Fast Image/Video Contrast Enhancement Based on Weighted Thresholded Histogram Equalization

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Abstract — *A fast and effective method for image contrast enhancement is presented. In the proposed method, the probability distribution function (histogram) of an image is modified by weighting and thresholding before the histogram equalization (HE) is performed. We show that such an approach provides a convenient and effective mechanism to control the enhancement process, while being adaptive to various types of images. We also discuss application of the proposed method in video enhancement. Experimental results are presented and compared with results from other contemporary methods.*

Index Terms — Contrast enhancement; histogram; histogram equalization; cumulative distribution function.

I. INTRODUCTION

Histogram equalization (HE) is a widely used method in image contrast enhancement. Applications of histogram equalization are found in many areas such as medical image processing, texture synthesis, as well as speech recognition. Also in recent years, the application of the HE methods to video enhancement has been drawing much interest.

It is known, however, that the traditional HE method suffers from the following drawbacks:

(1) It does not have the mechanisms that adjust the degree of enhancement. It is also especially difficult to achieve a well-balanced enhancement effect over different parts of an image, e.g., the background and detail parts of the image.
(2) It often causes unpleasant visual artifacts, such as over-enhancement, level saturation (clipping) and increase in the noise level.
(3) It could dramatically change the character of the image. For example, the average luminance of the image often becomes significantly different after the enhancement.

Because of the above shortcomings, histogram equalization is rarely used in practice in its original form. Variants of the HE method have been developed and in recent years, many improved HE-based enhancement techniques have been proposed.

The recently proposed enhancement methods, generally, belong to two categories: the adaptive (or local) HE methods (AHE), such as [1 - 4], and the improved global methods based on histogram equalization or histogram modification, such as [5 - 10]. In the AHE methods, equalization is based on the histogram and statistics obtained from the neighborhood around each pixel. In the improved global methods, various constraints are added to the global equalization or the modification procedures to achieve better performance.

AHE methods can usually provide stronger enhancement effects than global methods. However, due to their high computational load, AHE methods are not best suited for real time video enhancement. Thus, in this study, we focus on the global enhancement approach because of its computational speed. We propose a fast global HE-based enhancement scheme, which provides images with well-enhanced contrast and considerably less artifacts than the traditional global HE-based methods. The proposed enhancement method provides two parameters that allow convenient and effective control over the degree of enhancement.

Section II reviews the traditional HE method and some improved HE-based, recently proposed, methods. In section III, a *weighted thresholded* HE (WTHE) enhancement method is proposed. In section IV, we discuss the implementation of the proposed method in video enhancement. Section V presents experimental results and compares them with those resulting from other contemporary methods. Section VI draws conclusions and gives discussions.

II. HE-BASED ENHANCEMENT METHODS

The traditional histogram equalization technique is described as follows:

Consider a digital image, *F(i, j)*, with a total number of N pixels and a gray level range of [0, K-1]. The probability density function (PDF) of the image is approximated by

$$P(k) = \frac{n_k}{N}, \qquad \text{for } k = 0, 1, ..., K-1 \tag{1}$$

where n_k is the total number of pixels in the image that have gray level k.

The cumulative distribution function (CDF) of image *F(i, j)* is then obtained by

$$C(k) = \sum_{m=0}^{k} P(m), \quad \text{for } k = 0, 1, ..., K-1 \tag{2}$$

Using the CDF values obtained from (2), histogram equalization maps an input level k into an output level H_k using the following level-mapping equation:

$$H_k = (K-1) \times C(k) \tag{3}$$

For the traditional HE described above, the increment in the output level H_k can be easily seen to be

$$\Delta H_k = H_k - H_{k-1} = (K-1) \cdot P(k) \tag{4}$$

That is to say, the increment of level H_k is proportional to the probability of its corresponding level k in the original

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image. In theory, for images with continuous intensity levels and PDFs, such a mapping scheme would perfectly equalize the histogram. However, in practice, the intensity levels and PDF of a digital image are discrete. In such a case, the traditional HE mapping is no longer ideal. Instead, it results in undesirable effects where intensity levels with high probabilities often become over-enhanced, and the levels with low probabilities get less enhanced, their numbers reduced, or even eliminated in the resultant image. In other words, HE often introduces two types of artifacts into the enhanced image: over-enhancement for the more-frequent levels and loss of contrast for the less-frequent levels. Thus HE often over-enhances the background of the image and causes level saturation (clipping) effects in small but visually important areas. To overcome the visual artifacts of the HE method and add more flexibility to it, many researchers proposed different improvement schemes.

The adaptive HE (AHE) methods use local image information to enhance the image. In [1], several adaptive (AHE) techniques are reviewed and compared. The author also proposed a new AHE method based on a "modified cumulation function" that introduces two parameters, α and β. The two parameters, α and β, enable the user to control the effect of enhancement. It is further suggested that α=β is used to achieve visually pleasing results. In [2], an AHE method based on partially overlapping blocks is proposed. The use of partially overlapping blocks results in less computation than AHE schemes based on overlapping blocks, and at the same time less blockiness than the schemes based on non-overlapping blocks. In [3], a fast propagation-based algorithm is first proposed for obtaining the maximum, minimum and average of an image block. Using the above local statistical information, histogram stretching is then performed on the image that is divided into non-overlapping blocks. In [4], a video enhancement scheme is proposed using block-based HE. In this method, temporal filtering is employed to reduce the noise resulting from contrast enhancement.

In [5], a global HE-based enhancement method that uses the bin underflow and bin overflow (BUBO) mechanism is proposed. The PDF of the image is thresholded using a lower (underflow) threshold and an upper (overflow) threshold. HE is performed using the thresholded histogram. Both thresholds are obtained from one parameter, α, which the user controls. In [6], [7] and [8], the mean-shift problem of the traditional HE is discussed and mean-preserving HE methods are proposed. The histogram is segmented into two non-overlapping sections and equalization is performed separately on each section. The segmentation threshold used in [6] is the mean of the input image; in [7], the threshold is calculated based on maximizing the entropy of the enhanced image; in [8], the threshold is obtained based on the minimum mean brightness error (MMBE) criterion.

Other types of histogram-based enhancement schemes have also been proposed, such as the histogram modification [9] and the multi-peak equalization [10] methods. Meanwhile, many recent work, such as [2, 4, 5, 6, 11, 12], discuss the implementation of the HE-based techniques in real time video enhancement applications.

The general idea adopted by the recently proposed HE-based methods is to modify the histogram before the equalization procedure is performed. Through such modifications, artifacts that result from the traditional HE method are reduced. At the same time the ability to control the degree of enhancement is added.

Although these methods perform well, there are still some disadvantages to overcome. The AHE methods usually have high computational complexity and some of them suffer from block-related artifacts. The global methods, on the other hand, are usually less effective and less flexible than the adaptive methods. Also, although some of the new methods, such as the AHE [1] and the BUBOHE [5], do allow control of the degree of enhancement, the adaptivity and linearity of the control mechanisms could still be improved. In the next section, we propose a new enhancement method based on the modified global HE approach.

III. THE WTHE CONTRAST ENHANCEMENT SCHEME

The proposed weighted thresholded (WTHE) enhancement method performs histogram equalization based on a modified histogram. Each original probability density value *P(k)* in equation (4) is replaced by a weighted and thresholded PDF value $P_{wt}(k)$, yielding

$$\Delta H_k = (K-1) \cdot P_{wt}(k) \tag{5}$$

In the new level-mapping scheme given in (5), $P_{wt}(k)$ is obtained by applying a transformation function *Ω(.)* to *P(k)*, such that

$$P_{wt}(k) = \Omega(P(k)) = \begin{cases} P_u & \text{if } P(k) > P_u \\ \left(\dfrac{P(k)-P_l}{P_u - P_l}\right)^r \times P_u & \text{if } P_l \le P(k) \le P_u \\ 0 & \text{if } P(k) < P_l \end{cases} \tag{6}$$

The transformation function *Ω(.)* clamps the original PDF at an upper threshold P_u and at a lower threshold P_l, and transforms all values between the upper and lower thresholds using a normalized power law function with index $r>0$.

In our level-mapping scheme, the increment for each intensity level is decided by the transformed histogram (6). The increment can be controlled by adjusting the index *r* of the power law transformation function. To give an example, when $r<1$, the power law function will give a higher weight to the low probabilities in the PDF than the high probabilities (refer to Fig. 1 for an illustration). Therefore, with $r<1$, the less-probable levels are "protected" and over-enhancement is less likely to occur.

Also in equation (6), the weighted PDF $P_{wt}(k)$ is thresholded at an upper limit P_u. As a result, all levels whose PDF values are higher than P_u will have their increment clamped at a maximum value $\Delta_{\max} = (K-1) \cdot P_u$ (see equation (5) and (6)). Such upper clamping further avoids the dominance of the levels with high probabilities when allocating the output dynamic range. In our algorithm, the value of P_u is decided by

$$P_u = v \cdot P_{\max}, \qquad 0 \le v \le 1 \tag{7}$$

where P_{max} is the peak value (highest probability) of the original PDF and the real number v defines the upper threshold normalized to P_{max}. For example, with v=0.5, the cut-off point is set at 50% of the highest probability observed in the image. A lower value of v results in more high-probability levels being clamped, and thus the less the likelihood of their dominance in the output range. In our proposed algorithm, the normalized upper threshold v is used as another parameter that controls the effect of enhancement.

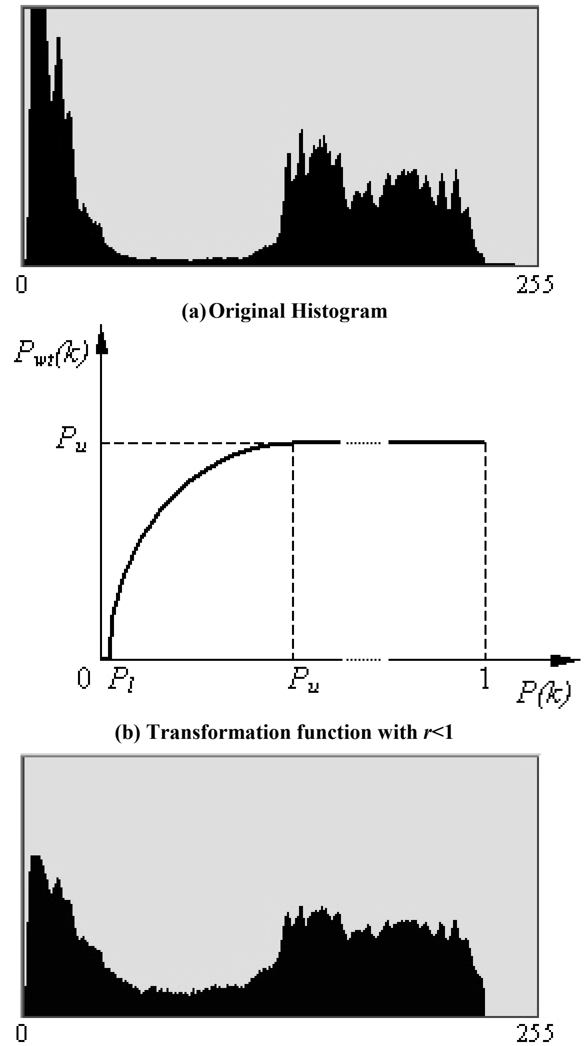
The lower threshold P_l in equation (6), on the other hand, is only used to cut out the levels whose probabilities are too low (and thus of little visual importance) so as to better utilize the full dynamic range. The value of P_l is less important in controlling the enhancement and is set at a very low fixed value (e.g., 0.01%) in our algorithm.

It can be seen from equation (6) that when r=1, P_u=1 and P_l=0 the proposed WTHE reduces to the traditional HE. The BUBOHE proposed in [5] can also be considered as a special case of the proposed method with r=1 and a simpler thresholding mechanism. See Fig. 1 for an illustration of weighting and thresholding the histogram.

In the proposed method, the power index r is the main parameter that controls the degree of enhancement. With r<1 (e.g., r=0.5), more dynamic range is allocated to the less-probable levels, thus preserving important visual details. When the value of r gradually approaches 1, the effect of the proposed method approaches that of the traditional HE. When r>1, more weight is shifted to the high-probability levels, and WTHE would yield even stronger effect than the traditional HE. Using r>1 is less common due to its higher likelihood to result in over-enhancement, yet it is still useful in specific applications where the levels with high probabilities (e.g., the background) need to be enhanced with extra strength.

The proposed transformation function (equation (6)) introduces thresholding to the histogram. In [5], a similar approach is adopted but the thresholds are manually set by the user. For the proposed WTHE method, the upper threshold P_u adapts to P_{max}, the highest probability observed in the image. Such a mechanism effectively alleviates the necessity of manually setting proper thresholds, resulting in consistent enhancement effect for different types of images without manually adjusting the parameters.

After the weighted thresholded PDF is obtained from equation (6), the cumulative distribution function (CDF) is obtained by



(a) Original Histogram

(b) Transformation function with r<1

(c) The weighted thresholded histogram

Fig. 1. Weighting and thresholding the histogram

$$C_{wt}(k) = \sum_{m=0}^{k} P_{wt}(m), \quad \text{for } k = 0, 1, ..., K-1 \tag{8}$$

and the HE procedure (level mapping) is

$$\tilde{F}(i, j) = W_{out} \times C_{wt}(F(i, j)) + M_{adj} \tag{9}$$

In (9), W_{out} is the dynamic range of the output image, and M_{adj} is the mean adjustment factor that compensates for the change of mean luminance level after enhancement. Here for simplicity we temporarily set W_{out} equal to the full luminance range, [0, K-1], and M_{adj} equal to 0, leaving equation (9) similar to the traditional form of HE (equation (3)). We will discuss how to control the values of W_{out} and M_{adj} in the next section.

IV. Implementation of WTHE in Video Enhancement

In our video experiments, we apply the proposed WTHE enhancement method on the luminance component (e.g., Y component for YUV video), leaving the chrominance components unchanged. Here we further discuss issues of enhancement gain control and luminance preservation.

Equation (9) introduces enhancement gain control that constrains the ratio between the output and input dynamic range, i.e.,

$$W_{out} = \min(255, G_{\max} \times W_{in}) \quad (10)$$

in which W_{in} is the dynamic range of the input image and G_{max} is a pre-set maximum gain of dynamic range. The enhancement gain control mechanism further avoids over-enhancement and helps preserve the sensation of the original content. Enhancement gain control is especially useful for scenes that have narrow (e.g., night scenes) or gradually changing (e.g., fade-in and fade-out scenes) dynamic ranges. In our experiments, G_{max} is set in the range of 1.5 to 2.0.

Also, in deciding the value of the output dynamic range W_{out}, a flywheel mechanism is employed. The values of W_{out} of the last few frames are recorded, and the actual value of W_{out} used to enhance the current frame is the weighted average of the current W_{out} value and the previous ones. Such an approach avoids abrupt changes in the output dynamic range between consecutive frames, which could often result in visually annoying flickers.

M_{adj} in equation (9) is the mean adjustment quantity that reduces the luminance changes after enhancement. To decide on the value of M_{adj}, we first calculate the mean of the enhanced image $\widetilde{F}(i, j)$ from equation (9), assuming M_{adj} =0. Then the difference between it and the mean of the original image is calculated. M_{adj} is set equal to the value closest to this mean difference such that it does not cause serious level saturation (clipping).

V. Experimental Results

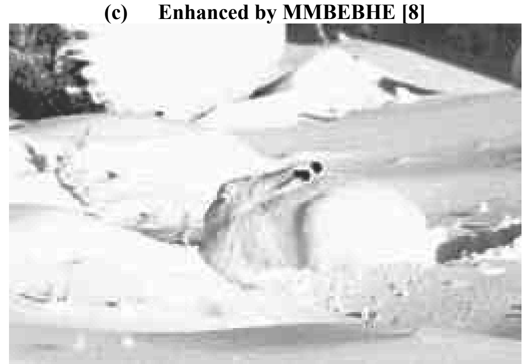
We tested the proposed WTHE method on a variety of images and video sequences. Here we show some of the results. As comparisons, we also show simulation results of some other recently proposed HE-based methods including BUBOHE [5], BBHE [6] and MMBEBHE [8].

In Fig.2, we show results from BBHE [6], MMBEBHE [8] and the proposed WTHE with r=0.5 and v=0.5. The corresponding histograms of the pictures in Fig. 2 are shown in Fig. 3.

(a) Original "Arctic Hare"

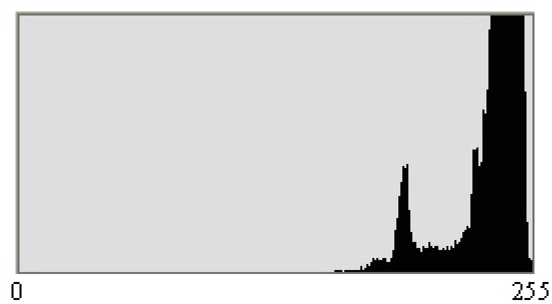
(b) Enhanced by BBHE [6]

(c) Enhanced by MMBEBHE [8]

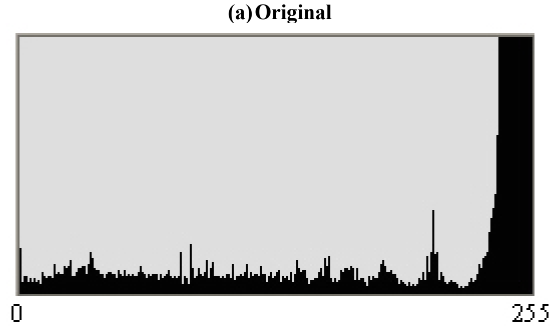


(d) WTHE with r=0.5, v=0.5

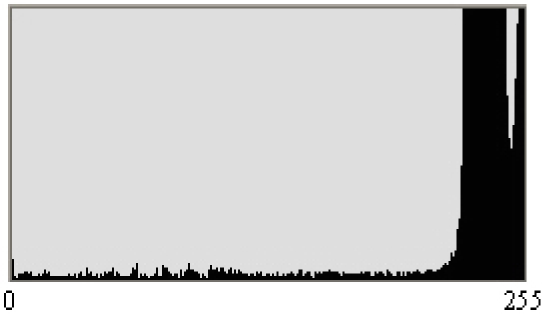
Fig. 2 Arctic Hare and enhancement results



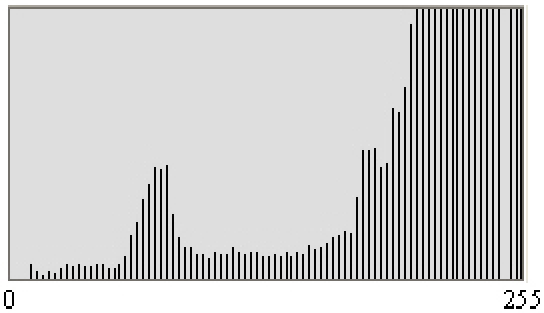
(a) Original



(b) BBHE



(c) MMBEBHE

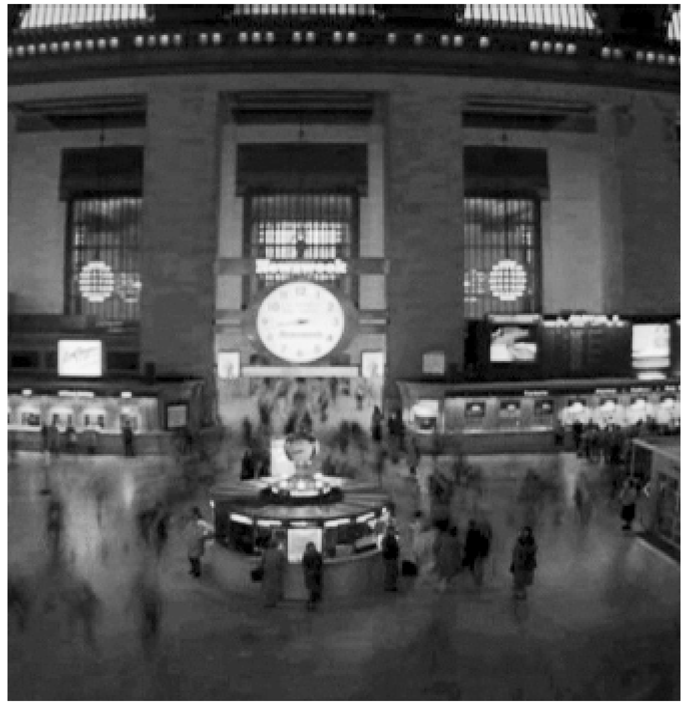


(d) WTHE with *r*=0.5 and *v*=0.5

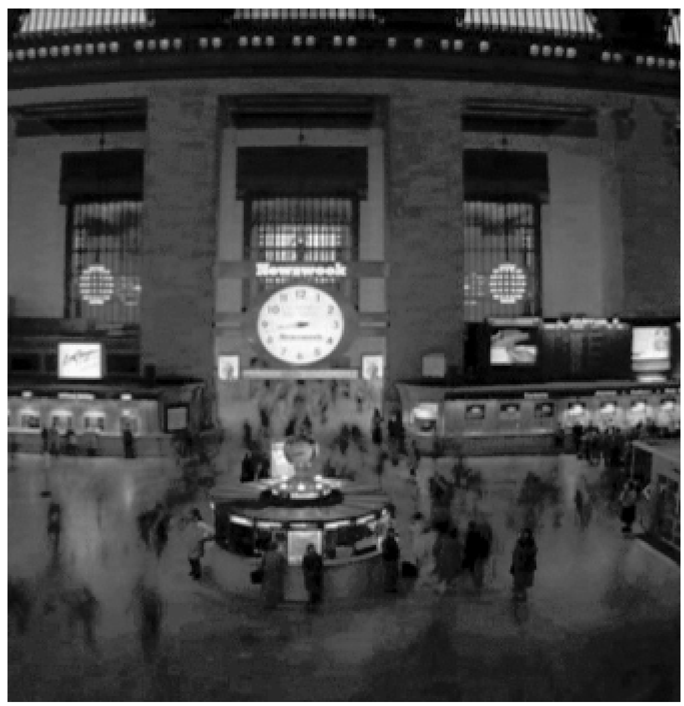
Fig. 3 Histograms of the images in Fig. 2.

Fig. 4 shows a frame from a test video sequence and the enhancement results using BUBOHE [5] and the proposed WTHE. This frame is a typical example that shows the white saturation effect that often result from global HE methods. The corresponding histograms are shown in Fig. 5.

(a) Original video frame: Station hall



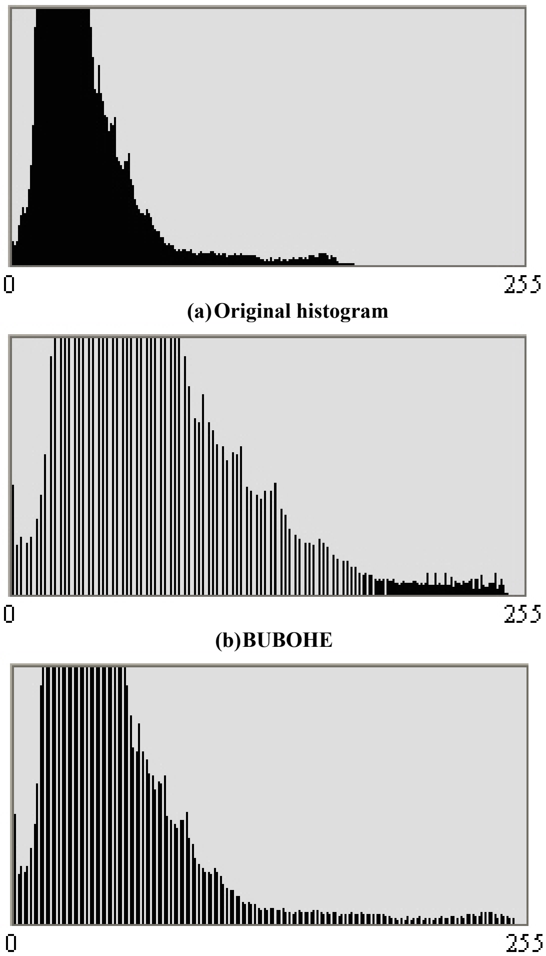
(b) Enhanced by BUBOHE [5]



(c) Enhanced by WTHE with *r*=0.3, *v*=0.5.

Fig. 4. Enhancement of a video frame

Notice the white saturation effect on the clock and the screens in Fig. 4(b). Compare to the same areas in Fig. 4(c) for improvements. Refer to Fig. 5 for corresponding histograms. The above areas correspond to the highest (about 4%) of levels in the histogram. Notice the better even distribution of intensity levels resulting from the proposed WTHE.



(a) Original histogram

(b) BUBOHE

(c) Proposed WTHE

Fig. 5 Histogram of the images in Fig. 4

Fig. 6 shows different degrees of enhancement resulting from the proposed WTHE method by adjusting the parameters. In Fig. 6, the value of parameter r is gradually increased while the value of parameter v is fixed at 0.5 for the first four images. The degree of enhancement increases correspondingly. In the middle right image where the value of r reaches 1.0, we set v to 1.0 to show that WTHE now has the same effect as the traditional HE (bottom right). The r>1 case is also shown in two images in Fig. 6.

VI. Conclusions

The experimental results show that the proposed WTHE is able to achieve visually pleasant enhancement effects. The over-enhancement and level saturation artifacts are effectively avoided. Compared with many other global HE-based enhancement methods, images enhanced using the WTHE method show well enhanced contrast and little artifacts, while being natural looking. Importantly, the control mechanism in WTHE is convenient and smooth by mainly adjusting the power factor r.

The proposed WTHE method provides a good trade-off between two features, adaptivity to different images and ease of control, which are difficult to achieve at the same time for the global HE-based enhancement methods. In practice, the proposed WTHE method is computationally simple and suitable for processor-based implementation. We tested the proposed WTHE algorithm on an embedded real time video processing system and achieved satisfactory results.

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Original r=0.1, v=0.5 r=0.3, v=0.5

r=0.5, *v*=0.5 *r*=0.8, *v*=0.5 *r*=1.0, *v*=1.0

r=1.2, *v*=1.0 *r*=1.5, *v*=1.0 Traditional HE

Fig. 6. Different degrees of enhancement using WTHE

Notice the gradual increase of the degree of enhancement in the first four enhanced images. WTHE with *r*=1.0, *v*=1.0 (middle right image) has the same effect as the traditional HE (bottom right image). The left two images in the bottom row are enhanced using *r*>1 and *v*=1.0. Although overall they are over-enhanced, they show better contrast in certain areas (e.g., the bottom left corner) than other images.

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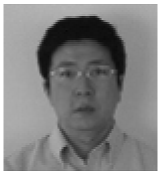

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