Image Enhancement for Backlight-Scaled TFT-LCD Displays

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***Abstract*— One common way to extend the battery life of a portable device is to reduce the LCD backlight intensity. In contrast to previous approaches that minimize the power consumption by adjusting the backlight intensity frame by frame to reach a specified image quality, the proposed method optimizes the image quality for a given backlight intensity. Image is enhanced by performing brightness compensation and local contrast enhancement. For brightness compensation, global image statistics and backlight level are considered to maintain the overall brightness of the image. For contrast enhancement, the local contrast property of human visual system (HVS) is exploited to enhance the local image details. In addition, a brightness prediction scheme is proposed to speed up the algorithm for display of video sequences. Experimental results are presented to show the performance of the algorithm.**

***Index Terms*— Contrast, image enhancement, LCD backlight, power management.**

I. Introduction

Batteries with limited amount of energy often power new generations of portable devices such as PDAs, smart phones, and media players; therefore, it is important to develop techniques to increase battery lifespan. For portable devices, power saving can be achieved by: 1) power-aware IC circuit design of controllers; 2) low-power digital/analog interface between the graphics controller and the LCD controller; and 3) efficient control of the light source of liquid crystal display (LCD). The first approach puts emphasis on increasing the efficiency of dc/ac power inverters, decreasing working voltage and frequency, limiting the power consumption in the idle mode, and shutting off unused digital/analog circuits [22]. The second approach uses encoding schemes that minimize the switching traffic of the electrical bus during transmission to reduce power consumption [1], [2]. The third approach focuses on controlling the backlight of LCD to lower the power consumption of display system. Since the light source of LCD accounts for a significant percentage of the total power consumption, reducing the intensity of backlight can effectively extend the battery life.

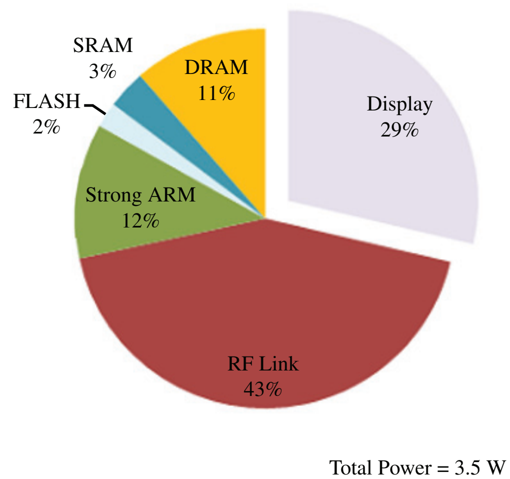

Fig. 1. Power distribution of an example embedded portable system.

For a typical portable handheld device, cold cathode fluorescent lamp (CCFL)—the main light source of TFT-LCD—consumes 20–50% of the total system power [6], (Fig. 1), [23]. Unfortunately, the LCD has to be continuously refreshed and cannot be turned off or put into sleep mode during the operation. Thus a sensible way to reduce the power consumption of LCD is to dim the backlight.

However, reducing the backlight degrades brightness and contrast (and hence the fidelity) of the image. Here the image fidelity is defined as the resemblance of the backlight-scaled image to the original image. There is no fidelity loss if the backlight-scaled image is identical to the original image. Since the reduction in backlight affects the visual experience, it is important to compensate the loss of image quality for backlight-scaled LCDs.

Image compensation is based on the idea that the eye's perception of the light emitted from the LCD panel (that is, the luminance of the LCD) is the product of: 1) intensity of the backlight, and 2) transmittance of the pixel [3]. Therefore, the LCD luminance under low backlight can be driven to the same level as that under full backlight by raising the transmittance. Since the adjustment of transmittance has little effect on the energy consumption, we can save power by dimming the

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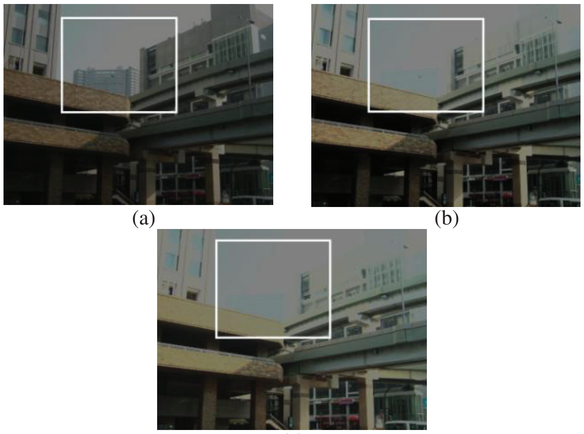


(a) (b) (c)

Fig. 2. Images under dim (50%) backlight. (a) Without enhancement. (b) CBCS. (c) QABS.

backlight and, in the mean time, compensating for the loss of LCD luminance by increasing the transmittance.

Two approaches to image enhancement for backlight-scaled LCD have been developed. One minimizes the power consumption of LCD backlight subject to a constraint on image quality [3]–[5]. The other optimizes the image quality for a given LCD backlight level.

The first approach boosts the pixel value based on the property that the LCD transmittance monotonically increases with pixel value [5]. In this approach, an image quality constraint is imposed, and pixels with high intensity are clipped after boosting if they exceed the range of color depth, resulting in the loss of details in high-intensity regions.

Many methods of the first approach can be found in the literature. Choi *et al*. proposed a method that increases the pixel value to recover the luminance [3] and evaluates the image quality degradation based on the number of clipped pixels. This method achieves power saving at the cost of visual quality. The concurrent brightness and contrast scaling (CBCS) method [6] truncates both ends of the image histogram to obtain a smaller dynamic range for the image, then stretches pixels in this range to the full range. Due to the truncation of the histogram, the method may remove image regions of high intensity, as illustrated in Fig. 2(b) where the building inside the box is lost. Liang *et al*. [5] incorporated an objective quality distortion function (mean square error) into a backlight switching strategy and proposed a quality-adaptive backlight scaling (QABS) scheme. Like CBCS, this method also suffers from the loss of image details, as shown in Fig. 2(c). Moshnyaga *et al*. [4] designed a power management method for LCD displays by detecting user's attention and setting the display to sleep or to the off mode if the user is not looking at the screen. To manage the power of a battery-operated multimedia system. Chang *et al*. [13] used a different image enhancement method for each power mode. Brightness compensation is used for the high-power mode and contrast enhancement for the low-power mode. Iranli *et al*. [12] proposed a temporally aware backlight scaling (TABS) method that exploits the just noticeable difference property [24] of human visual system (HVS) to minimize the distortion between the perceived brightness of the original image and that of the backlight-scaled image.

The second approach, on the contrary, does not dynamically adjust the backlight according to the image content. Rather, they work under a fixed backlight level or power mode determined by the user or the portable device. The algorithm proposed in this paper belongs to the latter approach.

Our algorithm attempts to preserve the contrast (rather than brightness) and exploits the unsharp mask [17] and bilateral filter [20] that decomposes an image into high- and low-frequency components. The local contrast property of HVS and the image characteristics are taken into consideration in the design of the algorithm, which preserves image details in both bright and dark regions. The algorithm is applicable to video sequences as well, for which the computational efficiency is critical since the data must be processed in real time. A preliminary version of this paper is described in [25].

The paper is organized as follows. In Section II, we introduce the principle of LCD display and backlight scaling techniques. The details of the proposed algorithm are described in Section III. Experimental results and performance evaluations are presented in Section IV. Finally, the summary is given in Section V.

II. Background

In this section, we review the local contrast property of the HVS, which is the basis of our algorithm, and describe the characteristics of LCD display. Then we discuss previous backlight scaling methods and compensation formulas.

A. HVS

The photoreceptors, namely rods and cones, on the retina, perceive the light hitting the eye and act as the sensors for our visual system [12]. Cones are divided into three types, red, green and blue, which are responsible for color vision at photonic levels of illumination (10^{-2}–10^{8} cd/m^2) [14] and are less sensitive than rods. Rods, which are sensitive to light, are responsible for visual perception in dim light (10^{-6}–10 cd/m^2) and do not contain color vision. The neurons can transfer a signal with a range of only around three orders of magnitude, and the range that the human eye can adapt is enormous, on the order of 10^{10}–10^{12}.

Therefore, we need a mechanism that enables our visual system to adapt to a certain luminance value and perceive images in a rather small dynamic range around this luminance value. The behavior of the adaptation mechanism to the variation of luminance depends on the local mean luminance for any given set of conditions, and such property, called "light adaptation" or "luminance masking" [9], is exploited in this paper.

The perceptual intensity of a stimulus is related to the absolute intensity of its surrounding luminance [21]. More precisely, according to Weber's law [8], [10], the difference ΔR in response is proportional to the relative luminance increase ΔL and inversely proportional to the absolute luminance L

$$\Delta R \propto \frac{\Delta L}{L}. \tag{1}$$

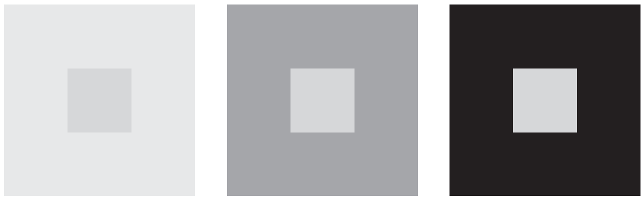


Fig. 3. Example of simultaneous contrast: The three inner squares have the same intensity, however, they appear progressively lighter as the background becomes darker.

Thus the perceptual response to an image under a different illumination can be maintained by keeping $\Delta L/L$ constant.

Furthermore, as illustrated in Fig. 3, the simultaneous contrast phenomenon of HVS shows that a region's perceived brightness does not depend simply on its intensity [14]. Although the perceptual quality of an image under dim light can be maintained by image enhancement, the absolute intensity of the enhanced image does not have to be identical to that of the original image viewed under normal backlight. The proposed algorithm exploits such a phenomenon as well.

B. Characteristics of LCD

A careful review of the LCD architecture is required before we tackle the backlight scaling problem. Fig. 4(a) shows a typical architecture of the LCD controller and panel [12]. The LCD controller receives the video data and determines a proper grayscale—i.e., the transmittance—for each pixel based on its pixel value.

Depending on the light source, there are three kinds of LCD displays. One is reflective LCD, which uses ambient light and a reflector instead of the backlight but is unsuitable for quality display. Another is transflective LCD, which requires the backlight and the ambient light to operate in a complementary way. The third one, which is what this paper is concerned about, is transmissive LCD that illuminates all pixels from behind. Unlike the other components in portable devices, the light source of transflective or transmissive LCDs cannot be shut down to prolong battery life. When the backlight is turned off, transmissive LCD displays nothing and transflective LCD delivers poor display quality.

The common light source of LCDs for portable devices is CCFL. Consider, for example, the new-generation HP iPAQ 2790 with 3.5″ display. Its power consumption monotonically increases with the backlight intensity, and the backlight consumes 50–60% of the total power [see Fig. 4(b)].

The amount of backlight passing through a pixel is controlled by the transmittance. To observers, a pixel looks dark when its transmittance is low and bright when its transmittance is high. Thus, as the backlight is reduced, the reduction of illumination can be compensated by scaling up the transmittance.

As shown in Fig. 4(c), each pixel of an LCD is composed of a liquid crystal (LC) cell, a thin-film transistor (TFT), and a storage capacitor [19]. The LC cell lies between the TFT substrates and the color filter substrate and rotates to different angles to control the transmittance. The TFT, a switching device, controls the number of electrons flowing into the capacitor, whose electrical field controls the transmittance of the LC cell.

For color LCDs, a color pixel consists of three sub-pixels: red, green, and blue [15]. Fig. 4(d) shows the *RGB* strip arrangement of pixels on an LCD screen [19]. The light emitted from these three sub-pixels is added to produce the desired color.

C. Principle of LCD Luminance

The luminance of a transmissive TFT-LCD perceived by eyes is determined by two parameters: backlight intensity and transmittance. More specifically, the luminance L for a pixel of value X (which can be red, green, or blue) is the product of its transmittance $t(x)$ and the backlight intensity B [7]

$$L = B \cdot t(x) = B_{\max} \cdot b \cdot t(x) \tag{2}$$

where $B_{\max}$ is maximum backlight, x denotes the normalized pixel value (with 8-bit color depth, $x = X/255$), and $b \in 0, 1$ is the backlight factor, with $b = 0$ representing no backlight and $b = 1$ the full backlight. Note that $t(x)$ is a linear mapping from the range [0, 1] to the range [0, 1]. Equation (2) indicates that the transmittance can be scaled up to maintain the luminance as the backlight is reduced.

D. Transmittance Scaling

Brightness compensation of an image is accomplished by transmittance scaling. Assume that the pixel value is increased from x to x' to compensate for the reduction of backlight. An identity transform function [Fig. 5(a)] results if $x' = x$. The scaling of transmittance can be performed in two ways, each leading to a different transform function [5]. One way is to increase the pixel value by the amount of luminance loss $1 - b$

$$t(x') = \min(1, x + 1 - b) \tag{3}$$

as shown in Fig. 5(b). The other way is to maintain the luminance L and boost the pixel value by

$$t(x') = \min(1, x/b) \tag{4}$$

as shown in Fig. 5(c). In either way, the range of pixel values that can be completely compensated is determined by the backlight factor b. At a given backlight intensity, the same transform function is applied to all images regardless of the difference in image characteristics. Oversaturated pixels are clipped, resulting in the loss of image details. This is illustrated in Fig. 6, where higher intensity regions lose more details because they have more oversaturated pixels.

Cheng *et al*. [7] propose a different approach that truncates high-end g_u and low-end g_l of the image histogram and stretches the pixels within these two bounds to the full range [0, 1] to maintain the contrast [Fig. 5(d)]. Pixels are scaled by

$$t(x') = \begin{cases} 0, & 0 \le x \le g_l, \\ cx + d, & g_l \le x \le g_u, \\ 1, & g_u \le x \le 1 \end{cases} \tag{5}$$

where

$$c = \frac{1}{g_u - g_l} = \frac{1}{b}, \tag{6}$$

$$d = \frac{-g_l}{g_u - g_l}. \tag{7}$$

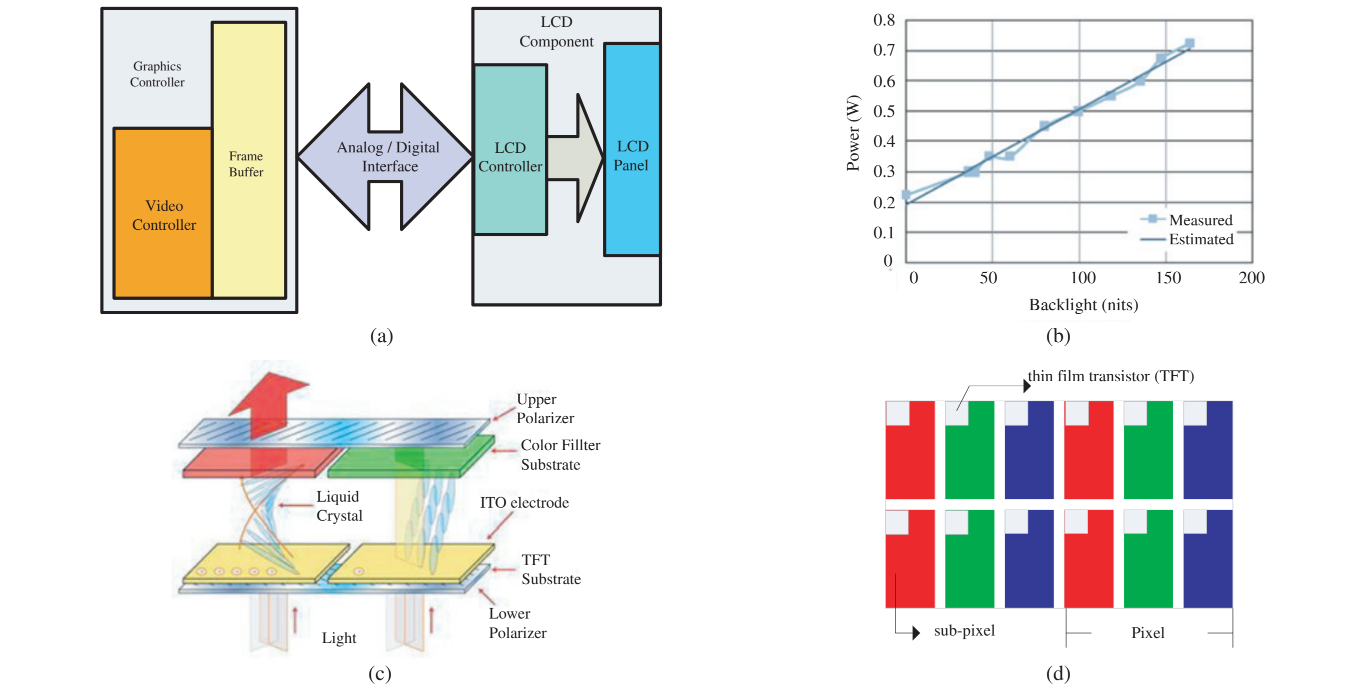


Fig. 4. (a) LCD system architecture. (b) Power consumption versus backlight intensity of a PDA. (c) LCD as a voltage-controlled light switch [18]. (d) Spatial color synthesis of LCD.

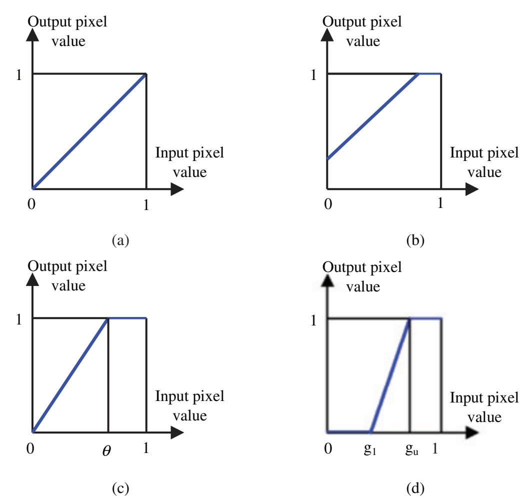


Fig. 5. Pixel transformation functions. (a) Identity. (b) Grayscale shift. (c) Grayscale spreading. (d) Single-bound grayscale spreading.

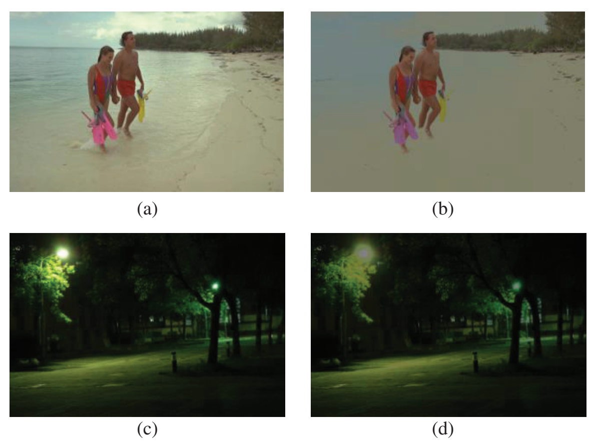


Fig. 6. Image enhancement by grayscale spreading. (a) Original image, average pixel intensity =151. (b) Enhanced image of (a) under 50% backlight. (c) Original image, average pixel intensity = 27. (d) Enhanced image of (c) under 50% backlight.

However, such pixel truncation destroys details in high- and low-intensity regions. An improved method is described next.

III. Proposed Algorithm

Existing transform functions for transmittance scaling are applied to the pixels of an image uniformly without taking the local contrast property of the HVS into consideration. As a result, pixels of the same intensity, regardless of location, remain equal in intensity after the transformation. This is inconsistent with the local contrast property of the HVS and may introduce image distortion, especially in regions with clipped pixels.

Recall that the goal of our method is to enhance the image under a given backlight intensity, which is either manually selected by the user or automatically determined by the portable device. Each image has to be processed only once. In contrast, previous methods attempt to search for a proper backlight intensity that yields satisfactory image quality. Each image needs to be processed a number of times before the appropriate backlight intensity level is found. Therefore, such methods are more sensitive to the computational cost of image operations, and introducing local image operations would worsen the problem. A new method is needed.

To exploit the local contrast property of the HVS, an image is decomposed into two layers, the base (low-frequency) layer and the detail (high-frequency) layer, in our algorithm

Fig. 7. Two-scale decomposition of the input intensity: (a) original image, (b) base layer, and (c) detail layer.

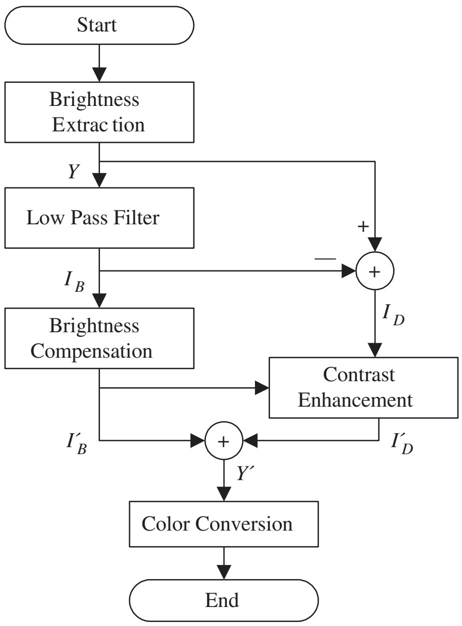


Fig. 8. Flow chart of the proposed algorithm.

by low-pass filtering the image in the spatial domain. The base layer contains the smoothed image, while the detail layer contains image details. A bilateral filter has been used for image decomposition [20]. For computational efficiency, however, a simple low-pass filter is used instead. An example of the decomposition is shown in Fig. 7.

In the base layer, we determine the transform function (one for the entire image) to compensate for the reduction of backlight. Pixels are clipped as the transform function is applied to the image. However, unlike previous methods that use brute-force pixel clipping, our method clips the pixels according to the image characteristics and the given backlight level to minimize the loss of image details.

In the detail layer, we boost the local contrast of the image in accordance with the local contrast property of HVS. The final image is the superposition of the resulting base layer and detail layer images. The flowchart of the proposed algorithm is shown in Fig. 8, and the details of the algorithm are described in the following.

A. Brightness Extraction and Decomposition

The first step of our algorithm extracts the brightness Y of an input color image from its *RGB* components

$$Y = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B. \tag{8}$$

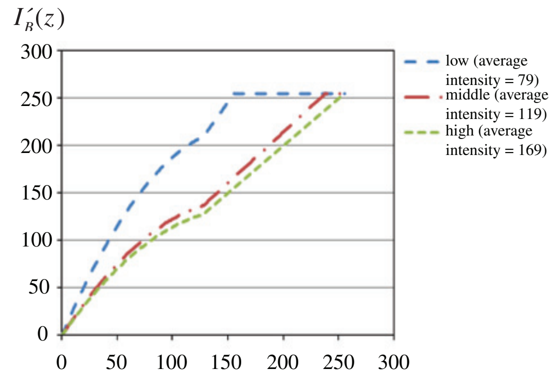


Fig. 9. Transform functions for images with different average intensities. For low average intensity, the clipping threshold can be set lower, and vice versa.

The brightness image is then decomposed into two layers by a 3 × 3 low-pass filter

$$\begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} \tag{9}$$

which is an approximation of the Gaussian filter. The response of the low-pass filter to the brightness image is the base layer image I_B. The difference between the original brightness image Y and the base layer image I_B is the detail layer image I_D

$$I_D = Y - I_B. \tag{10}$$

Then, brightness compensation and contrast enhancement are applied to I_B and I_D, respectively.

B. Brightness Compensation

In the second step of the algorithm, a transform function is determined and applied to scale up the magnitude of the base layer image. To preserve the image brightness as much as possible, clipping is applied to the bright pixels only, not to the dark pixels. Therefore, there is only one clipping threshold θ, and it is in the high pixel value range (see Fig. 9). The task here is to determine θ and the shape of the transform function. Pixels over θ are scaled up and clipped to 255, and the ones below θ are scaled up in a linear or quadratic fashion without clipping.

We compute the average image intensity μ of the image and determine the threshold θ based on μ and the backlight factor b. Depending on μ, we classify images into three groups, high intensity, low intensity, and middle intensity, and assign a different threshold for each group

$$\theta = \begin{cases} \theta_{\min}, & \text{if } \mu < 64, \\ (\mu - 64)\,\frac{(\theta_{\max} - \theta_{\min})}{128-64} + \theta_{\min}, & \text{if } 64 \le \mu < 128, \\ \theta_{\max}, & \text{otherwise} \end{cases} \tag{11}$$

where $\theta_{\min} = 255 \cdot b$ and $\theta_{\max} = 255$. When μ is low, the image has relatively few high-intensity pixels. Therefore, a low θ allows most pixels of the image to be effectively compensated to higher values (and hence higher image brightness). When

μ is over 128, the image is relatively bright, so setting θ to 255 prevents clipping and hence avoids any loss of image details for high-intensity regions. When μ is in the middle range, θ is a linear function of μ. Here the range [64, 128] is determined empirically.

Let the value of the base layer image at a pixel z be $I_B(z)$. Then the transform function is of the following form

$$I'_B(z) = \begin{cases} \frac{2}{3} \cdot (m(I_B(z) - \theta_{\min})^2 + n) \\ \quad + \frac{1}{3} \cdot (255 \cdot I_B(z)/\theta), & \text{if } I_B(z) \le \theta_{\min}, \\ \frac{255-n}{\theta-\theta_{\min}}(I_B(z) - \theta_{\min}) + n, & \text{if } \theta_{\min} < I_B(z) \le \theta, \\ 255, & \text{otherwise} \end{cases} \tag{12}$$

$$n = 255 \cdot \frac{\theta_{\min}}{\theta} \tag{13}$$

$$m = \frac{-n}{\theta_{\min}^2} \tag{14}$$

where $I'_B(z)$ is the response of the transform function. In other words, the base layer image $I_B(z)$ is scaled up to $I'_B(z)$ after the brightness compensation. Note that when $I_B(z) \le \theta_{\min}$, the base layer image is scaled up more aggressively to compensate for the backlight reduction.

C. Contrast Enhancement

The third step of the algorithm performs contrast enhancement by applying Weber's law [1], [8] to the image. As described in Section II-A, the perception of local contrast at a pixel depends on the relative brightness of the pixel with respect to its surrounding pixels. In our algorithm, the base layer image works as the reference, and the detail layer image as the relative brightness difference, for the local contrast measurement. Let the value of the detail layer image at a pixel z be $I_D(z)$. Then the local contrast at z can be computed by

$$\frac{I_D(z)}{I_B(z)}. \tag{15}$$

Since $I_B(z)$ is adjusted to $I'_B(z)$ after the brightness compensation, the following relationship must hold to maintain the local contrast

$$\frac{I_D(z)}{I_B(z)} = \frac{\zeta(z)}{I'_B(z)} \tag{16}$$

where $\zeta(z)$ is the adjusted difference at z. Since $I_B(z)$, $I'_B(z)$, and $I_D(z)$ are known, $\zeta(z)$ can be easily obtained by

$$\zeta(z) = \frac{I_D(z)}{I_B(z)} \cdot I'_B(z). \tag{17}$$

The luminance of the display is scaled down by b under dim backlight; therefore, $\zeta(z)$ must be scaled up by 1/b for the perceptual brightness difference to remain constant. The value of the detail layer image at z becomes

$$I'_D(z) = \zeta(z)/b \tag{18}$$

and the enhanced brightness image $Y'(z)$ can be obtained by

$$Y'(z) = I'_B(z) + I'_D(z). \tag{19}$$

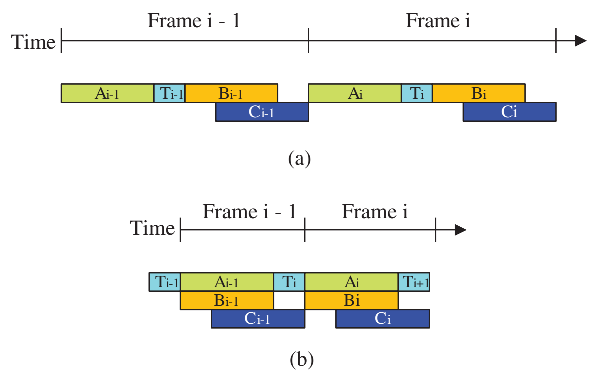


Fig. 10. Speedup of video processing. (a) Original scheme. (b) Modified scheme. Ai is the time for accessing frame I and computing its average intensity, Bi for brightness compensation using transform function Ti, and Ci for contrast compensation. Ti in (b) is obtained by using the average intensity of frame i-1 and Ti in (a) by using the average intensity of frame i.

D. Color Conversion

The final step of our algorithm restores the color components by maintaining the ratio between the three color components. Let $[R', G', B']^T$ and $[R, G, B]^T$ represent the color components of the final image and the original image, respectively. Then

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} Y'/Y & 0 & 0 \\ 0 & Y'/Y & 0 \\ 0 & 0 & Y'/Y \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{20}$$

E. Speedup of Video Enhancement

The processing of image data in the algorithm described so far involves two passes. In the first pass, the algorithm accesses the image, calculates the average image intensity, and computes the transform function. In the second pass, the algorithm accesses the image data again and performs bright and contrast compensations, as shown in Fig. 10(a), where the transform function that is needed for brightness compensation is obtained from the first pass. The algorithm can be extended to enhance video data displayed on TFT-LCDs. However, the main issue here is computational efficiency because the processing of each video frame has to be completed within a frame time. Our current implementation of the algorithm on a general PC allows us to process 11 frames of VGA video per second. In this section, we describe a method for improving the computational efficiency of the algorithm. Further platform-dependent optimization of the algorithm, although definitely possible, is beyond the scope of this paper. Nevertheless, the complexity of the algorithm per pixel is shown in Table I.

The speedup is achieved by simplifying the original two-pass algorithm to one-pass. The basic idea is to use the average intensity of the previous frame as a prediction of the average intensity of the current frame when computing the transform function; the remaining process of the algorithm remains the same [Fig. 10(b)]. This way, the operations of the second pass are merged into the first pass, and the image data access is performed once instead of twice.

This prediction is achieved by taking the average intensity of the previous frame. To start the prediction process, the

TABLE I
COMPLEXITY PER PIXEL

Algorithm	Instruction	Multiplication	Addition	Division	Shift
Step 1	Brightness extraction	3	2	0	0
	Low-pass filter	0	8	0	6
	High-pass filter	0	1	0	0
Step 2	Intensity averaging	0	1	0	0
Step 3	Contrast enhancement	1	1	2	0
Step 4	Color conversion	3	0	1	0
Total		7	13	3	6

following default transform function is used for the first frame

$$I'_B(z) = \begin{cases} \frac{I_B(z)}{b}, & \text{if } I_B(z) \le \theta_{\min}, \\ 255, & \text{if } I_B(z) > \theta_{\min} \end{cases} \tag{21}$$

where b is the given backlight factor.

The underlying assumption of the prediction method is that the average intensity varies slowly from frame to frame. This assumption allows us to accelerate the video enhancement algorithm. While the assumption is valid for most video sequences, it may become invalid at, for example, scene changes. When this occurs, the performance of the transform function for brightness compensation may be affected due to the inaccuracy of average intensity prediction, but only limited to the first frame after the scene change. The local contrast boosting is not affected. In practice, the effect of inaccurate transform function at a single isolated frame is mostly unnoticeable for video sequences. Overall, the proposed average intensity prediction represents a good tradeoff between speedup and performance, and our experiment on a 2-GHz PC shows that it increases the output video rate from 11 to 25 frames/s for video of VGA size.

IV. Experimental Results

A set of 11 images [see Figs. 11, 12(a), and 14(a)] taken by the authors are tested to compare the proposed image enhancement algorithm against QABS [7], CBCS [6], and TABS [12]. In order to prevent color transformation from affecting the results, we apply the same color transform function to all algorithms. The output images of these four algorithms on a test image under 50% backlight are shown in Fig. 12 and zoomed up in Fig. 13. Similar results are obtained for the other test images. All tests show that our algorithm outperforms the other algorithms especially in preserving the image detail of high-intensity regions.

The proposed algorithm is also tested under different backlight intensities. Figs. 14 and 15 show the results under 50% and 70% backlight. Clearly, the enhanced images [Fig. 15(c) and (e)] have higher image fidelity than the images without enhancement [Fig. 15(b) and (d)].

Note that our algorithm does not attempt to recover the original image intensity. Rather, it focuses on the preservation of local details while compensating for the brightness reduction. As a result, it produces images with perceptual quality better than those methods that only attempt to minimize the intensity error between the output-enhanced image and the original image.

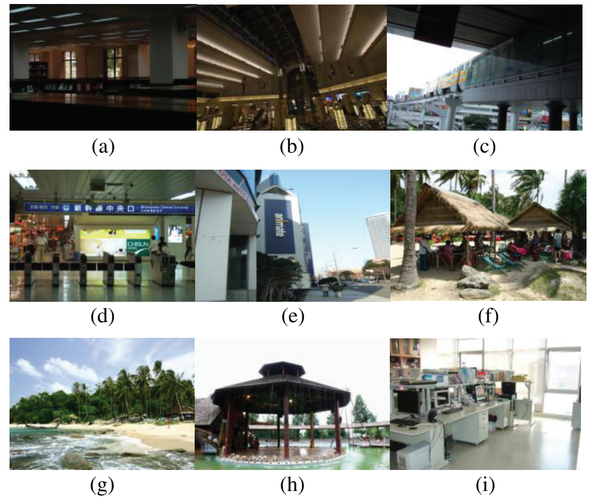


Fig. 11. Additional test images. (a) Library. (b) Department. (c) Train. (d) Station. (e) Building. (f) Island. (g) Seacoast. (h) Park. (i) Lab.

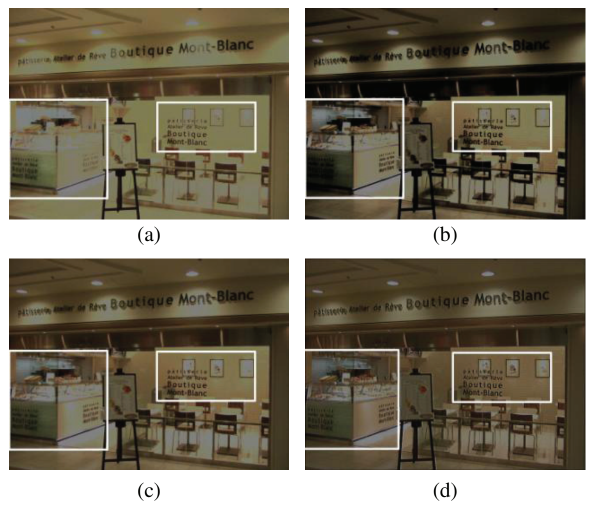


Fig. 12. Performance comparison under 50% backlight for test image "restaurant." (a) QABS. (b) CBCS. (c) TABS. (d) The proposed algorithm.

To have a quantitative measure of the performance, we design two metrics to measure the degree of edge preservation, one employing the Sobel operator (Fig. 16) and the other the just noticeable difference (JND) algorithm [11]. The former calculates the edge loss rate ε_E defined as the ratio between the number of missed edge pixels ψ_{Em} and the number of original edge pixels ψ_{Ei}

$$\varepsilon_E = \frac{\psi_{Em}}{\psi_{Ei}}. \tag{22}$$

Here, a pixel is declared to be a missed edge pixel if it is an edge pixel in the original image but not in the enhanced image.

The second metric employs the JND algorithm for edge pixel classification to compute the edge loss rate ε_D

$$\varepsilon_D = \frac{\psi_{Dm}}{\psi_{Di}} \tag{23}$$

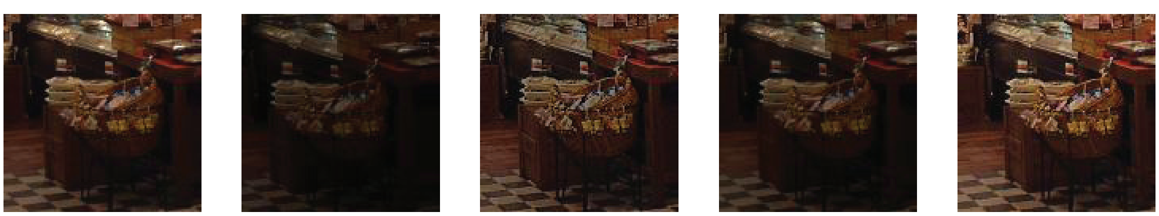
(a) (b) (c) (d)

Fig. 13. Zoom-in images of the left box (top) and the right box (bottom) in Fig. 12. (a) QABS. (b) CBCS. (c) TABS. (d) Proposed algorithm.

(a) (b) (c)

(d) (e)

Fig. 14. Performance evaluation of the proposed algoritm under different backlight levels for test image "shop." (a) Original image under full backlight. (b) Original image under 50% backlight. (c) The proposed algorithm under 50% backlight. (d) Original image under 70% backlight. (e) The proposed algorithm under 70% backlight.



(a) (b) (c) (d) (e)

Fig. 15. Detailed images of the regions marked in Fig. 14. (a) Original image under full backlight. (b) Original image under 50% backlight. (c) The proposed algorithm under 50% backlight. (d) Original image under 70% backlight. (e) The proposed algorithm under 70% backlight.

where ψ_{Dm} is the number of missed edge pixels and ψ_{Di} the number of original edge pixels.

Tables II and III show the two edge loss rates for the four algorithms under 50% backlight. We can see that, in general, as the average intensity increases, the preservation of image details decreases. Also, on the average, the proposed algorithm achieves more than 10% improvement over the other three algorithms.

We also measure the two average edge loss rates defined by (22) and (23) for video sequences generated by the fast

1	2	1
0	0	0
-1	-2	-1

(a)

1	0	-1
2	0	-2
1	0	-1

(b)

Fig. 16. Two kernels of sobel operator. (a) X-direction. (b) Y-direction.

TABLE II
EDGE LOSS RATE ε_E (%)

Name	Average intensity (μ)	CBCS	QABS	TABS	Proposed
Library	43	11.52	11.52	35.34	11.39
Department	64	23.90	24.45	39.57	22.52
Shop	78	24.55	26.98	41.72	19.61
Train	92	33.42	34.04	37.52	19.18
Station	97	20.89	23.59	42.35	22.73
Island	112	39.17	43.77	50.24	27.64
Restaurant	119	21.42	42.35	36.45	28.49
Building	142	50.18	45.23	39.83	27.00
Seacoast	144	49.65	46.58	47.19	29.40
park	148	43.83	48.19	47.46	29.44
Lab	161	40.71	55.03	41.65	31.06
Average		32.66	36.52	41.76	24.45

TABLE III
EDGE LOSS RATE ε_D (%)

Name	Average intensity (μ)	CBCS	QABS	TABS	Proposed
Library	43	13.75	13.75	36.22	8.89
Department	64	25.00	23.36	37.31	18.06
Shop	78	28.72	27.26	43.36	12.48
Train	92	36.75	37.03	40.61	14.02
Station	97	30.24	27.35	52.88	22.29
Island	112	40.19	41.72	37.23	13.94
Restaurant	119	41.44	48.85	45.63	30.7
Building	142	57.98	50.11	43.37	25.39
Seacoast	144	53.96	43.47	37.35	14.40
park	148	50.41	48.92	40.47	17.46
Lab	161	57.24	60.10	45.45	29.02
Average		39.61	38.36	41.81	18.79

TABLE IV
AVERAGE EDGE LOSS OF VIDEO SEQUENCES (%)

	ε_E		ε_D	
Name	Before Speedup	After Speedup	Before Speedup	After Speedup
Bus	8.27	8.27	10.00	10.00
Character	8.91	8.91	19.80	19.80
Crew	13.97	14.00	11.30	11.29
Harbour	32.32	32.31	6.82	6.82
Mobile	20.59	20.61	6.85	6.85
Sailormen	20.91	20.91	9.08	9.08
Flower Garden	32.83	32.79	8.72	8.72

video enhancement scheme described in Section II-E. A total of seven video sequences are tested under 50% backlight. The average edge loss rates are shown in Table IV. We can see that the objective video quality remains almost the same before and after the speedup. Sample frames of one of the test sequences are shown in Fig. 17 for comparison of subjective video quality.

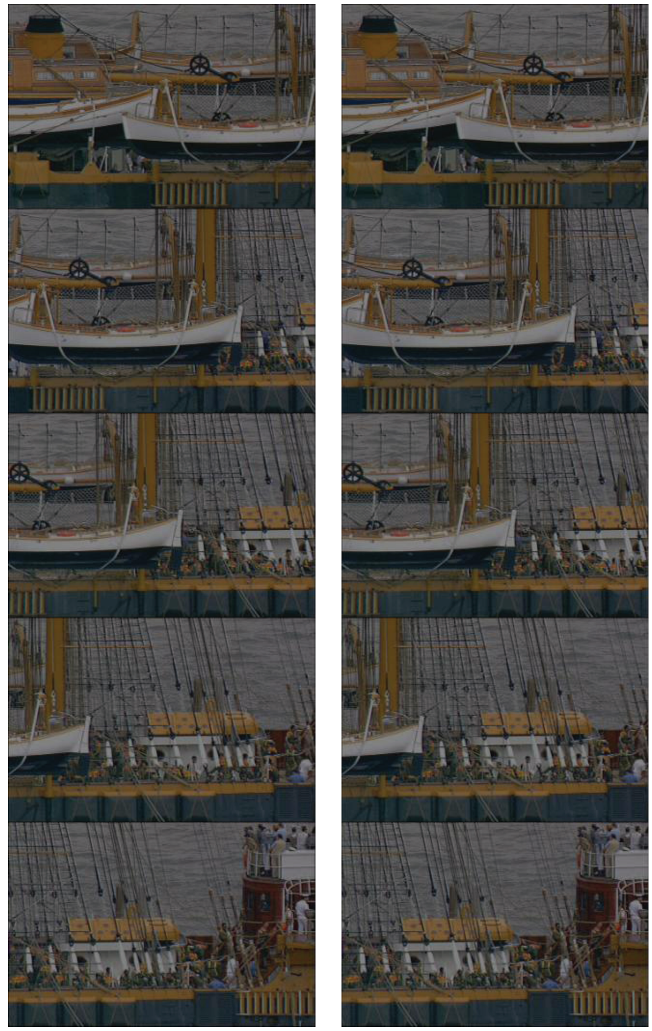


Fig. 17. Sample frames of two video sequences before and after speedup under 50% backlight original scheme (left column) and modified scheme (right column).

V. CONCLUSION

We have presented an image enhancement algorithm that exploits the property of the HVS to improve the perceptual quality of images displayed on TFT-LCDs under dim backlight. This algorithm can be applied to save the power consumption of portable devices while producing good image quality.

This two-scale image decomposition and processing algorithm improves the image quality by global brightness compensation, which counteracts the reduction of backlight, and local contrast enhancement, which preserves the image details. Its superior performance is achieved by adaptively changing the brightness compensation function and fully utilizing the dynamic range of pixels to enhance the local details of the image.

To speed up the algorithm for video data, we also have developed a scheme that significantly accelerates the algorithm from 11 to 25 frames/s and achieves good tradeoff between performance and speed.

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