follows.

$$\begin{aligned} P_R &= 0.00005b_R^2 + 0.0078b_R + 0.3908 \\ P_G &= 0.0002b_G^2 + 0.0208b_G + 1.0809 \quad (Watt), \\ P_B &= 0.00008b_B^2 + 0.0104b_B + 0.6507 \end{aligned} \qquad (8)$$

where b_R, b_G, and b_B are luminance in nits.

4. Chromaticity-Luminance Scaling (CLS)

We propose a backlight scaling algorithm for an LED-backlit TFT-LCD monitor. The proposed algorithm consists of two phases. In the first phase, *chromaticity scaling*, the image is chromatically scaled subject to perceivable colorfulness difference. The optimal ratio of RGB backlights is found to achieve maximum power savings at the same luminance. In the second phase, *luminance scaling*, the luminance is scaled down to achieve maximum power savings subject to perceivable lightness difference.

4.1 Chromaticity Scaling

The motivation of chromaticity scaling is that most images have different distributions in their RGB histograms. To achieve more power savings, the RGB channels can be scaled differently. The side effect of scaling RGB channels differently is color shift. Therefore, we use the color difference defined by Equ (1) to govern the chromaticity scaling. We define the following notation to represent an image after chromaticity scaling.

$$I(b_R, b_G, b_B) \equiv p_{i\in\{R,G,B\}} = \begin{cases} p_i, & p_i \le b_i \\ b_i, & p_i > b_i \end{cases} \qquad (9)$$

When the red, green, and blue backlight are down-scaled from 1.0 to b_R, b_G, and b_B respectively, the red, green, and blue subpixel will be clipped by b_R, b_G, and b_B respectively. We use $\Delta E(I1, I2)$ to indicate the average color difference between the original image I_1 and chromaticity-scaled image I_2. Given Q as the color shift constraint, the following algorithm finds the optimal chromaticity scaling factors that save the most power consumption with the least color shift.

```
Chromaticity_Scaling:
```
$S_R = \Delta E^*_{ab}(I(1,1,1), I(b_R-\delta, b_G, b_B)) / P_R(b_R-\delta);$

$S_G = \Delta E^*_{ab}(I(1,1,1), I(b_R, b_G-\delta, b_B)) / P_G(b_G-\delta);$

$S_B = \Delta E^*_{ab}(I(1,1,1), I(b_R, b_G, b_B-\delta)) / P_B(b_B-\delta);$

Find $MIN(S_R, S_G, S_B)$ *, whose* $\Delta E^*_{ab} \le Q$ *;*

`if (found) then`

Depend on $MIN(S_R, S_G, S_B)$ *, update either* b_R*,* b_G*, or* b_B *with* $b_R-\delta$*,* $b_G-\delta$*, or* $b_B-\delta$ *accordingly;*

```
  goto Chromaticity_Scaling;
else
  return bR, bG, and bB
```

4.2 Luminance Scaling

The original CBCS algorithm is used in the second phase. The RGB backlights are scaled simultaneously by a factor b_L such that no more color shift will be introduced. Since the ratio between the RGB is fixed, this phase is called luminance scaling. The following LED power equation is used instead.

$$P_R(b_L b_R)+P_G(b_L b_G)+P_B(b_L b_B) \tag{10}$$

The transfer functions of chromaticity and luminance scaling are shown in Fig 3.

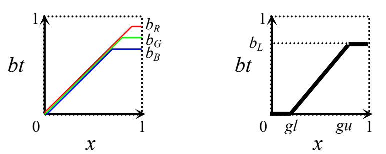

Fig 3: Transfer functions of chromaticity and luminance scaling.

5. Experimental Results

The CLS algorithm was implemented in VHDL on an FPGA board, the Spartan3-based Xilinx Multimedia Development Board. This prototype receives NTSC composite video signal, performs the proposed CLS image processing, and outputs the VGA signal to drive the 19" TFT-LCD monitor. The FPGA also implements the pulse width modulators (PWM) to control the backlight intensity of RGB channels.

We applied the CLS algorithm to the USID benchmark images [10]. The results are shown in Table 1. When the color difference constraint of 2 was given, the power savings of range from 30% to 70%.

Table 1: Optimal solutions for benchmark images subject to $2\Delta E^*_{ab}$

Image#	R	G	B	Power Savings
4.1.01	0.64	0.56	0.46	62.52%
4.1.02	0.46	0.37	0.33	75.65%
4.1.03	0.62	0.57	0.57	56.03%
4.1.04	0.86	0.68	0.68	40.64%
4.1.05	0.68	0.78	0.83	30.07%
4.1.06	0.80	0.80	0.81	28.68%
4.1.07	0.78	0.80	0.64	42.61%
4.1.08	0.77	0.78	0.63	44.05%

6. Conclusions

We have proposed the Chromaticity and Luminance Scaling algorithm for minimizing power consumption of LED-backlit TFT-LCD monitors. The chromaticity scaling is guided by the CIELAB color difference to scale the red, green and blue backlight individually. The luminance scaling is based on the prior Concurrent Brightness and Contrast Scaling algorithm, which was solidified by our psychophysical vision experiments. We prototyped an experimental LED backlight module for characterizing its power consumption in red, green, and blue. The proposed algorithm was implemented by an FPGA board. For the benchmark images, up to 76% power consumption can be reduced.

7. ACKNOWLEDGMENTS

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