POWER-CONSTRAINED CONTRAST ENHANCEMENT FOR OLED DISPLAYS BASED ON HISTOGRAM EQUALIZATION

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ABSTRACT

A novel power-constrained contrast enhancement algorithm for organic light-emitting diode (OLED) displays is proposed in this work. We first develop the log-modified histogram equalization (LMHE) scheme, which reduces overstretching artifacts of the conventional histogram equalization technique. Then, we model the power consumption in OLED displays, and incorporate it into LMHE to achieve the optimal tradeoff between contrast enhancement and power saving. Simulation results demonstrate that the proposed algorithm can reduce the power consumption significantly, while preserving image qualities.

Index Terms— Contrast enhancement, histogram equalization, power saving, and OLED.

1. INTRODUCTION

The rapid development of imaging technology empowers mobile devices, such as mobile phones, to take and process digital photographs and transmit them through networks. However, since lighting conditions and image acquisition systems are not ideal, we often obtain low quality photographs with limited dynamic ranges especially for dark scenes. Histogram equalization (HE) is an approach to enhance low contrast images, which attempts to make the histogram of light intensities of pixels within an image as uniform as possible [1]. Due to its simplicity and effectiveness, HE is employed in various applications, including digital photography and medical imaging.

Whereas a variety of HE techniques have been proposed for the contrast enhancement of general images [2, 3], little effort has been made to adapt the enhancement process to the characteristics of display devices. A large portion of power is consumed by display panels in mobile devices [4]. Since power saving is important in mobile devices, it is desirable to develop an image processing algorithm, which is capable of saving power in display panels as well as enhancing the contrast of output images.

Researches on power saving in display panels have been carried out independently of contrast enhancement. They can be classified into hardware techniques and software techniques. The hardware techniques focus on the design of efficient mixed-signal circuits that drive pixel matrices, and are independent of the characteristics of input images. The software techniques [4, 5] attempt to reduce backlight intensities for TFT-LCD displays, while preserving the same level of perceived qualities. These software techniques can be adjusted according to input images. These techniques [4, 5], however, are devised for TFT-LCD displays only.

OLED display panels have been adopted in recent high-end electronic devices, such as MP3 players, mobile phones, and even televisions. OLED is regarded as the most efficient emissive device among existing display panels [6]. It drives each pixel independently, and provides superior color reproducibility to TFT-LCD. Furthermore, OLED consumes less power than TFT-LCD in general. Due to these advantages, OLED is expected to be used in a wider range of display devices in near future.

While recent researches on contrast enhancement have been focused on device-independent algorithms or on algorithms for TFT-LCD devices, little work has been done to optimize the contrast enhancement on OLED displays. In this work, we propose a power constrained HE scheme for OLED displays. First, before HE, the proposed algorithm modifies the histogram of an input image using a logarithm mapping to avoid extreme slopes in the transformation function. Then, we make a power consumption model of OLED displays, and incorporate it into the HE procedure. Simulation results demonstrate that the proposed algorithm can control the power consumption adaptively, and can provide high image qualities even when it reduces the power consumption significantly.

2. HISTOGRAM EQUALIZATION

We briefly review the traditional HE technique. We represent the histogram with a column vector $\mathbf{h}$ whose kth element h_k denotes the number of pixels with intensity k. Then, the probability mass function (PMF) p_k of intensity k is calculated by dividing h_k by the total number of pixels in the image:

$$p_k = \frac{h_k}{\mathbf{1}^T \mathbf{h}}, \tag{1}$$

where $\mathbf{1}$ denotes the column vector, all elements of which are 1. The cumulative distribution function (CDF) c_k of intensity k is then obtained by

$$c_k = \sum_{i=0}^{k} p_i. \tag{2}$$

HE obtains the transformation function, which maps input pixel intensities to output pixel intensities, to make the histogram of the output image as uniform as possible. Let x_k denote the transformation function. Specifically, the transformation function maps intensity k in the input image to intensity x_k in the output image. In HE, the transformation function is obtained by multiplying the CDF c_k by the maximum intensity of the output image [1, 3]. For a b-bit image, $(2^b - 1)$ is the maximum intensity, and the transformation function is given by

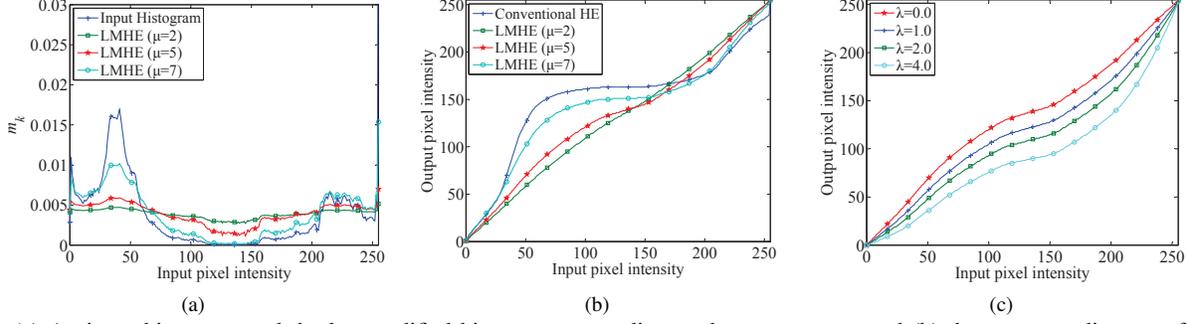$$x_k = \lfloor (2^b - 1)c_k + 0.5 \rfloor. \tag{3}$$

Fig. 1. (a) An input histogram and the log-modified histograms according to the parameter μ and (b) the corresponding transformation functions when LMHE only is applied. (c) Power-constrained transformation functions for various λ's when $\mu = 5$.

In Eq. (3), $(2^b - 1)c_k$ is rounded off to the nearest integer, since output intensities should be integers. Without loss of generality, we consider only 8-bit images in this work. Thus, $2^b - 1 = 255$.

If we ignore the rounding-off operation in Eq. (3), we can combine Eqs. (2) and (3) into a recurrence equation

$$x_k - x_{k-1} = 255 \cdot p_k \quad \text{for } 1 \leq k \leq 255, \tag{4}$$

with an initial condition $x_0 = 255 \cdot p_0$. This can be rewritten in vector notations as

$$\mathbf{Dx} = \bar{\mathbf{h}}, \tag{5}$$

where $\mathbf{D} \in \mathbb{R}^{256 \times 256}$ is the differential matrix

$$\mathbf{D} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ -1 & 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & -1 & 1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & -1 & 1 & 0 \\ 0 & 0 & 0 & \cdots & 0 & -1 & 1 \end{bmatrix} \tag{6}$$

and $\bar{\mathbf{h}}$ is the normalized column vector of $\mathbf{h}$, given by

$$\bar{\mathbf{h}} = \frac{255}{\mathbf{1}^T \mathbf{h}} \mathbf{h}. \tag{7}$$

The conventional HE technique has drawbacks. First, the transformation function gets an extreme slope, when a histogram bin has a very large value. Note from Eq. (4) that the transformation function has sharp transition between x_{k-1} and x_k when h_k, or equivalently p_k, is large. This may cause contrast overstretching, noise amplification, or contour artifacts in the output image. Second, the level of contrast enhancement cannot be controlled, since the conventional HE is a fully automatic algorithm without any parameter.

3. PROPOSED ALGORITHM

3.1. Log-Based Histogram Pre-Modification

We propose a histogram pre-modification approach, which reduces large values of histogram bins before the HE procedure to avoid extreme slopes in the transformation function. Several algorithms have been proposed to pre-modify an input histogram. For example, Wang and Ward [2] clamped large histogram values to a threshold, and then modified the resulting histogram using the power law. Also, Arici *et al.* [3] reduces the values of histogram bins for large smooth areas, and mixes the resulting histogram with the uniform histogram.

We propose an alternative histogram pre-modification scheme using a logarithm function, which is monotonically increasing and

can reduce large values effectively. We use the following logarithm function to convert the input histogram value h_k to a modified histogram value m_k.

$$m_k = \frac{\log(h_k \cdot h_{\max} \cdot 10^{-\mu} + 1)}{\log(h_{\max}^2 \cdot 10^{-\mu} + 1)}, \tag{8}$$

where $h_{\max}$ denotes the maximum element within the input histogram $\mathbf{h}$. The constant 1 prevents the logarithm function from having a negative value. μ is the parameter that controls the level of histogram modification. As μ gets larger, $h_k \cdot h_{\max} \cdot 10^{-\mu}$ in Eq. (8) becomes a smaller number. Therefore, a large μ makes m_k almost linearly proportional to h_k, since $\log(1 + x) \cong x$ for a small x. Thus, the histogram is modified less strongly. On the other hand, as μ gets smaller, $h_{\max} \cdot 10^{-\mu}$ becomes dominant and $\log(h_k \cdot h_{\max} \cdot 10^{-\mu} + 1) \cong \log(h_{\max} \cdot 10^{-\mu})$. Consequently, m_k becomes a constant regardless of h_k making the modified histogram uniform.

Let $\mathbf{m} = [m_0, m_1, \cdots, m_{255}]^T$ denote the modified histogram. Then, the HE procedure can be performed with the modified histogram $\mathbf{m}$ instead of the original histogram $\mathbf{h}$. More specifically, the HE in Eqs. (5) and (7) can be performed with the modified histogram $\mathbf{m}$ as follows.

$$\mathbf{Dx} = \bar{\mathbf{m}}, \tag{9}$$

where

$$\bar{\mathbf{m}} = \frac{255}{\mathbf{1}^T \mathbf{m}} \mathbf{m}. \tag{10}$$

We call this equalization technique as the log-modified histogram equalization (LMHE).

Fig. 1 (a) plots the input histogram and the modified histograms for various μ's. We see that LMHE reduces large values in the input histogram, and that the histogram is more strongly modified as μ becomes smaller. As shown in Fig. 1 (b), large values in the input histogram around pixel intensity 40 cause a steep slope in the transformation function. LMHE reduces this steep slope. As μ becomes smaller, the transformation function gets closer to the identity function. Thus, by controlling the single parameter μ, LMHE can obtain the transformation function, which varies between the identity function and the conventional HE transformation function.

3.2. Power Model for OLED Displays

In order to achieve the power saving and the contrast enhancement simultaneously, we first model the power consumption in an OLED display. In [7], it was experimentally shown that the power to display a single color pixel can be approximated by

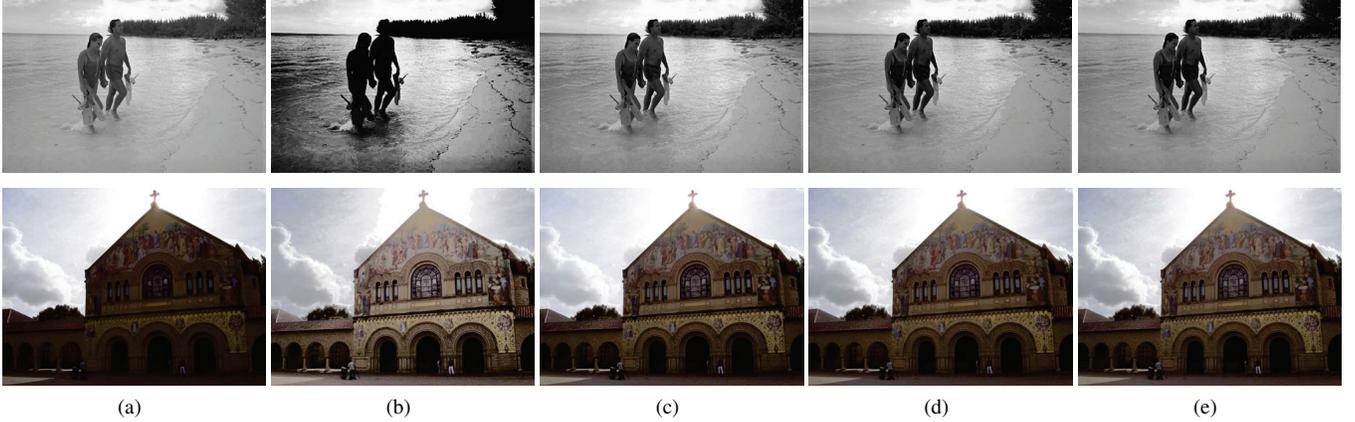$$P = \omega_0 + \omega_r R^\gamma + \omega_g G^\gamma + \omega_b B^\gamma, \tag{11}$$

Fig. 2. Contrast enhancement of the "Beach" and "Church" images: (a) input image, (b) the conventional HE, (c) WAHE, (d) WTHE, (e) the proposed LMHE without the power constraint.
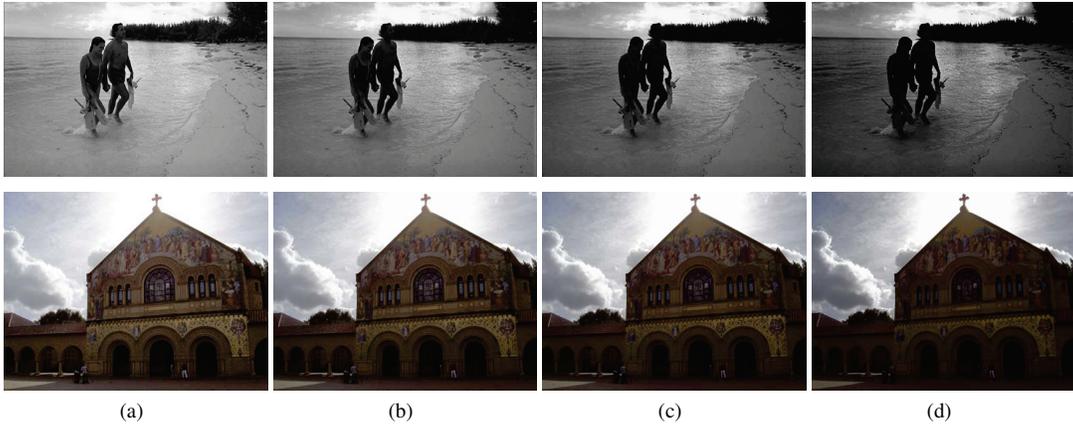

Fig. 3. The results of the proposed power-constrained LMHE: (a) $\lambda = 0$, (b) $\lambda = 1$, (c) $\lambda = 2$, (d) $\lambda = 4$.

where R, G, B are the red, green, and blue intensities of the pixel, and the power γ is due to the gamma correction of R, G, B values in the sRGB standard. Also, ω_0 accounts for static power consumption independent of the intensities, and $\omega_r, \omega_g, \omega_b$ are weighting coefficients that express different characteristics of red, green, and blue subpixels.

In this work, we control pixel intensities to save power in an OLED display. Thus, we ignore the parameter ω_0 for static power consumption. Also, although a typical value of γ is about 2.2, we set γ to 2 to employ a quadratic power model. This quadratic approximation greatly facilitates the optimization of the power-constrained HE in the next subsection. In this way, we model the total dissipated power (TDP) for displaying a color image by

$$\text{TDP} = \sum_{i=0}^{N-1} (\omega_r R_i^2 + \omega_g G_i^2 + \omega_b B_i^2), \tag{12}$$

where N denotes the number of pixels in the image, and (R_i, G_i, B_i) denotes the RGB color vector of the ith pixel.

For a gray scale image, the TDP is similarly modeled by

$$\text{TDP} = \sum_{i=0}^{N-1} Y_i^2, \tag{13}$$

where Y_i is the luminance intensity of the ith pixel. Note that there are h_k pixels with intensity k in the input image, and these pixels are assigned intensity x_k in the output image by the transformation function. Therefore, TDP in Eq. (13) can be written as

$$\text{TDP} = \sum_{i=0}^{255} h_k x_k^2 = \mathbf{x}^T \mathbf{H} \mathbf{x}, \tag{14}$$

where $\mathbf{x} = [x_0, x_1, \cdots, x_{255}]^T$ represents the transformation function, and $\mathbf{H}$ is a diagonal matrix whose kth diagonal element is h_k.

3.3. Power-Constrained LMHE

We incorporate the power model into the LMHE technique. We have two contradictory goals: to enhance the contrast by equalizing the histogram, and to save the power consumption by reducing the histogram values for large intensities. To compromise between these two goals, we employ the Lagrangian multiplier technique.

We can perform LMHE by solving $\mathbf{D}\mathbf{x} = \bar{\mathbf{m}}$ in Eq. (9) or equivalently minimizing $\|\mathbf{D}\mathbf{x} - \bar{\mathbf{m}}\|^2 = (\mathbf{D}\mathbf{x} - \bar{\mathbf{m}})^T (\mathbf{D}\mathbf{x} - \bar{\mathbf{m}})$. On the other hand, we can save the power consumption by decreasing $\mathbf{x}^T \mathbf{H} \mathbf{x}$ in Eq. (14). Therefore, the contrast enhancement and the power saving can be achieved simultaneously by minimizing the sum of these two terms. However, in such a case, the last element

x_{255} in $\mathbf{x}$ may be less than 255 due to the power saving term $\mathbf{x}^T\mathbf{H}\mathbf{x}$. This reduces the dynamic range of the output image, which is not desirable. To avoid the dynamic range reduction, we add the condition $x_{255} = 255$ into the cost function by modifying $\mathbf{D}$ and $\bar{\mathbf{m}}$. More specifically, we add one more row $[0, 0, \cdots, 0, 1]$ to $\mathbf{D}$ and one more element 255 to $\bar{\mathbf{m}}$. Let us denote these augmented matrix and vector by $\mathbf{D}_a$ and $\bar{\mathbf{m}}_a$, respectively.

Then, the Lagrangian cost function is given by

$$J(\mathbf{x}) = (\mathbf{D}_a\mathbf{x} - \bar{\mathbf{m}}_a)^T(\mathbf{D}_a\mathbf{x} - \bar{\mathbf{m}}_a) + \alpha\mathbf{x}^T\mathbf{H}\mathbf{x}, \quad (15)$$

where α is a Lagrangian multiplier. By differentiating the cost function $J(\mathbf{x})$ with respect to $\mathbf{x}$ and setting it to $\mathbf{0}$, we obtain the power-constrained transformation function

$$\mathbf{x} = (\mathbf{D}_a^T\mathbf{D}_a + \alpha\mathbf{H})^{-1}\mathbf{D}_a^T\bar{\mathbf{m}}_a. \quad (16)$$

The multiplier α controls the tradeoff between power saving and contrast enhancement. When $\alpha = 0$, the transformation function $\mathbf{x}$ in Eq. (16) is reduced to the solution to the LMHE equation in Eq. (9) without the power constraint. Thus, only the contrast enhancement is considered. As α gets larger, the power term becomes more dominant, and fewer pixels are assigned large intensity values in the output image.

Since the two terms $(\mathbf{D}_a\mathbf{x} - \bar{\mathbf{m}}_a)^T(\mathbf{D}_a\mathbf{x} - \bar{\mathbf{m}}_a)$ and $\mathbf{x}^T\mathbf{H}\mathbf{x}$ in (15) have different orders of magnitude, it is convenient to change the variable by

$$\lambda = \alpha \cdot \sum_{i=0}^{N-1} Y_{\text{input},i}, \quad (17)$$

where $Y_{\text{input},i}$ is the luminance intensity of the ith pixel in the input image. Then, we control λ instead of α. We have found experimentally that λ in the range $[0, 5]$ produces satisfactory results.

Fig. 1 (c) shows the transformation functions for the input histogram in Fig. 1 (a) for various λ values. In this test, μ is fixed to 5. We see that as λ gets higher, the transformation function provides lower output intensities to reduce the power consumption.

4. EXPERIMENTAL RESULT

We evaluate the performance of the proposed algorithm on various test images, but show the results on only two images "Beach" (866×576) and "Church" (640×480) because of the page limitation.

First, we compare the proposed LMHE with the conventional HE techniques. In this test, the power constraint is not considered, i.e., $\lambda = 0$. Fig. 2 shows the processed images obtained by the conventional HE, the weighted approximated HE (WAHE) [3], the weighted thresholded HE (WTHE) [2], and the proposed LMHE. The conventional HE in Fig. 2 (b) yields excessive contrast stretching on both images. WAHE in Fig. 2 (c) alleviates this overstretching, but loses some details in the backgrounds, such as the sky in the "Church" image. Both WTHE and the proposed algorithm in Fig. 2 (d) and (e) provide satisfactory results, but the proposed algorithm has the advantage that it requires the tuning of only a single parameter μ, whereas WTHE has two parameters. In this test, μ is set to 2 and 6 for the "Beach" and "Church" images, respectively. The two parameters of WTHE are also controlled to yield the best subjective image qualities.

Next, Fig. 3 shows the processed image of the proposed power-constraint LMHE for various λ's. Note that Fig. 3 (a) is exactly identical with Fig. 2 (e). As λ gets larger, the overall brightness of images decreases, but the subjective contrast is well preserved. Especially, when these images are displayed on light emissive OLED
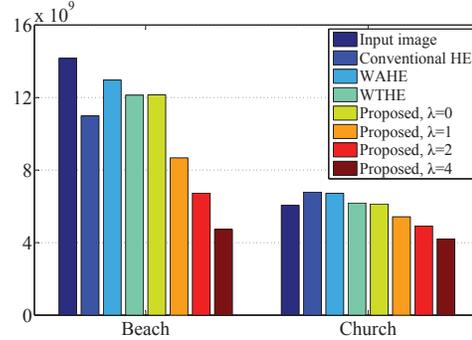

Fig. 4. The TDP measures on various result images from different algorithms.

panels, it is hard to distinguish the case without the power constraint ($\lambda = 0$) from the case when λ is a moderate number less than 4.

Fig. 4 compares the qualitative TDP's of the images in Figs. 2 and 3. We see that the proposed algorithm can achieve power saving by increasing λ. Since the "Beach" image is relatively bright, the proposed algorithm can achieve more power saving. When $\lambda = 4$, more than 50% of power is saved on the "Beach" image.

5. CONCLUSION

We proposed a power-constrained contrast enhancement algorithm for OLED displays. We first developed the LMHE scheme to avoid overstretching artifacts in the conventional HE. Then, we made a power consumption model of OLED displays, and incorporated it into LMHE. Simulation results confirmed that the proposed algorithm provides high image qualities even when it reduces the power consumption significantly.

6. REFERENCES

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