CONTRAST ENHANCEMENT USING HISTOGRAM EQUALIZATION WITH BIN UNDERFLOW AND BIN OVERFLOW

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ABSTRACT

The histogram equalization (HE) is a widely used contrast enhancement method. But what is missing from the HE is a mechanism to control the rate of enhancement. The enhanced image always follows the uniform distribution. This paper presents a simple enhancement rate control mechanism for the HE. The gradient of the mapping function is controlled by putting contraints on the probability density function with the bin underflow (BU) and bin overflow (BO). The BUBO operation can provide the rate of enhancement from non to the full HE with a single parameter. With the enhancement rate control mechanism available, the HE can be used to perform image processing tasks such as black/white level stretch or automatic brightness control as well as variable rate contrast enhancement.

1. INTRODUCTION

Contrast enhancement (CE) is used widely in image processing. One of the most popular CE methods is the histogram equalization (HE) [1, 2]. The HE uses the cumulative distribution function (CDF) of a given image as a mapping from the given image to the enhanced image. The image enhanced by the HE follows the uniform distribution [2]. The fact that the enhanced image utilizes the available levels fully reflects the enhanced contrast.

The HE has several nice properties. The HE is simple. All it takes to apply the HE is to estimate the probability density function (PDF) and sum it cumulatively to obtain the CDF. When simple bin counting is used for the estimation of the PDF, as is the most case, the HE becomes a non-parametric method [3]. It adapts to the statistics of the given image no matter what distribution it may be. The HE is very effective. It provides images with uniform distributions. But it may be too effective for some images or for some applications. Although the HE surely provides images of higher contrast, it cannot be said it provides images of higher quality. Images with uniformly distributed levels are not usually very pleasing.

This paper provides a simple method to regulate the rate of enhancement by the HE. The proposed method is to put constraints on the gradient of the mapping function used to enhance the contrast. Noting that the gradient of the mapping function is just the scaled PDF, we put constraints on the estimated PDF. The constraints work as if we fill the bin for the PDF estimation up to a point when the bin has underflow, and throw away the surplus over another point when the bin has overflow. By setting the two points for the underflow and overflow, we can control the rate of enhancement effectively. In fact, we can change the rate of enhancement gradually from non to the full HE with a single parameter. The required operations are the thresholding and a simple adjustment, which can be implemented efficiently either by software or hardware. With the rate control mechanism, the HE can be used to perform various tasks such as the black/white level stretch [4, 5], or the brightness control [4].

Section 2.1 reviews the HE and Section 2.2 introduces the proposed enhancement rate control mechanism. Section 2.3 and 2.4 discuss how to utilize the proposed method for the black/white level stretch and for the brightness control, respectively. Experimental results are presented with examples in Section 3, and conclusion is drawn in Section 4.

2. CONTRAST ENHANCEMENT USING BIN UNDERFLOW AND BIN OVERFLOW

2.1. Histogram Equalization

The first step of the HE is to estimate the PDF of a given image $f(i, j) \in [1, K]$ for $i \in [1, M]$ and $j \in [1, N]$. Any density estimation method [3] can be used for the estimation of the PDF. The simplest method is to use the bin counting such that

$$\text{pdf}[k] = \frac{1}{MN} \|\{(i, j)|f(i, j) = k\}\|. \tag{1}$$

Once the PDF is estimated, the CDF is obtained by

$$\text{cdf}[k] = \sum_{l=1}^{k} \text{pdf}[l]. \tag{2}$$

The mapping function $\Phi(\cdot) : [1, K] \rightarrow [1, K]$ applied to the given image to enhance the contrast is the CDF itself scaled to provide correct levels. The enhanced image is given by

$$g(i,j) = \Phi(f(i,j)) \tag{3}$$
$$= K \cdot \mathrm{cdf}[f(i,j)]. \tag{4}$$

The PDF of the enhanced image g is uniform on $[1, K]$, which reflects the enhanced contrast. As can be seen in the steps involved in the HE, there is no mechanism for controlling the rate of enhancement. The next section addresses a simple but effective way to control the rate of enhancement of the HE.

2.2. Enhancement Rate Control

The HE enhances the contrast by applying the mapping function with steep gradient at the levels many pixels have, while that with gradual gradient at the levels less pixels have. Hence, the rate of enhancement can be controlled by putting constraints on the gradient of the mapping function. Note that with the HE, the mapping function is the scaled CDF. The gradient of the mapping function is given by

$$\frac{d}{dk}\Phi(k) = K \cdot \mathrm{pdf}[k]. \tag{5}$$

We can put constraints on the maximum and minimum gradients of the mapping function by

$$K \cdot c_{BU} \leq K \cdot \mathrm{pdf}[k] \leq K \cdot c_{BO} \tag{6}$$

where $K \cdot c_{BU}$ and $K \cdot c_{BO}$ are the allowed minimum and maximum gradient of the mapping function, respectively.

The constraints work as if we fill the bin for the PDF estimation up to c_{BU} when the bin has underflow, and we throw away the surplus over c_{BO} when the bin has overflow:

$$\widetilde{\mathrm{pdf}}[k] = \begin{cases} c_{BO}, & \text{if } \mathrm{pdf}[k] > c_{BO} \\ \mathrm{pdf}[k], & \text{if } c_{BU} \leq \mathrm{pdf}[k] \leq c_{BO} \\ c_{BU}, & \text{if } \mathrm{pdf}[k] < c_{BU}. \end{cases} \tag{7}$$

We call c_{BU} and c_{BO} the bin underflow (BU) and bin overflow (BO) thresholds. One way to set the BU and BO thresholds is

$$c_{BU} = (1-\alpha)/(MN) \tag{8}$$
$$c_{BO} = (1+\alpha)/(MN). \tag{9}$$

With this setup, we can control the rate of CE from non at $\alpha = 0$ to the full HE at $\alpha = \infty$.

A problem with the BUBO operation is that $\widetilde{\mathrm{pdf}}[k]$ does not add up to one. We need to compensate for the discrepancy. Denote the cumulative sum of $\widetilde{\mathrm{pdf}}[k]$ by $\widetilde{\mathrm{cdf}}[k]$, then the mapping function $\Psi(\cdot) : [1, K] \to [1, K]$is given by

$$\Psi(k) = K \cdot (\widetilde{\mathrm{cdf}}[k] - (\widetilde{\mathrm{cdf}}[K]/K) \cdot k) + k. \tag{10}$$

The difference between $\widetilde{\mathrm{cdf}}[k]$ and the straight line between $(0, 0)$ and $(K, \widetilde{\mathrm{cdf}}[K])$ is modulated onto the straight line between $(0, 0)$ and (K, K).

Of course we can normalize $\widetilde{\mathrm{pdf}}[k]$ by the number of pixels actually counted. But such operation requires divisions by a number that changes with the given image, whereas the operation in (10) requires a division by a fixed, usually dyadic, number K. It has an advantage in terms of implementation. Another advantage of using (10) is that $\Psi(k)$ always has positive gradient

$$\frac{d}{dk}\Psi(k) = K \cdot \widetilde{\mathrm{pdf}}[k] - \widetilde{\mathrm{cdf}}[K] + 1 \tag{11}$$

with $\widetilde{\mathrm{cdf}}[K] < 1$. Saturation of levels is less likely.

With the enhancement rate control mechanism available, the HE can be used to perform the CE with variable enhancement rate. The enhancement rate control is efficient because operations involved in the rate control are the thresholding in (7) and the simple adjustment by (10). The operations are easy to implement by either software or hardware.

With the proposed method, the HE can also perform various tasks of image processing. The following subsections discuss how to set the BUBO operation for a couple of widely used tasks.

2.3. Black Level and White Level Stretch

Images with reduced dynamic range show black region that is not so black and white region that is not so white. Image quality can be improved significantly by making black darker and white brighter. These concepts are called the black level stretch (BLS) and white level stretch (WLS).

The BLS can be applied by the BU operation. The goal is to flatten the mapping function below a certain level, below which not many pixels have. The BU operation with the threshold that depends on the level k such that

$$c_{BU}[k] = \begin{cases} c_{BU}, & \text{if } k \geq k_B \\ c_{BUB}, & \text{otherwise} \end{cases} \tag{12}$$

with $c_{BUB} < c_{BU}$ can be used to lower the gradient for $k < k_B$. As a result, levels near k_B are mapped to lower valued levels, making black in the given image darker.

Similarly, the WLS can be applied by the BU operation with the BU threshold

$$c_{BU}[k] = \begin{cases} c_{BUW}, & \text{if } k > k_W \\ c_{BU}, & \text{otherwise} \end{cases} \tag{13}$$

with $c_{BUW} < c_{BU}$, so that the gradient for $k > k_W$ is lowered. Levels near k_W are mapped to higher valued levels, making white in the given image whiter.

2.4. Brightness Control

It is necessary to modify the average brightness of the image, for example, depending on the viewing condition or the types of display devices. The average brightness can be changed by the BU operation. Note that the BU operation modifies the minimum gradient of the mapping function. By using the decreasing BU threshold

$$c_{BU}[k] = \beta(k - K/2) + c_{BU} \tag{14}$$

with $\beta < 1$, we can manipulate the mapping function to rise early at lower levels, so that the average brightness is shifted up. With the increasing BU threshold, or with $\beta > 1$ in (14), we can manipulate the mapping function not to rise until at higher levels, so that the average brightness is shifted down.

The ability to change the brightness is useful for progressive format displays such as LCD, PDP, or DLP. One of the features that can be found in CRT but missing in progressive format devices is the automatic beam limiter (ABL). The ABL is designed to regulate the average beam current to prevent overloading the tubes. It acts to lower the average brightness for bright images, and *vice versa*. The slope of the BU threshold, or β, can be set adaptively depending on the average brightness of the given image to simulate the ABL.

3. EXAMPLES AND DISCUSSION

In this section, we demonstrate the application of the BUBO operation for the variable rate contrast enhancement, the black/white level stretch and the brightness control with an example. A 256 level grayscale image called the *canal* image is used.

Figure 1 shows an example of the contrast enhancement rate control with the BUBO operation. The BUBO thresholds are set by (8) and (9) with $\alpha = 0, 0.125, 0.25, 0.5, 1, 2$ and 4. As it can be seen with the shapes of the mapping functions, the rate of enhancement changes gradually from non at $\alpha = 0$ to the full HE at $\alpha = 4$. It can be seen in the center column of Figure 1 that the trend of enhancement, in other words, which levels are stretched and which levels are compressed, is consistent for all the values of α. The enhancement rate control by the BUBO operation is effective. The operations required for the control is the thresholding by (7), and the adjustment by (10), all of which can be implemented easily with either software or hardware. The enhancement rate control by the BUBO operation is efficient.

Figure 2 shows an example of the BLS and WLS. For $k < 32$ and $k > 224$, the BU threshold is set to $c_{BUB} = \gamma \cdot c_{BU}$ and $c_{BUW} = \gamma \cdot c_{BU}$ with $\gamma = 1, 0.5$, and 0.25. α is set to 0.25. As γ decreases, the shape of the mapping function flattens for $k < 32$, so that levels near 32 are mapped to darker levels. For $k > 224$, pdf$[k]$ is greater than c_{BUW} already. The WLS does not affect the CE of this image, which

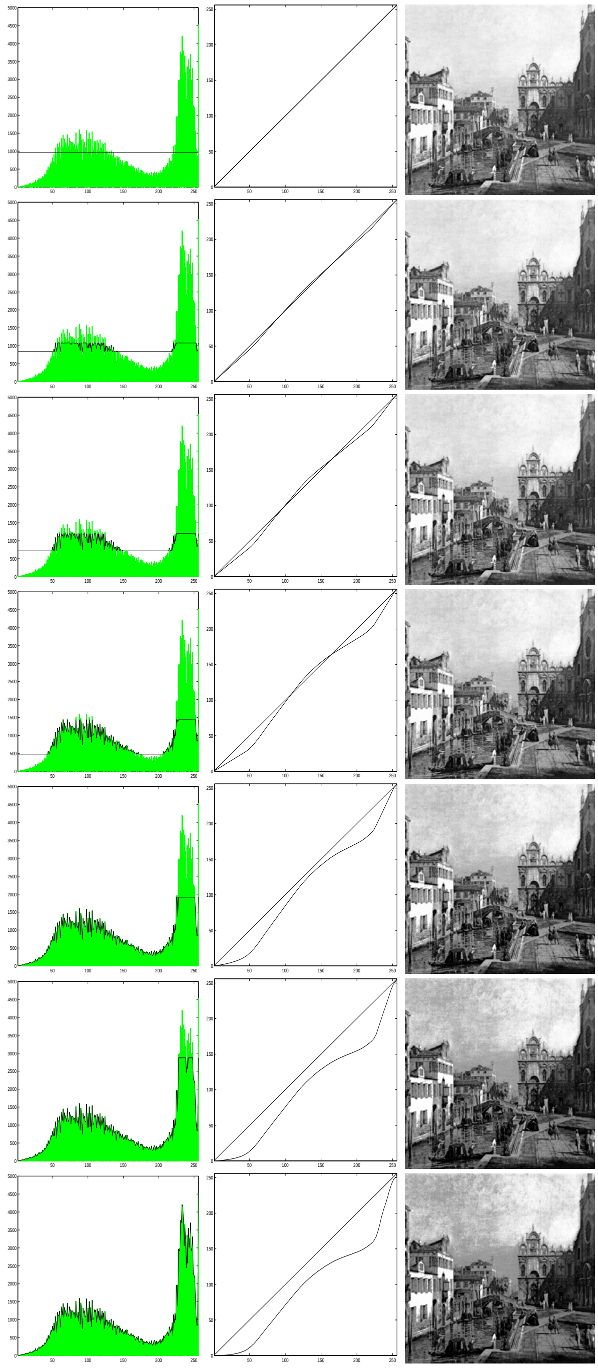

Fig. 1. Contrast enhancement rate control by the BUBO operation, left: PDF after BUBO, center: mapping function, right: enhanced image, with $\alpha = 0, 0.125, 0.25, 0.5, 1, 2,$ and 4 from top to bottom.

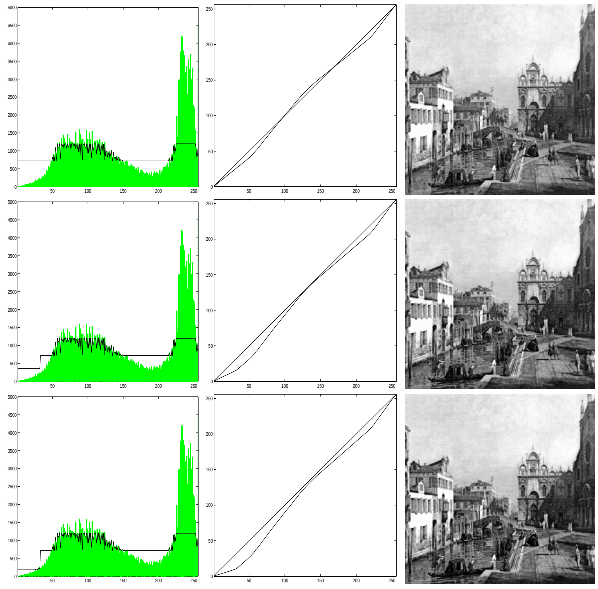

Fig. 2. Black level stretch by the BUBO operation, left: PDF after BUBO, center: mapping function, right: enhanced image, with $\alpha = 0.25$, $c_{BUB} = \gamma \cdot c_{BU}$ for $\gamma = 1, 0.5$, and 0.25 from top to bottom.

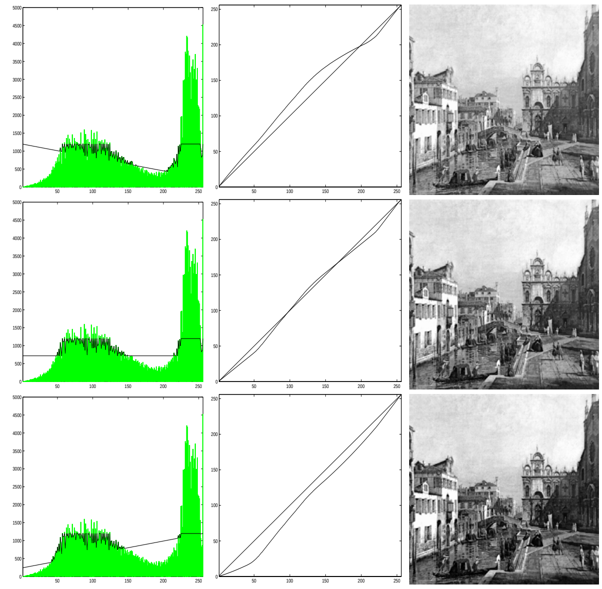

Fig. 3. Brightness control by the BUBO operation, left: PDF after BUBO, center: mapping function, right: enhanced image, with $\alpha = 0.25$, $\beta = -1/512, 0$ and $1/512$ from top to bottom.

is preferable because it prevents the saturation of white levels.

Figure 3 shows an example of the brightness control. With β in (14) less than one, the mapping function is above the strait line between $[0, 0]$ and $[K, K]$. With β greater than one, the mapping function is below the straight line. The mean brightness of the given image is 160.8. The mean brightness of the enhanced image changes from 157.9 at $\beta = 0$ to 167.6 for $\beta = -1/512$ and to 147.6 for $\beta = 1/512$, when $\alpha = 0.25$. The average brightness changes with β as expected.

The HE with the BUBO operation at moderate enhancement rates provides stable CE with various types of images. The proposed method is tested with a vast image database that consists of several test DVD's, test images, and captured broadcasting signals. The proposed method is also ported to the FPGA implementation, and is validated with real-time broadcasting signals.

4. CONCLUSION

This paper provides an enhancement rate control mechanism for the HE. By putting constraints on the PDF of the image, the minimum and maximum gradients of the mapping function used for the enhancement are regulated. With the enhancement rate control mechanism, the HE can enhance the contrast to variable rates, and also perform various image processing tasks such as black/white level stretch or automatic brightness control.

5. REFERENCES

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