DTM: Dynamic Tone Mapping for Backlight Scaling

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Abstract - This paper proposes an approach for pixel transformation of the displayed image to increase the potential energy saving of the backlight scaling method. The proposed approach takes advantage of human visual system characteristics and tries to minimize distortion between the perceived brightness values of the individual pixels in the original image and those of the backlight-scaled image. This is in contrast to previous backlight scaling approaches which simply match the luminance values of the individual pixels in the original and backlight-scaled images. Moreover, the proposed dynamic backlight scaling approach, which is based on tone mapping, is amenable to highly efficient hardware realization because it does not need information about the histogram of the displayed image. Experimental results show that the dynamic tone mapping for backlight scaling method results in about 35% power saving with an effective distortion rate of 5% and 55% power saving for a 20% distortion rate.

Categories and Subject Descriptors
B.4.2 [Input/Output Devices]: *Image display*
General Terms: Algorithms, Human Factors, Management
Keywords: LCDs, Backlight-scaling, Power Management

1. Introduction

Current generation of portable computers and instruments utilize backlit Liquid Crystal Displays (LCDs.) These displays have also appeared in applications ranging from medical equipment to automobiles, gas pumps and retail terminals. The small size and battery-powered operation associated with LCD equipped apparatus mandate low component count and high efficiency for these circuits. Size constraints place severe limitations on circuit architecture and long battery life is usually a priority. Laptop and handheld portable computers offer an excellent example.

The LCD displays currently available require two power sources, a backlight supply and a contrast supply. The display backlight is the single largest power consumer in a typical portable apparatus, accounting for almost 30-50% of the battery drain with the display at maximum intensity [1]. As such, every effort must be expended to maximize the backlight efficiency.

Study of LCD energy management should consider the problem from an interdisciplinary viewpoint. The backlight presents a cascaded energy attenuator to the battery (cf. Figure 1.) Battery energy is lost in the DC conversion to high voltage AC for driving the Cold Cathode Florescence Lamp (CCFL.) This section of the energy attenuator is the most efficient; where conversion efficiencies exceeding 90% are possible. On the other hand, the CCFL, although it is the most efficient electrical-to-light converter available today, has losses exceeding 80%. Additionally, the optical transmission efficiency of present displays is under 50% for monochrome, with much lower efficiency for color types. Additional improvements in electrical efficiency, while certainly desirable, are reaching the point of diminishing returns. Clearly, overall backlight efficiency gains must come from the lamp and display improvements.

In [2], Chang et. al. proposed *Dynamic backlight Luminance Scaling* technique (DLS) to reduce the energy consumption of the LCD displays. This technique is based on a key idea that eye's perception of the light, which is emitted from the LCD panel, is a function of two parameters, 1) the light intensity of the backlight and 2) the transmittance of the LCD panel. Therefore, by carefully adjusting these two parameters one can achieve the same perception in human eyes at different values of the backlight intensity and the LCD transmittance. However, since the energy consumption of the backlight lamp can be reduced significantly by reducing its intensity, one can save energy by simply dimming the backlight and then compensating the loss of brightness by adjusting the LCD transmittance. However, this approach suffers from two main drawbacks, a) it manipulates every pixel on the screen one-by-one, limiting the application of this approach to still images or low-frame-rate videos; b) It achieves energy saving at the cost of loss in visual information. Reference [3] improved this simple approach by eliminating the pixel-by-pixel transformation of the displayed image through minor hardware modifications to the built-in LCD reference driver. These modifications could implement any single-band grayscale spreading function to improve the brightness and contrast of the displayed image extending the applicability of the approach to streaming applications.

More recently, reference [4] further improved the previous approaches in two aspects. First, by using a global histogram equalization technique to preserve most of visual information, and second, by modifying the architecture of built-in LCD reference driver in order to produce any piece-wise linear image transformation function. This approach has two main disadvantages, a) the empirical distortion characterization curve used in this approach is dependent on the type of the displayed image, e.g. landscape, portrait, and fireworks; b) similar to all of previous approaches this approach also requires histogram information of the displayed image to calculate the image transformation function.

Although all of the aforementioned techniques are considered effective backlight scaling approaches, they overlook a very important deciding factor in their optimization process, that is, the human visual system characteristic. All of these approaches rely on the luminance values of pixels of the displayed image as their optimization variables. However, luminance value of a light source is not the same as its perceived brightness.

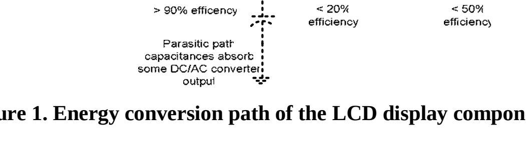

Figure 1. Energy conversion path of the LCD display component.

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This paper proposes a backlight scaling technique which is based on a tone reproduction operator. This operator maps the original image χ to a transformed image $\chi`$ such that the perceived brightness of the image is preserved while its dynamic range is reduced. This reduction in the dynamic range of the image will further increase the potential for backlight scaling, and therefore, maximize the energy saving. Moreover, the proposed operator can be calculated without any information about the individual pixels of the displayed image or its histogram, further improving the video frame-rate and power savings due to elimination of any hardware/software support for image histogram generation.

In the following, the basic background on the human visual system, principles of photographic tone mapping, and finally the TFT LCD architecture and prior work in dynamic backlight scaling will be discussed. Next, in section 3 dynamic tone mapping approach will be explained. Sections 4 and 5 will provide the supporting experimental results and conclusions of this technique.

2. Background and Preliminaries

2.1 Human Visual System

When light reaches eye, it hits the photoreceptors on the retina, which send an electrical signal through nerves to the brain, where an image is formed. The photoreceptors in our retina, namely *rods* and *cones*, act as the sensors for the *Human Visual System* (HVS.) The incoming light can have a dynamic range of nearly 1:10^{14}, whereas the neurons can transfer a signal with dynamic range of only about 1:10^3. The human eye can discern a dynamic range of about 10-12 orders of magnitude. As a result, there is the need for some kind of adaptation mechanism in our vision. This means that we first adapt to some (unchanging) luminance value, and then perceive images in a rather small dynamic range around this luminance value. One of the most important characteristics that changes with different adaptation levels is the *Just Noticeable Difference* (JND.)

The Difference Threshold (or JND) is the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience. Let ΔL and L_a denote the JND and the adaptation luminance, respectively. Blackwell [5] showed that the ratio $\Delta L/L_a$ varies as a function of the adaptation level, L_a and thus, established the relationship between L_a and ΔL to be

$$\Delta L(L_a) = 0.0594 \cdot (1.219 + L_a^{0.4})^{2.5} \tag{1}$$

Simply stated, Blackwell's equation states that if there is a patch of luminance $L_a+\varepsilon$ where $\varepsilon \geq \Delta L$ on a background of luminance L_a, it will be discernible, but a patch of luminance $L_a+\varepsilon$, where $\varepsilon < \Delta L$ will not be perceptible to the human eye.

Let us now consider the brightness perception. *Brightness* is the magnitude of the subjective sensation which is produced by visible light. Although the radiance can easily be measured, the brightness, being a subjective metric, cannot be exactly quantified. Nevertheless, brightness is often approximated as the logarithm of the luminance, or the luminance raised to the power of 1/2 to 1/3 depending on the context. More precise, studies have shown that there is no one single formula, but rather the brightness-luminance relation depends on the adaptation level to the ambient light. In this paper, we will rely on the work of Stevens, which is also extensively used in the field of computer graphics.

Stevens et al. [6] devised the '*brils*' units to measure the subjective value of brightness. According to Stevens, one *bril* equals the sensation of brightness that is induced in a fully dark-adapted eye by a brief exposure to a 5-degree solid-angle white target of 1 micro-lambert luminance.[1] Let B denote brightness in *brils*, L the original luminance value in lamberts, and L_a denote the adaptation luminance of the eye. Then,

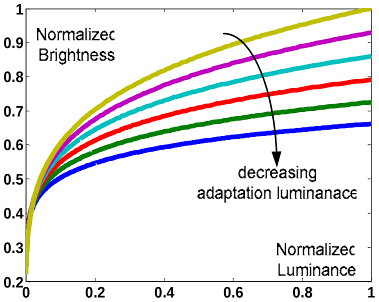

Figure 2. Brightness vs. luminance characteristic of the HVS.

$$B = \lambda \cdot \left(\frac{L}{L_a}\right)^{\sigma} \tag{2-a}$$

where

$$\sigma = 0.4 \cdot \log_{10}(L_a) + 2.92 \tag{2-b}$$

$$\lambda = 10^{2.0208} \times L_a^{0.336}$$

Typical perceived brightness characteristic curves are shown in Figure 2. Note that the slope of each curve represents the *human contrast sensitivity* that is the sensitivity of the HVS brightness perception to the changes in the luminance. Furthermore, as L_a is decreased, the human contrast sensitivity decreases. Finally, the HVS exhibits higher sensitivity to changes in luminance in the darker regions of an image.

Two images with different luminance values can result in the same brightness values, and can appear to the HVS as being identical. Actually, according to equation (2-a) we are very poor judges of an absolute luminance; all that we can judge is the ratio of luminance values, i.e. the brightness.

2.2 Tone reproduction

A classic photographic task is the mapping of the potentially high dynamic range of real world luminance values to the low dynamic range of the photographic print. The range of light that people experience in the real world is vast. However, the range of light one can reproduce on prints spans at best about two orders of absolute dynamic range [7]. This discrepancy leads to the *tone reproduction* problem: how should one map measured/sensed scene luminance to print luminance and produce a satisfactory picture?

The success of photography has shown that it is possible to produce images with limited dynamic range that convey the appearance of realistic scenes. This is fundamentally possible because the human eye is sensitive to relative, rather than absolute, luminance values. Consider a typical scene that poses a problem for tone reproduction in photography, a room illuminated by a window that looks out on a sunlit landscape. A human observer inside the room can easily see individual objects in the room as well as features in the outdoor landscape. This is because the eye adapts locally as we scan the different regions of the

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[1] One lambert is equal to 3,183 cd/m^2.

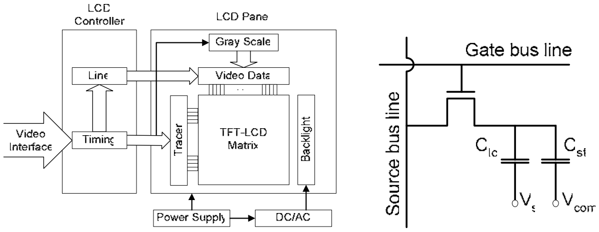
scene. If we attempt to photograph our view, the result is disappointing. Either the window is over exposed and we cannot see outside, or the interior of the room is underexposed and appears dark. In 1993, Tumblin et al. [7] introduced this concept to the computer graphics community and proposed a primitive tone mapping operator. Since then a great deal of work has been done on the tone reproduction. Generally speaking, the tone reproduction literature can be divided into two main categories. The first category of techniques uses a global tone mapping operator, which ignores the spatial information about the luminance of the original scene and adopts a single non-decreasing function as its tone mapping operator. Reference [8] used a model of brightness perception to derive this mapping operator. Reference [9] utilized a global multiplier to maintain the visibility threshold. In reference [11] another global operator was proposed which is based on histogram adjustment. This method used an image histogram to implicitly segment the image so that separate scaling factors can be used in different luminance zones.

The second category of techniques tries to reproduce the visibility of different objects in the scene. This is done through multiple mapping functions which are adopted based on local luminance information of the original scene. Reference by Chiu et al. [10], who used a spatially varying exposure ramp over the image, was the first to propose a spatially varying dynamic range reduction operator. Later work by Pattanaik et al. [12] developed a still image operator based on the HVS, incorporating color adaptation, local contrast, and dynamic range. The basic challenge for a spatially varying tone mapping operator is that it needs to reduce the global contrast of an image without affecting the local contrast to which the HVS is sensitive. To accomplish this, an operator must segment the high dynamic range image, either explicitly or implicitly, into regions that the HVS does not correlate during dynamic range reduction. Otherwise, the local varying operators would result in disturbing "reverse gradients" which are typically observed as halos around light sources. References [13]-0 presented other tone mapping operators which successfully separate the contrast differences that matter to vision from those that do not.

2.3 LCD architecture and Backlight Scaling

Figure 3a shows the typical architecture of an LCD controller and panel. The LCD controller receives the video data and generates a proper grayscale – i.e., transmissivity of the panel– for each pixel based on its pixel value. All of the pixels on a transmissive LCD panel are illuminated from behind by the backlight.

Each pixel has an individual liquid crystal cell, a Thin Film Transistor (TFT), and a storage capacitor (cf. Figure 3b.) The electrical field of the capacitor controls the transmittance of the liquid crystal cell. The capacitor is charged and discharged by the TFT. The gate electrode of the TFT controls the timing for charging/discharging of the capacitor when the pixel is scanned (or addressed) by the tracer for refreshing its content. The (drain-) source electrode of the TFT controls the amount of charge. All of the gate electrodes of the pixels on the same row are driven by a single gate driver (called a *gate bus line*) and are enabled at the same time the row is traced. Similarly, a single source driver (called a *source bus line*) drives all source electrodes of the pixels on the same column. The source driver supplies the desired voltage level (called *grayscale voltage*) according to the pixel value. In other words, ideally, the pixel value transmittance, $t(X)$, is a linear function of the grayscale voltage $v(X)$, which is in turn a linear function of the pixel value X. The transfer function of source driver which maps different pixel values, X, into different voltage levels, $v(X)$ is called the *grayscale-voltage function*. If there are 256 grayscales, then the source driver must be able to supply 256 different grayscale voltage levels.



a. LCD component architecture b. TFT cell schematic

Figure 3. TFT-LCD screen

Mathematically speaking, in a transmissive TFT-LCD monitor, for a pixel with value X, the luminance $L(X)$ of the pixel is:

$$L(X) = b.t(X) \tag{3-a}$$

where $t(X)$ is the transmissivity of the TFT-LCD cell for pixel value X, and $b\in[0,1]$ is the (normalized) *backlight illumination factor* with $b=1$ representing the maximum backlight illumination and $b=0$ representing no backlight. Note that $t(X)$ is a linear mapping from [0,255] domain to [0,1] range. In backlight scaled TFT-LCD, b is scaled down and accordingly $t(X)$ is increased to achieve the same image luminance.

Reference [2] describes two backlight luminance dimming techniques. These techniques dim the backlight and compensate for the luminance loss by adjusting the grayscale of the image to increase its brightness or contrast. More precisely,

$$L(X) = \beta.t(\Phi(X,\beta)) \tag{3-b}$$

where $0<\beta\leq 1$ is the *backlight scaling factor* and $\Phi(X,\beta)$ is the pixel transformation function.

Let x denote the *normalized pixel value*, i.e., assuming an 8-bit color depth, $x=X/255$. The authors of [2] scale the backlight luminance by a factor of β while increasing the pixel values from x to $\Phi(x,\beta)$ by two mechanisms. Clearly, $\Phi(x,\beta)=x$ denotes the identity pixel transformation function. The "backlight luminance dimming with brightness compensation" technique uses the following pixel transformation function:

$$\Phi(x,\beta) = \min(1, x+1-\beta) \tag{4-a}$$

whereas the "backlight luminance dimming with contrast enhancement" technique uses this transformation function:

$$\Phi(x,\beta) = \min(1, \frac{x}{\beta}) \tag{4-b}$$

In these schemes, the optimal backlight factor is determined by the backlight luminance dimming policy subject to the given distortion rate. To calculate the distortion rate, an image *histogram estimator* is required for calculating the statistics of the input image. In this approach there is no consideration for HVS characteristic (cf. sec. 2.1) and only raw image luminance values are used to characterize the image distortion. Note that the image histogram simply denotes the marginal distribution function of the image pixel values.

Reference [3] proposes a different approach in which the pixel values in both dark and bright regions of the image are used to enable a further dimming of the backlight. The key idea is to first truncate the image histogram on both ends to obtain a smaller dynamic range for the image pixel values and then to spread out the pixel values in this range (by applying an *affine transformation*) so as to enable a more aggressive backlight dimming while maintaining the contrast fidelity of the image.

This approach maximizes the number of pixel values that are preserved in order to achieve the minimum image distortion. The main disadvantage of this cost function is that it treats the gray scale values in the dark and white regions of the image the same way, which is in conflict with the perceived brightness characteristic of the HVS as shown in Figure 2. More recently, reference [4] proposed an approach for image transformation, based on the image histogram. In this approach, the dynamic range of the original image is reduced such that the incurred image distortion is no more than a pre-specified value. Then, the backlight scaling technique is used to reduce the energy consumption of the LCD panel.

3. Dynamic Tone Mapping (DTM) for Backlight Scaling

Let $L_{\max}^{orig}$ and $L_{\max}^{DTM}$ denote the maximum luminance of the original image and the dynamically tone-mapped and backlight-scaled image, respectively. Moreover, let χ^{orig} and χ^{DTM} denote the pixel value information of the original and backlight scaled images. Then, the perceived image distortion between images χ^{orig} and χ^{DTM} can be quantified by function $D(\chi^{\mathrm{orig}}, \chi^{\mathrm{DTM}}$.)

Converse Tone Mapping (CTM) Problem: Given an original image χ^{orig} and maximum allowable image distortion D_{max}, find the tone mapping operation $\psi : [0, L_{\max}^{orig}] \rightarrow [0, L_{\max}^{DTM}]$ such that $L_{\max}^{DTM}$ is minimized while

$$D(\chi^{\mathrm{orig}}, \chi^{\mathrm{DTM}}) \leq D_{max} \tag{5}$$

where $\chi^{DTM} \equiv \psi(\chi^{orig})$.

The aforementioned problem is the converse of the tone mapping problem, because in the tone mapping problem, the goal of optimization is to find the mapping operator Ψ such that for a given maximum display luminance, the image distortion is minimized [7]. In contrast, in the CTM problem, the goal of optimization is to find the minimum of maximum luminance value that guarantees a given maximum image distortion level. Unfortunately, due to complexity of HVS,, and therefore the complexity of the image distortion function, *D*, neither the CTM problem nor the tone mapping problem have closed form solutions.

3.1 Preservation of the Perceived Brightness

To solve the CTM problem, this paper proposes a heuristic approach based on *pixel brightness preservation*. The key idea is to make sure that the JND in the backlight scaled image and that in the original image are equal. In this way, the image perception is preserved, i.e., both images have the same discernible details.

Mathematically speaking, let L_a^{orig} and L_a^{DTM} denote the adaptation luminance for the original and the backlight scaled images. Based on equation (1), the JND for the original image is $\Delta L(L_a^{orig})$ and the JND for the backlight scaled image will be $\Delta L(L_a^{DTM})$. Therefore, to preserve the discernible details of the image, we ought to find a tone mapping function, Ψ, such that, $\Delta L(L_a^{DTM}) = \psi(\Delta L(L_a^{orig}))$.

As a simple solution, one can assume a variable scaling function where the scaling factor changes depending upon the local luminance value. Subsequently, the lighter regions of the image will be scaled more non-linearly than the darker regions so as to take advantage of the decreasing human contrast sensitivity from dark to light regions of the image (cf. Sec. 2.2.) However, this approach requires manipulation of individual pixel values, which may be undesirable real-time implementation. Therefore, this paper adopts Ψ, to be a constant scaling function $\psi(x) = \kappa \cdot x$, where κ can be calculated from equation (1) as a function of L_a^{orig} and L_a^{DTM},

$$\kappa = \left(\frac{1.219 + \left(L_a^{DTM}\right)^{0.4}}{1.219 + \left(L_a^{orig}\right)^{0.4}} \right)^{2.5} \tag{6}$$

where L_a^{orig} and L_a^{DTM} may be approximated by half of the maximum backlight luminance before and after backlight scaling, i.e., $0.5L_{\max}^{orig}$ and $0.5L_{\max}^{DTM}$.

Equation (6) represents the key difference between our approach and those reported previously in references [2], [3], and [4]. In those approaches, κ is essentially set as $L_{\max}^{DTM} / L_{\max}^{orig}$ in order to preserve the pixel luminance values, whereas in our approach κ is given by equation (6). In addition, to capture the human contrast sensitivity (cf. Sec. 2.2, Figure 2), we will use a functional form for the transformation function, Ψ, which is similar to that of the human brightness perception function, i.e. (cf. eqn. 2),

$$\psi(\chi^{orig}) = \kappa(L_a^{orig}, L_a^{DTM}) \cdot \left(\frac{\chi^{orig}}{L_a^{orig}} \right)^{\gamma(L_a^{orig}, L_a^{DTM})} \tag{7}$$

where $\kappa(L_a^{orig}, L_a^{DTM})$ is simply the luminance intensity adjustment factor as given by equation (4) and $\gamma(L_a^{orig}, L_a^{DTM})$ is the human contrast sensitivity change between the original image and the backlight scaled image, that is,

$$\gamma(L_a^{orig}, L_a^{DTM}) = \left(\frac{\sigma^{orig}}{\sigma^{DTM}} \right) \tag{8}$$

The motivation behind introduction of parameter $\gamma(L_a^{orig}, L_a^{DTM})$ is to affect large and small luminance values differently. More precisely, if only the $\kappa(L_a^{orig}, L_a^{DTM})$ factor was used, in the transformed backlight scaled image the contrast between two pixels would have been increased uniformly with respect to that of the original image; however, with introduction of $\gamma(L_a^{orig}, L_a^{DTM})$, as the contrast between two pixels in the original image increases the contrast between same two pixels in the backlight scaled image would increase but, grow more slowly for smaller pixel luminance values. Therefore, the result would be a single tone mapping function which takes into account the sensitivity saturation of HVS (cf. Figure 2.)

3.2 Image distortion characterization

To deal with the complexity of image distortion function, *D*, an approach similar to that of reference [4] is used. In this approach, first the image distortion function is characterized for a set of benchmark images as a function of the dynamic range of the tone-mapped images. Next, standard curve fitting tools are used to generate an empirical image distortion curve based on this data. Later, this empirical curve is used as the image distortion function *D* to find the minimum required dynamic range for any given image to achieve the maximum image distortion of D_{max} after tone-mapping.

We have adopted the *universal image quality index* proposed in [16] as our distortion measure and used a set of benchmark images from the USC SIPI Image Database (USID) [17]. The USID is considered the de facto benchmark suite in the signal and image processing research field [18]. Figure 5 depicts the resulting distortion values for these images when the dynamic range of the transformed image is set to twelve different values. Figure 4 is a subset of benchmarks reported to provide a visual reference for the distortion measure. Next, we used standard curve fitting tools provided in MATLAB version 7, release 14 to find the best "average" and "worst-case" global fits to these distortion values. The result is an empirical curve depicted in Figure 5, which maps target dynamic range of transformed images to the observed distortion values.

4. Experimental Results

The CCFL luminance is a complex function of the driving current, ambient temperature, warm-up time, lamp age, driving waveform, lamp dimensions, and reflector design [1]. In our test-bed platform only the driving current is controllable. Therefore, we model the CCFL luminance as a function of the driving current only and ignore the other parameters. Accounting for the saturation phenomenon in the CCFL light source, we use a two-piece linear function to characterize the power consumption of CCFL as a function of normalized luminance:

$$P_{backlight}(\beta) = \begin{cases} A_{lin}.\beta + C_{lin} & 0 \le \beta \le C_s \\ A_{sat}.\beta + C_{sat} & C_s < \beta \le 1 \end{cases} \tag{9}$$

Relationship between the CCFL luminance and the driver's power dissipation for the CCFL in LG Philips transmissive TFT-LCD LP064V1 [19] is shown in Figure 7. The CCFL illumination increases monotonically as the driving power increases from 0 to 80% of the full driving power. For values of driving power higher than this threshold, the CCFL illumination starts to saturate. The saturation phenomenon is due to the fact that the increased temperature and pressure inside the tube adversely impact the efficiency of emitting visible light[1]. After interpolation, we obtain the following coefficient values for the CCFL in LG Philips transmissive TFT-LCD LP064V1:

C_s=0.8234, A_{lin}=1.9600, C_{lin}=-0.2372, A_{sat}=6.9440, C_{sat}= –4.3240.

The hydrogenated amorphous silicon (a-Si:H) is commonly used to fabricate the TFT in display applications. For a TFT-LCD panel, the a-Si:H TFT power consumption can be modeled by a quadratic function of pixel value $x \in [0,1]$ [20]

$$P_{TFT\ Panel}(x) = a.x^2 + b.x + c \tag{10}$$

We performed the current and power measurements on the LG Philips, LP064V1 LCD. During these measurements we set the CCFL backlight luminance to maximum and displayed a full screen rectangle with grayscale level equal to *x*, i.e. R=G=B=*x* for all pixels on the screen. Then, the total power consumption of the display is recorded. Next, these power values are used to derive the parameters of equation (10.) The measurement data are shown in Figure 6. The regression coefficients are thus determined as:

a=0.02449, b= –0.04984, and c=0.993.

To show the effectiveness of DTM approach the power saving for different images from USC SIPI database is reported in table 1. These power savings are generated for three different values of distortion levels. Clearly, by increasing the maximum tolerable distortion level the power saving should increase, which is also confirmed with listed results.

5. Conclusions

In this paper, dynamic tone mapping for backlight scaling with pre-specified image distortion level was proposed. The proposed approach was based on matching of perceived brightness values of the individual pixels in the original image and those of the backlight scaled image. Experimental results showed the effectiveness of DTM method. In future, alternative distortion measures and histograms equalization methods will be evaluated.

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Original	Dynamic range=200	Dynamic range = 100	Original	Dynamic range=200	Dynamic range = 150
					
Normalized power =1	Distortion=4.3% Power saving=36.19%	Distortion=10.6% Power saving=45.24%	Normalized power =1	Distortion=5% Power saving=35.72%	Distortion=12% Power saving=46.49%
					
Normalized power =1	Distortion=3.3% Power saving=37.16%	Distortion=7.4% Power saving=48.28%	Normalized power =1	Distortion=3.6% Power saving=32.21%	Distortion=5.1% Power saving=42.57%

Figure 4.Sample images and their corresponding transformed versions

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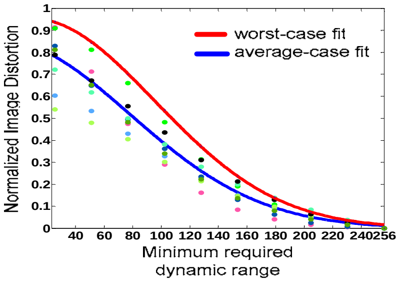

Figure 5. Image distortion vs. Dynamic Range

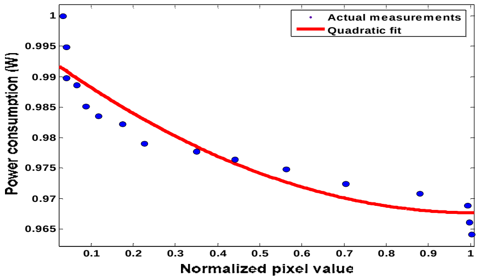

Figure 6. Pixel transmittance, vs. total power consumption of the TFT-LCD panel

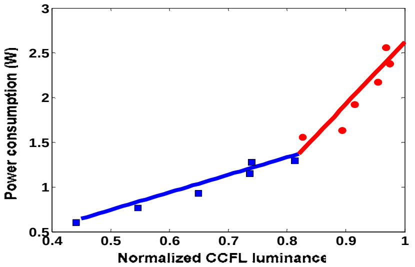

Figure 7. Normalized CCFL luminance vs. power consumption

	Power saving (%)		
Name	**Distortion = 5%**	**Distortion = 10%**	**Distortion = 20%**
Lena	37.43	49.28	59.52
Autumn	35.16	49.20	61.53
Football	36.62	45.85	55.57
Peppers	36.60	44.34	56.55
Greens	35.33	45.26	53.58
Pears	37.51	47.16	54.49
Onion	34.26	48.21	60.53
Trees	36.69	44.31	54.62
West	38.52	51.18	57.50
Pout	32.57	43.22	49.54
Sail	32.33	39.18	46.51
Splash	36.55	47.20	53.53
Girl	36.45	45.30	52.52
Baboon	39.52	46.10	52.51
TreeA	31.53	40.98	49.52
HouseA	35.49	48.15	53.48
GirlB	35.65	51.28	52.59
Testpat	37.53	48.22	53.54
Elaine	36.33	45.18	55.50
Average	35.88	46.16	54.38

Table 1. Power saving for different distortion levels