Temporal Vision-Guided Energy Minimization for Portable Displays

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ABSTRACT

This paper presents a novel backlight driving technique for liquid crystal displays. By scaling the intensity, frequency, and duty cycle of the backlight, this technique not only increases the perceived brightness but also prolongs the service time of rechargeable batteries. The increased brightness comes from a perceptual effect of temporal vision – a brief flash appears brighter than a steady light of the same intensity, called Brücke brightness enhancement effect. The prolonged service time comes from the relaxation phenomenon – a lithium-ion battery lasts longer by pulsed discharge. Combining these two effects, a great amount of service time can be obtained at the cost of flickering. We performed visual experiments to parameterize the Brücke effect and derived an optimization algorithm accordingly. To demonstrate the potential energy savings of this technique, we profiled the power consumption of an Apple iPod and fabricated an LED driving module. Based on experimental data, 75% of energy consumption can be saved and the service time can be extended to 300%.

Categories and Subject Descriptors

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

General Terms

Algorithms, Measurement, Design, Human Factors.

Keywords

Power minimization, TFT-LCD, temporal vision, backlight management.

1. Introduction

Power consumption has become the most 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. The liquid crystal display (LCD) has been widely used in battery-powered portable electronics such as laptop computers, personal digital assistants, cell phones, and global positioning systems. In these portable applications that require small-sized 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 (tube), plasma, projection, organic/inorganic LED, etc. The low optical efficiency of the TFT-LCD panel is the major cause of its high power consumption.

A TFT-LCD monitor, as shown in Figure 1, consists of two major components: TFT-LCD panel and backlight module. Each sub-pixel 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 sub-pixel and blocks light for a dark sub-pixel. In other words, in a transmissive display, the desired luminance is obtained by absorbing unwanted light, and energy is wasted in the process. Generally, only less than 5% of light can be delivered to the viewer, while the rest 95% is wasted in the monitor. The nominal transmittance rate of each layer (cf. Figure 1) is listed as follows.

Layer	Transmittance
Front polarizer	90%
Color filter	30%
TFT – aperture ratio	80% - 95%
Liquid crystals	95%
Rear polarizer	50%

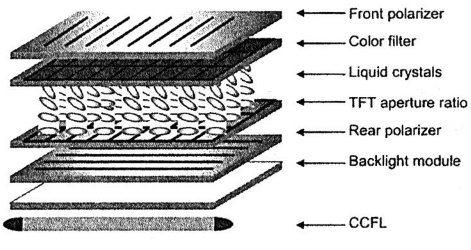

Figure 1. Structure of a CCFL-backlit TFT-LCD panel. From top to bottom: front polarizer, color filters, LC, TFT, rear polarizer, and backlight module.

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More than 50% of light is blocked by the rear polarizer. The *aperture ratio*, representing the area percentage not occupied by the TFTs and wires, depends on the pixel circuit design and can be as high as 95%. About 5% of light is absorbed by the liquid crystals. Each of the red, green, and blue color filters transmits roughly 1/3 of visible wavelength. The front polarizer blocks another 10% right before the light exits the panel. The power consumption of the LCD panel is almost constant so it is independent of the panel transmittance (i.e. pixel value). On the contrary, the power consumption of the backlight is a strong function of its output luminance.

Terminologies

Luminance is a physical measure defined as cd/m^2. The luminance of an object can be measured by a luminance meter. *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. Brightness and lightness are psychophysical terms and cannot be measured by instruments. Intuitively speaking, brightness represents the perceived luminance when there is only one single color in sight, while lightness represents the relative brightness of the color when the reference white is also present [1].

Backlight Luminance Scaling

The luminance of an LCD, L, is the product of the backlight luminous intensity b and the panel transmittance t: $L \cong b \cdot t$. One can decrease the backlight luminous intensity to save the power consumption. The panel transmittance should be increased accordingly such that the luminance remains the same. In addition, for LCDs, higher transmittance can reduce the light leakage problem of liquid crystals and increase the image quality in terms of color saturation and viewing angles.

Consider a pixel consisting of red, green, and blue sub-pixel. Its color is determined by the product of the backlight luminous intensity (b_w) and the transmittance of each sub-pixel (t_R,t_G,t_B):

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

L_R:L_G:L_B is the luminance ratio of red, green, and blue. For example, white is obtained at the ratio of 0.27:0.67:0.06. An LCD generates different colors by changing the transmittance ratio of sub-pixels t_R:t_G:t_B. By increasing (t_R,t_G,t_B), one can lower b_W to save power and preserve (L_R,L_G,L_B). This class of techniques is called *backlight scaling*. Note that (t_R,t_G,t_B) are bounded by [0,1]. When (t_R,t_G,t_B) need to be greater than 1, the original luminance can not be recovered and image distortion in terms of brightness/contrast occurs.

Backlight Scaling Algorithms

Backlight 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) [3].

$$\begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix} = (\alpha \cdot b_W) \cdot \begin{bmatrix} t_R / \alpha \\ t_G / \alpha \\ t_B / \alpha \end{bmatrix} \tag{2}$$

Choi's algorithm can preserve the luminance of the dark regions, but the bright regions will be over-saturated. In their work, the number of over-saturated pixels was chosen to evaluate the image quality loss.

Since preserving the original luminance is not always possible, finding a proper alternative transformation of luminance, $L^*=f(L)$, is the key of backlight scaling algorithms. Cheng *et al.* proposed an algorithm to compensate for the luminance loss by increasing the contrast [4]. The following linear transformation was used:

$$L^* = \begin{cases} 0, & L < gl \\ c(L-gl), & gl \le L \le gu \\ \alpha \cdot b_W, & gu < L \end{cases} \tag{3}$$

where c, gl, and gu are constants generated by the optimization algorithm. Although Cheng's algorithm is a compromise between preserving the brightness and preserving the contrast, it does preserve the original *tonality*, i.e., the proportional difference between bright and dark regions. The relationship between brightness and contrast, however, was employed 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 [5]:

$$L^* = h'(L), \tag{4}$$

where h' is the derivative of the cumulative distribution function of the histogram. Histogram equalization can reproduce each gray level distinctly without over-saturation or under-saturation. However, tonality will be distorted when the original histogram tends to be irregular.

Backlight Blinking

Conventional requirements of backlight design are spatial, temporal, and chromatic uniformity. Recently, the modern LCD technologies call for different backlight driving methods. For example, *backlight blinking* is adopted by LCD-TVs to deal with the *motion blur* problem. Unlike CRT monitors, because of the longer response time of liquid crystals, when steady backlight is used in an LCD, the fast moving edges appear to be blurred and degrade the sharpness of motion pictures. One solution is to pulse-drive (or "blink") the backlight in order to generate CRT-like pulses. According to temporal vision study, a pulse-type display (e.g. CRT) is immune from motion blur than a hold-type display (e.g. LCD).

For a blinking backlight driven by square wave of frequency f, duty cycle d, and intensity b_w, equation 1 can be rewritten as

$$\begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix} = (d \cdot b_W) \cdot \begin{bmatrix} t_R \\ t_G \\ t_B \end{bmatrix}. \tag{5}$$

The duration of each blink is d/f. Although the time-average luminance can be simply determined to be $d \cdot b_w$, the perceived brightness of blinking backlight, however, is not a simple function of luminance.

2. Temporal Vision

A number of temporal visual effects are involved in our study.

Brightness of Flashing Light

The *Talbot-Plateau* law states that the brightness of a temporally modulated stimulus, when fused, is equal to the brightness of a steady light with the same time-averaged luminance. The concept is similar to pulse-width-modulation (PWM). Consider a series of flashes in a square waveform, which can be qualified by its frequency f, duty cycle d, and intensity (magnitude) m. The Talbot-Plateau law recognizes that two flashing lights have the same brightness if $m_1 d_1 = m_2 d_2$. Note that when d=100% the light is steady. In other words, if two flashing lights have the same time-average luminance, they have the same brightness.

The *Broca-Sulzer* effect states that the suprathreshold stimuli, whose duration is on the order of 50-100 milliseconds, appear brighter than stimuli of either shorter or longer durations [6]. This effect was discovered in 1902, when the flashing pattern of lighthouses was of great interest. The findings still inspire the design of electronics nowadays. For example, how to design the flashing pattern of the LED warning indicators of a cell phone such that it can efficiently draw the user's attention with minimum energy. Figure 2 depicts the time course of flashing lights of different intensity.

The Broca-Sulzer effect cannot be intuitively comprehended based on daily visual experience: A longer flash looks dimmer than a shorter flash. For example, "a 50ms light looks dimmer than a 40ms light" means that our visual sensation of a 40ms flash will be subtracted 10ms later. The phenomenon has been revisited by modern techniques and found to be caused by the neural mechanism.

The *Brücke brightness enhancement effect* is that when a light is flickered on and off, its brightness varies according to the frequency of flicker, reaching a maximum over a narrow range of frequencies at approximately 5 to 20 Hz, depending on the intensity of the flickering light [6].

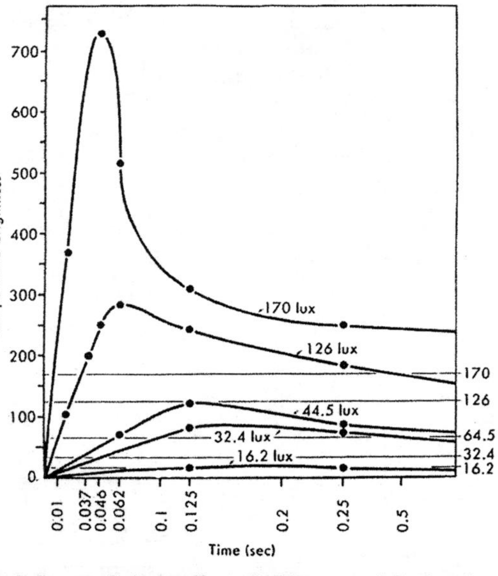


Figure 2. Broca-Sulzer effect: Brightness of flashes having various luminances, as functions of flash duration [6].

Flickering

The *critical flicker fusion frequency* (CFFF) indicates the transition from the perception of flicker to that of fusion occurs over a range of temporal frequencies. The *Ferry-Porter law* predicts that the CFFF increases as the luminance of the flashing stimulus increases:

$$f_{CFF}(L) = a \cdot \log(L) + b. \tag{6}$$

The CFFF is not only a function of luminance, but also the stimulus size (*Franit-Harper law*), wavelength (*Hecht-Shlaer law*), etc. In this paper, only luminance is considered, because the display size is fixed and the colors of displayed image have to be preserved.

3. Experimental Platform

Power/Energy Characterization

To demonstrate our concept, we measured and characterized the power and energy consumption of an Apple iPod®, a globally available portable device which is capable of playing mp3 music and mpeg4-compressed video clips. Its major components include a hard disk drive, an LED-backlit LCD, a lithium-ion battery, a button/wheel interface, and a video processor (cf. Figure 3).

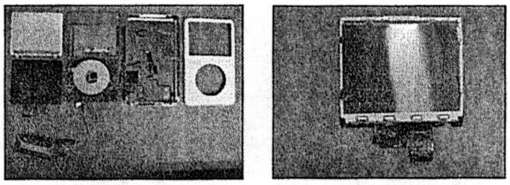


Figure 3. iPod's backlight consists of four white LEDs in series.

Figure 4 shows the power profile of playing a video clip. The spikes in the very beginning occurred when a video clip started to play, where access to the hard disk drive consumed a significant amount of power. The following table lists the power consumed in different states of the 1.8", dual-disk, 4,200 rpm Toshiba MK6008GAH hard disk drive.

State	Power (mW)
Start	1800
Reading, Writing, Seeking	1000 - 1100
Idle	400
Standby, Sleep	7 - 12

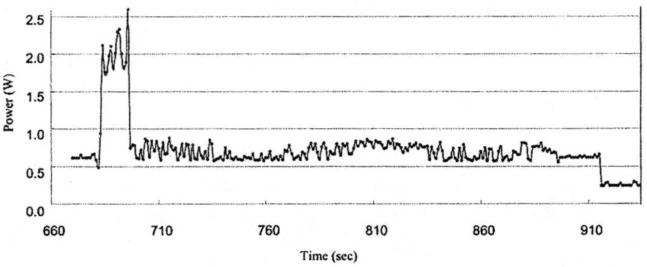


Figure 4. Power profiling of iPod playing a 323-second video clip.

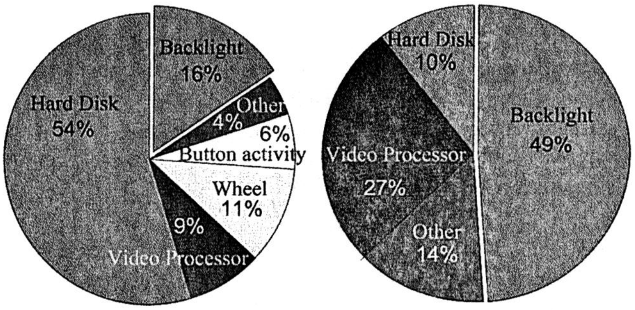


Figure 5. Power (left) and energy (right) breakdown of iPod playing a 323-second video clip. The backlight consumes 49% of total energy.

Although the hard disk drive consumes up to 54% of power spontaneously, compared with 16% by the backlight, it entered the idle state right after the video data was fetched. The right pie chart shows the breakdown of energy consumption. The backlight consumes as much as 49% of the total energy.

We performed luminance and power characterization of the LED backlight by a Konica-Minolta CS-200 chroma meter. The results are shown in Figure 6.

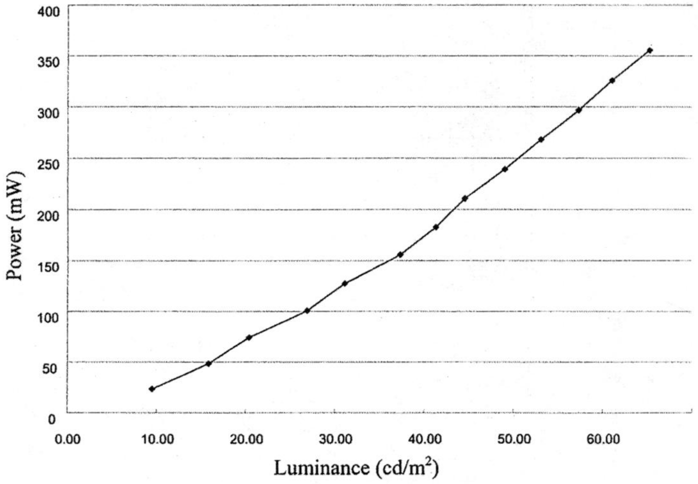


Figure 6. Power vs. luminance of the iPod backlight.

Based on the measurement data, the luminance vs. power relationship can be modeled by the following quadratic function:

$$P = 0.0374b^2 + 3.2194b - 10.5760 \quad \text{(mW)} \tag{7}$$

The *relaxation phenomenon* of lithium-ion batteries is that: after draining an impulse of current, if the cell is allowed to relax long enough, then the concentration gradient decreases and a charge recovery takes place at the electrode [7]. We used the *B#* battery simulator [8] to simulate the relaxation phenomena over a range of different duty cycles. The following parameters were used: V_{init}=4.5V, $V_{\text{cut-off}}$=3.7V, I=0.8A, and $V_{\text{cut-off}}$=3.7V. The simulation results are shown in Figure 7. The battery service time can be modeled by an exponential function:

$$S = 64\cdot(9.5256e^{-2.2885d}) \quad \text{(second)} \tag{8}$$

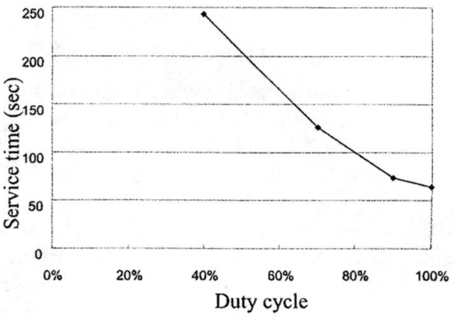


Figure 7. Relaxation phenomenon [7] simulated by the B# battery simulator [6]. Under the given conditions, as duty cycle decreases, the service time increases exponentially.

LED Driver and Illuminance Sensor

We fabricated an LED driving module, which is capable of driving six LED backlights with controllable intensity, frequency, and duty cycle. We also crafted a simple illuminance sensor by using a photoresistor and an analog-to-digital converter IC to detect the ambient light.

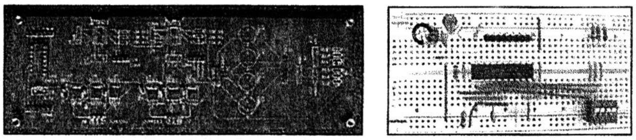


Figure 8. Fabricated LED driving module (left) and illuminance sensor (right).

4. Visual Experiments

We conducted visual experiments to parameterize the Brücke brightness enhancement effect, Ferry-Porter law and the relationship between favorite display luminance and ambient light.

Ferry-Porter Law

The conventional psychophysical *method of adjustment* was used to find the CFFF of three observers in a dark laboratory [2]. The iPod backlight was driven by 50% square waveforms at frequency 20, 25, 30, 35, and 40 Hz. The 4cm*5.5cm backlight was placed 70 cm away from the observer. Each observer was asked to find the CFFF by adjusting the intensity. The results are shown in Figure 9.

By linearly fitting the data to equation 6, the Ferry-Porter law can be modeled as

$$f_{CFF}(L) = 9\log(L) + 28. \quad \text{(Hz)} \tag{9}$$

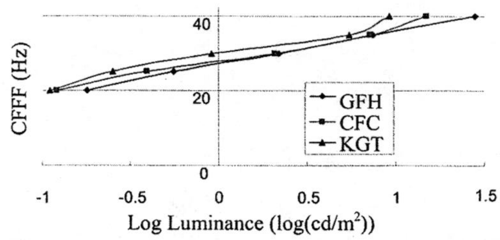


Figure 9. Experimental data of the Ferry-Porter law from three observers as CFFF vs. log(luminance).

Brücke Brightness Enhancement Effect

In the experiment of Brücke effect, two 1-degree white LED lights were placed side by side for the observer to match. One was driven by adjustable constant intensity, while the other was driven by 50% square waveforms over a range of 30, 40, and 50 cd/m^2. Each observer was asked to match the brightness by adjusting the steady light. The results are shown in Figure 10.

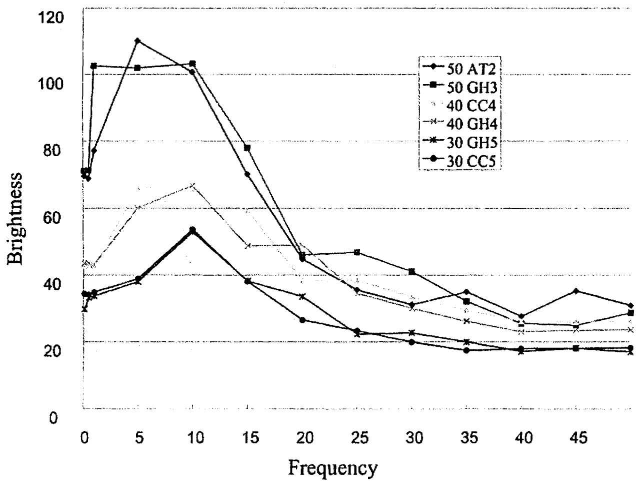


Figure 10. Experimental data of the Brücke effect: Brightness vs. frequency from 3 observers at luminance 30, 40, and 50 cd/m^2.

In Figure 10, flashes with higher intensity have higher brightness. According to equation 9, the CFFFs are 43, 42, and 41 Hz for 50, 40, and 30 cd/m^2, respectively. Beyond 43 Hz, the brightness was about half of the intensity because of the 50% duty cycle. When the frequency approached to zero (DC), the brightness reached about the full intensity. At these low frequencies, the observers could distinct the on-cycles from the off-cycles and chose the high brightness of on-cycles to match. The brightness reached the maximum of about twice intensity around 10 Hz. The frequency range between CFFF and 10 Hz of Figure 10 is redrawn as brightness vs. period in Figure 11.

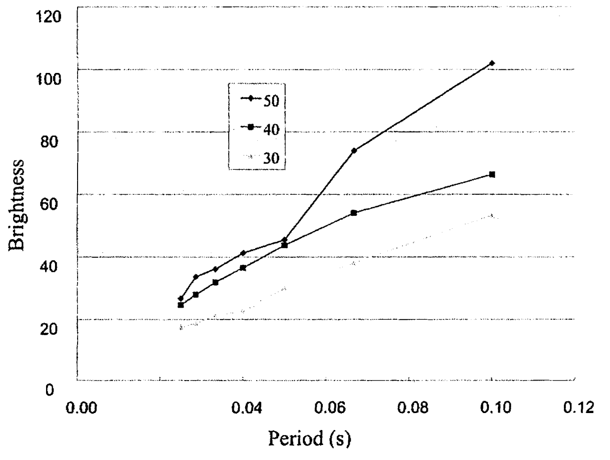


Figure 11. In the range between CFFF (≅ 42 Hz) and 10 Hz, the relationship between brightness and 1/*f* can be linearly approximated.

Summarizing the above observations, we approximate the Brücke effect by:

$$L'_{50\%}(L,f)=$$
$$\begin{cases} L/2, & f_{CFF}(L)<f \\ \dfrac{L}{2}+(\dfrac{1}{f}-\dfrac{1}{f_{CFF}(L)})(\dfrac{3L/2}{0.1-\dfrac{1}{f_{CFF}(L)}}), & 10<f<f_{CFF}(L). \end{cases} \quad (10)$$

Surrounding Effects

The surround luminance is one of the most important factors in visual sensation. When the user adapts to a dark surround, he/she may dim the backlight to the lowest level and still has the full range of lightness and chroma. In the mean time, a considerable amount of power savings is achieved without any side effect. In literature of display ergonomics such as TCO'03, the luminance ratio of display to surround is recommended to be set between 10:1 and 100:1. We conducted visual experiments to find the relationship between favorite display luminance vs. surround luminance. We visited three users in different offices and measured the surround illuminance. The users were asked to perform different tasks at different levels of surround illuminance with their favorite display luminance. If we assume the reflectance of the surround is similar to middle gray (i.e. 18% reflectance, Munsell N5), then the reflected luminance can be estimated as a linear function of illuminance. The results are shown in Figure 12.

The tasks included movie watching, web surfing, and text editing. Generally the favorite display luminance increases linearly as the surround illuminance. The movie watching task had much lower display luminance because the display was driven in the *direct draw* mode. For the same user, text editing had lower display luminance than web surfing in order to reduce eye strain. The curves have different trends in the bright portion (>100 lux) and dark portion (<100 lux). The reason may be the users switching between the photopic mode (light adapted, cone-dominating) and scotopic mode (dark adapted, rod-dominating).

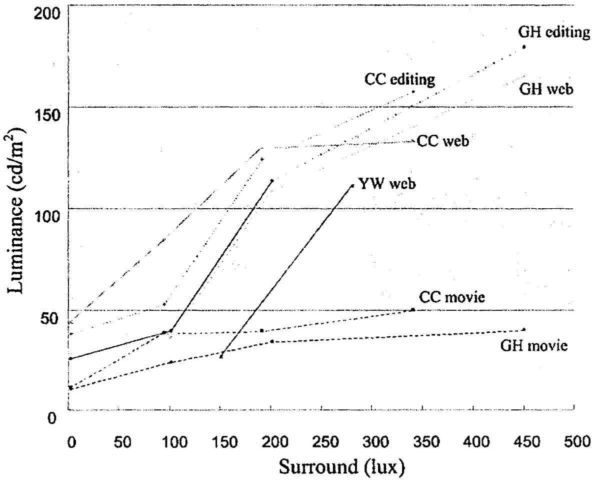
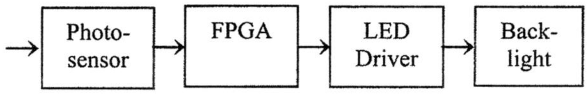


Figure 12. Favorite display luminance vs. surround illuminance of three users on movie watching, web surfing, and text editing.

5. Proposed Algorithm

Based on equation 10, we can reduce the magnitude and frequency of the backlight and still obtain the same brightness. Assume the following system consisting the abovementioned blocks.



For the brightness of a steady light of luminance L, we blink the backlight with the following duty cycle, magnitude and frequency instead:

$$d^* = 50\% \tag{11}$$

$$m^* = L/2 \tag{12}$$

$$f^* = \frac{2}{3} f_{CFF}(L) + \frac{10}{3}. \tag{13}$$

By equation 8 and 10, we can estimate the power consumption and battery service time as follows.

	Baseline	Backlight Scaling	Proposed
Power consumption	100%	50%	25%
Battery service time	100%	235%	314%

When the backlight intensity is reduced to 50%, the existing backlight scaling techniques [3-5] can cut power consumption by 50% and extend battery service time to more than 235%. The proposed technique, on the other hand, can cut power consumption by 75% and extend battery service time to more than 300% while preserving the same brightness at the cost of flickering. The visual effects of different techniques are shown as follows.

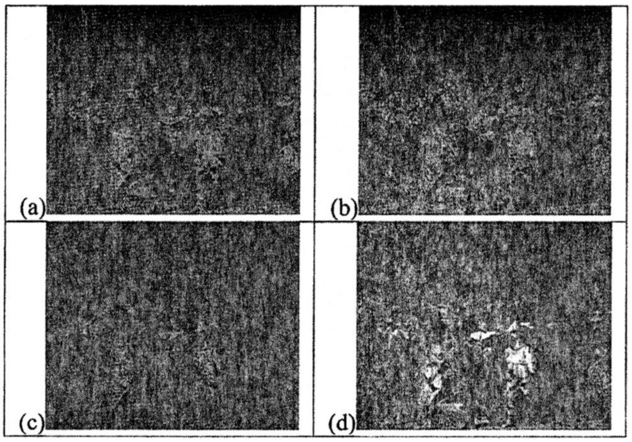


Figure 13. Simulated visual effects of (a) Choi, (b) Iranli, (c) Cheng, and (d) Proposed algorithm without showing the flickering.

Since flickering cannot be reproduced on paper, we suggest the following simple experiment to experience the flickering. Use a CRT monitor driven by analog signals from a computer, in which the refresh rate is adjustable. Note that an LCD, which re-samples the refresh rate, will not do. First, dial the luminance of the CRT (commonly labeled as "brightness" mistakenly) to the maximum, where the flickering is more pronouncing. Shortening the viewing distance can also enhance the perceived flickering. Then adjust the refreshing rate to the point where flickering starts to appear. Let this refreshing rate, say 75 Hz, be the critical fused flickering frequency. To experience a 20% loss in flickering, adjust the refresh rate from 75 to 60 Hz and observe the flickering.

6. Conclusions

We have presented a novel backlight driving technique for liquid crystal displays. By scaling the intensity, frequency, and duty cycle of the backlight, this technique not only increases the perceived brightness but also prolongs the service time of rechargeable batteries. A great amount of energy can be saved at the cost of flickering. We have employed the Brücke brightness enhancement effect from temporal vision and the relaxation phenomenon of lithium-ion batteries. Although the preliminary results are encouraging, this study is still in its infancy. Our future works include developing a metric for measuring the flickering, refining the visual experiments and collecting more data, and implementing the proposed algorithm in FPGA.

7. ACKNOWLEDGMENTS

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