Contrast Enhancement Using Brightness Preserving Bi-Histogram Equalization

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ABSTRACT

Histogram equalization is widely used for contrast enhancement in a variety of applications due to its simple function and effectiveness. Examples include medical image processing and radar signal processing. One drawback of the histogram equalization can be found on the fact that the brightness of an image can be changed after the histogram equalization, which is mainly due to the flattening property of the histogram equalization. Thus, it is rarely utilized in consumer electronic products such as TV where preserving original input brightness may necessary in order not to introduce unnecessary visual deterioration. This paper proposes a novel extension of histogram equalization to overcome such drawback of the histogram equalization. The essence of the proposed algorithm is to utilize independent histogram equalizations separately over two subimages obtained by decomposing the input image based on its mean with a constraint that the resulting equalized subimages are bounded by each other around the input mean. It will be shown mathematically that the proposed algorithm preserves the mean brightness of a given image significantly well compared to typical histogram equalization while enhancing the contrast and, thus, provides much natural enhancement that can be utilized in consumer electronic products.

Keywords: Histogram equalization, contrast enhancement, image enhancement, bihistogram equalization.

1. INTRODUCTION

Histogram equalization is the one of the well-known methods for enhancing the contrast of given images in accordance with the sample distribution of an image [1, 2]. Useful applications of the histogram equalization scheme include medical image processing and radar image processing [3, 4]. In general, histogram equalization flats the density distribution of the resultant image and enhances the contrast of the image as a consequence, since histogram equalization has an effect of stretching dynamic range.

In spite of its high performance in enhancing contrasts of a given image, however, it is rarely employed in consumer electronics such as TV since the straight use of histogram equalization may change the original brightness of an input image, deteriorate visual quality, or, introduce some annoying artifacts. Note that the mean brightness of the resultant output image approaches to the middle gray level as the output density of the histogram equalizer uniforms. In theory, it can be shown for the histogram equalization of an analog image that the mean of the equalized image is the middle gray level regardless of the input mean, which is not a desirable property in some applications where mean preserving is necessary.

In this paper, a novel extension of the histogram equalization, which will be referred to as the *mean preserving bi-histogram equalization* (BBHE) [5], is proposed to overcome the aforementioned problems of the typical histogram equalization. The ultimate goal of the proposed algorithm is to preserve the mean brightness of a given image while the contrast is enhanced.

The BBHE firstly decomposes an input image into two subimages based on the mean of the input image. One of the subimages is the set of samples less than or equal to the mean whereas the other one is the set of samples greater than the mean. Then the BBHE equalizes the subimages independently based on their respective histograms with the constraint that the samples in the formal set are mapped into the range from the minimum gray level to the input mean and the samples in the latter set are mapped into the range from the mean to the maximum gray level. In other words, one of the subimages is equalized over

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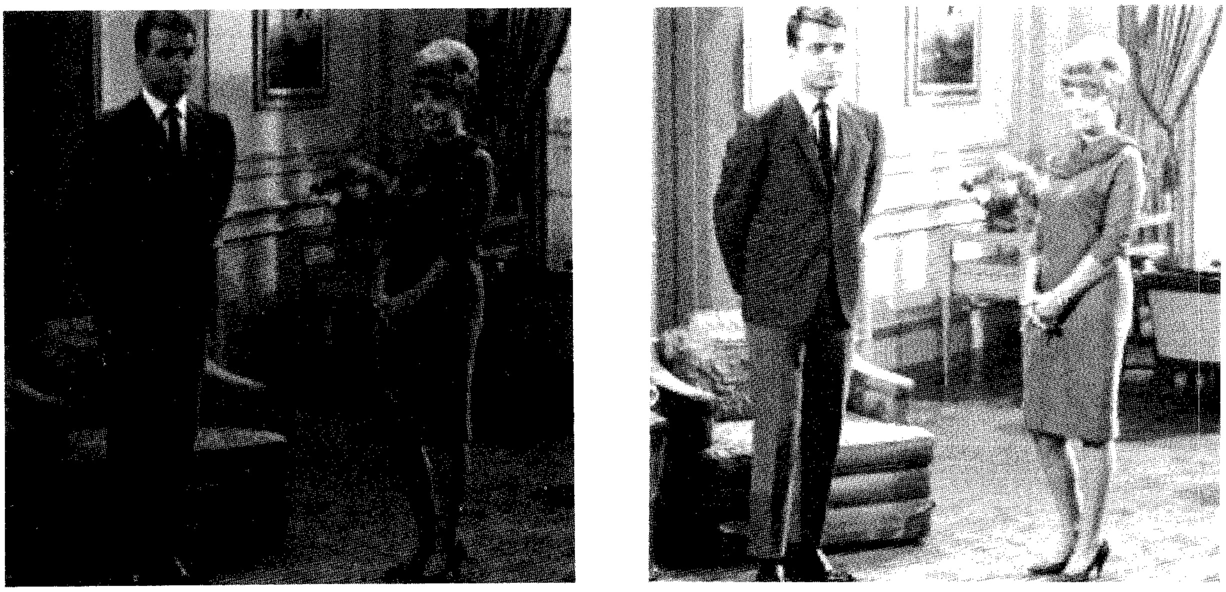

Figure 1: The original image *couple* and the result of histogram equalization.

the range up to the mean and the other subimage is equalized over the range from the mean based on the respective histograms. Thus, the resulting equalized subimages are bounded by each other around the input mean, which has an effect of preserving mean brightness.

In what follows, typical histogram equalization for digital input image is reviewed in Section 2, and the details of the BBHE with mathematical formulation is followed in Section 3. Section 4 establishes mathematical analysis on the mean brightness of the output of the BBHE. To illustrate the performance and the property of the BBHE, experimental results are drawn in Section 5.

2. HISTOGRAM EQUALIZATION

Let $\mathbf{X} = \{X(i,j)\}$ denote a given image composed of L discrete gray levels denoted as $\{X_0, X_1, \cdots, X_{L-1}\}$, where $X(i,j)$ represents an intensity of the image at the spatial location (i,j) and $X(i,j) \in \{X_0, X_1, \cdots, X_{L-1}\}$. For a given image $\mathbf{X}$, the probability density function $p(X_k)$ is defined as

$$p(X_k) = \frac{n^k}{n}, \tag{1}$$

for $k = 0, 1, \cdots, L-1$, where n^k represents the number of times that the levele X_k appears in the input image $\mathbf{X}$ and n is the total number of samples in the input image. Note that $p(X_k)$ is associated with the histogram of the input image which represents the number of pixels that have a specific intensity X_k. In fact, a plot of n^k vs. X_k is known as the histogram of $\mathbf{X}$. Based on the probability density function, we define the cumulative density function as

$$c(x) = \sum_{j=0}^{k} p(X_j) \tag{2}$$

where $X_k = x$, for $k = 0, 1, \cdots, L-1$. Note that $c(X_{L-1}) = 1$ by definition. Histogram eqaulization is a scheme that maps the input image into the entire dynamic range, (X_0, X_{L-1}), by using the cumulative density function as a transform function. That is, let us define a transfom function $f(x)$ based on the cumulative density function as

$$f(x) = X_0 + (X_{L-1} - X_0)c(x), \tag{3}$$

then the output image of the histogram equalization, $\mathbf{Y} = \{Y(i,j)\}$, can be expressed as

$$\mathbf{Y} = f(\mathbf{X}) \tag{4}$$

$$= \{f(X(i,j)) | \forall X(i,j) \in \mathbf{X}\}. \tag{5}$$

One example of the histogram equalization is illustrated in Fig. 1, where the first image is an original image *couple* and the second one is the result of the histogram equalization. This result shows the high performance of the histogram equalization in enhancing the contrast of an image as a consequence of

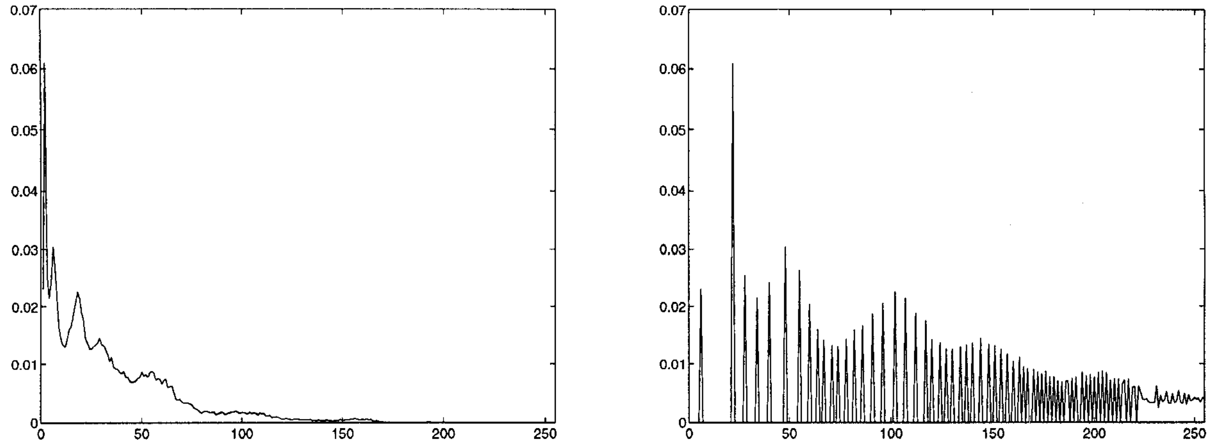

Figure 2: The respective histograms of the images shown in Fig. 1.

the dynamic range expansion, which can be easily understood by comparing the respective histograms of those images shown in Fig. 2.

As addressed previously, histogram equalization can introduce a significant change in brightness of an image, which hesitates the direct application of the histogram equalization schme in consumer electronics. For instance, Fig. 3 shows an original image *hands* and the resultant image of the histogram equalization which are composed of 256 gray levels. Observe here that the histogram equalized image is much brighter than the input image. It can be also observed that the overall contrast of the input image is degraded after the histogram equalization. This is a direct consequence of the excessive change in brightness by the histogram equalization when the image has a high density over low gray levels. Note that the histogram equalization maps its input gray to a gray level which is proportional to the cumulative density up to the input gray level regardless of the input gray level.

Another example which shows the limitation of the histogram equalization is illustrated in Fig. 4, where the first image is a given original image *F16* and the second one is the result of histogram equalization. The respective histograms of those images are shown in Fig. 5 and the transform function associated with (3) is depicted in Fig. 6. First, unnatural enhancement can be seen from this example around the cloud after the histogram equalization. In other words, one would perceive totally different visual recognition around the cloud after the equalization. Moreover, if we investigate closely the images before and after the equalization, one can observe that the contrasts around the letters and the emblem on the airplane are degraded. The reason for such limitations of the histogram equalization for this example can be easily understood from Fig. 6. Note that the bright gray levels are mapped to relatively much dark gray levels by the histogram equalizatation, which is simply due to the fact that the input image has a high density over bright gray levels as can be seen from the first histogram shown in Fig 5.

More fundamental reason behind the such limitations of the histogram equalzation is that the historam equalzation does not take the mean brightness of an image into account. In the subsequent sections, a new contrast enhancement algorithm is formally proposed based on the histogram equalization. The proposed algorithm utilizes the mean brightness which is the one of the important statistics of an image.

3. BRIGHTNESS PRESERVING BI-HISTOGRAM EQUALIZATION

Denote by X_m the mean of the image $\mathbf{X}$ and assume that $X_m \in \{X_0, X_1, \cdots, X_{L-1}\}$. Based on the mean, the input image is decomposed into two subimages $\mathbf{X}_L$ and $\mathbf{X}_U$ as

$$\mathbf{X} = \mathbf{X}_L \cup \mathbf{X}_U \qquad (6)$$

where

$$\mathbf{X}_L = \{X(i,j) | X(i,j) \leq X_m, \forall X(i,j) \in \mathbf{X}\} \qquad (7)$$

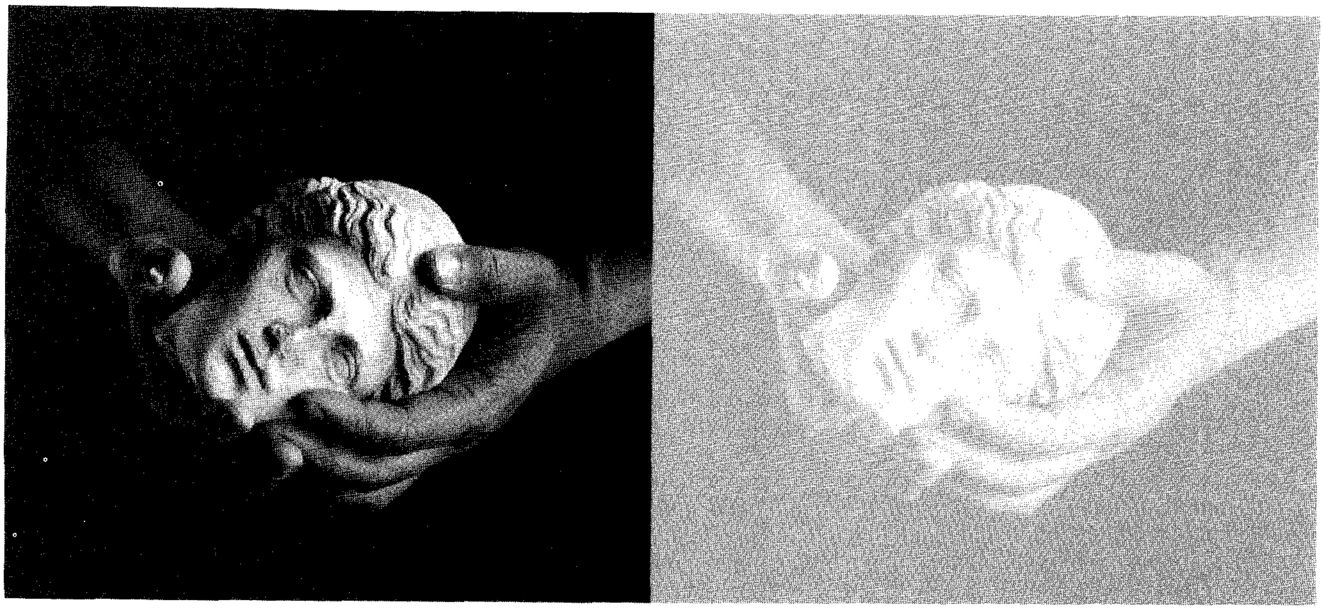

Figure 3: The original image *hands* and the result of histogram equalization.

and

$$\mathbf{X}_U = \{X(i,j) | X(i,j) > X_m, \forall X(i,j) \in \mathbf{X}\}. \quad (8)$$

Note that the subimage $\mathbf{X}_L$ is composed of $\{X_0, X_1, \cdots, X_m\}$ and the other subimage $\mathbf{X}_U$ is composed of $\{X_{m+1}, X_{m+2}, \cdots, X_{L-1}\}$.

Next, define the respective probability density functions of the subimages $\mathbf{X}_L$ and $\mathbf{X}_U$ as

$$p_L(X_k) = \frac{n_L^k}{n_L}, \quad \text{where } k = 0, 1, \cdots, m, \quad (9)$$

and

$$p_U(X_k) = \frac{n_U^k}{n_U}, \quad \text{where } k = m+1, m+2, \cdots, L-1, \quad (10)$$

in which n_L^k and n_U^k represent the respective numbers of X_k in $\{\mathbf{X}\}_L$ and $\{\mathbf{X}\}_U$, and n_L and n_U are the total numbers of samples in $\{\mathbf{X}\}_L$ and $\{\mathbf{X}\}_U$, respectively. Note that $n_L = \sum_{k=0}^{m} n_L^k$, $n_U = \sum_{k=m+1}^{L-1} n_U^k$, and $n = n_L + n_U$. The respective cumulative density functions for $\{\mathbf{X}\}_L$ and $\{\mathbf{X}\}_U$ are then defined as

$$c_L(x) = \sum_{j=0}^{k} p_L(X_j) \quad (11)$$

and

$$c_U(x) = \sum_{j=m+1}^{k} p_U(X_j), \quad (12)$$

where $X_k = x$. Note that $c_L(X_m) = 1$ and $c_U(X_{L-1}) = 1$ by definition.

Similar to the case of histogram equalization where a cumulative density function is used as a transform function, let us define the following transform functions exploiting the cumulative density functions

$$f_L(x) = X_0 + (X_m - X_0)c_L(x) \quad (13)$$

and

$$f_U(x) = X_{m+1} + (X_{L-1} - X_{m+1})c_U(x). \quad (14)$$

Based on these transform functions, the decomposed subimages are equalized independently and the composition of the resulting equalized subimages constitutes the output of the BBHE. That is, the output image of the BBHE, $\mathbf{Y}$, is finally expressed as

$$\begin{aligned} \mathbf{Y} &= \{Y(i,j)\} && (15) \\ &= f_L(\mathbf{X}_L) \cup f_U(\mathbf{X}_U), && (16) \end{aligned}$$

where

$$f_L(\mathbf{X}_L) = \{f_L(X(i,j)) | \forall X(i,j) \in \mathbf{X}_L\} \quad (17)$$

and

$$f_U(\mathbf{X}_U) = \{f_U(X(i,j)) | \forall X(i,j) \in \mathbf{X}_U\}. \quad (18)$$

If we note that $0 \le c_L(x), c_U(x) \le 1$, it is easy to see that $f_L(\mathbf{X}_L)$ equalizes the subimage $\mathbf{X}_L$ over the

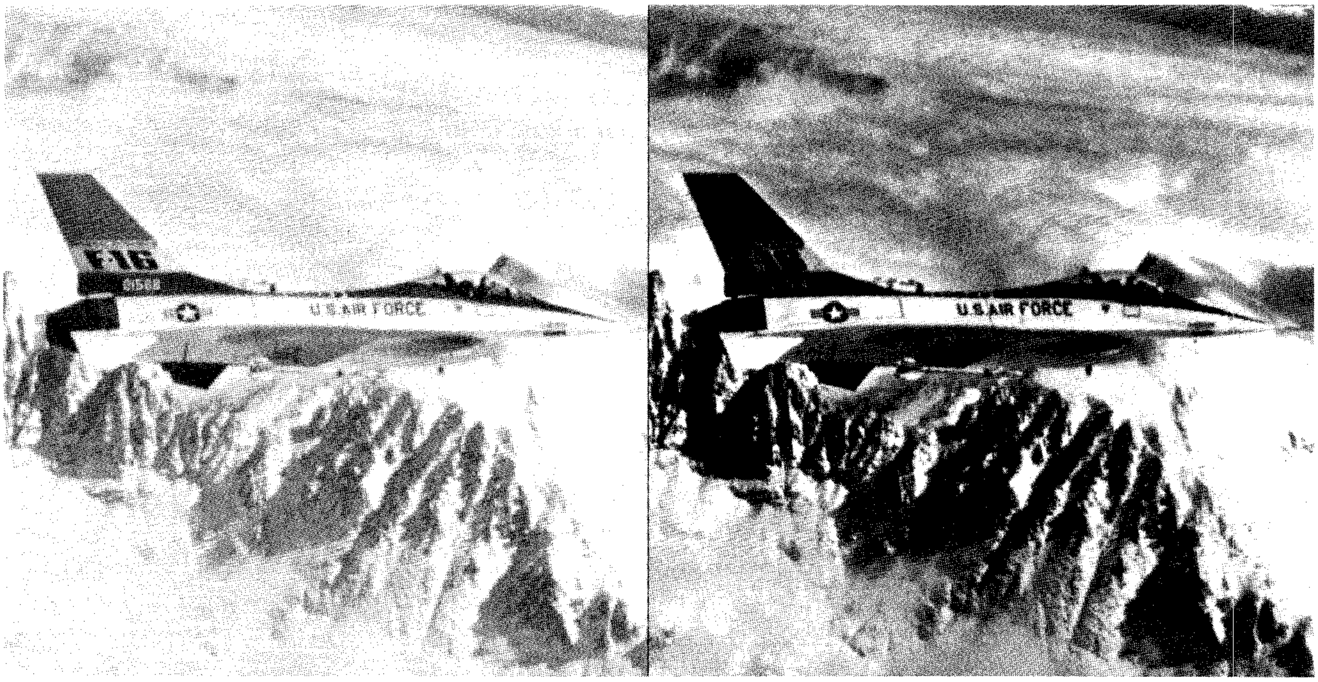

Figure 4: The original image *F16* and the result of histogram equalization.

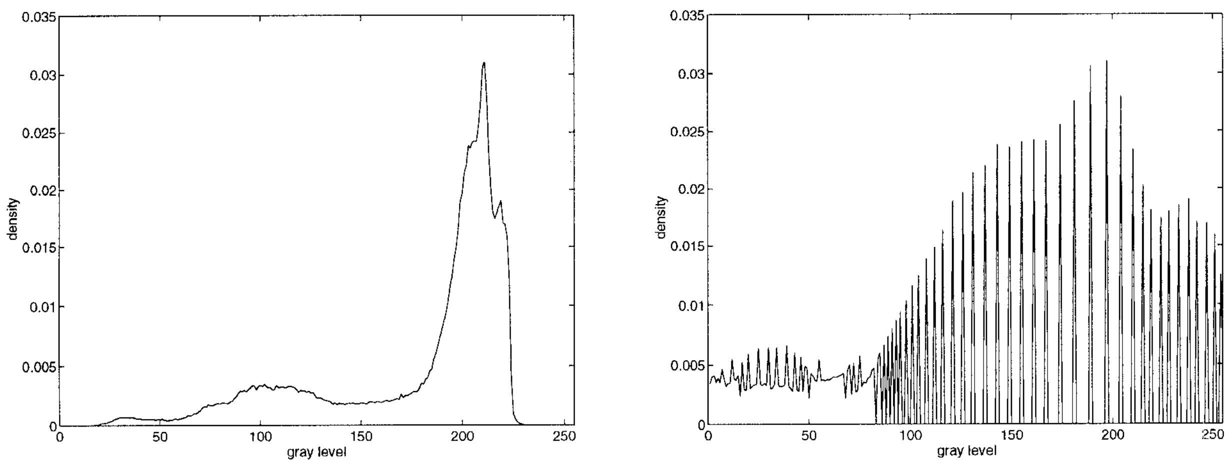

Figure 5: The respective histograms of the images shown in Fig. 4.

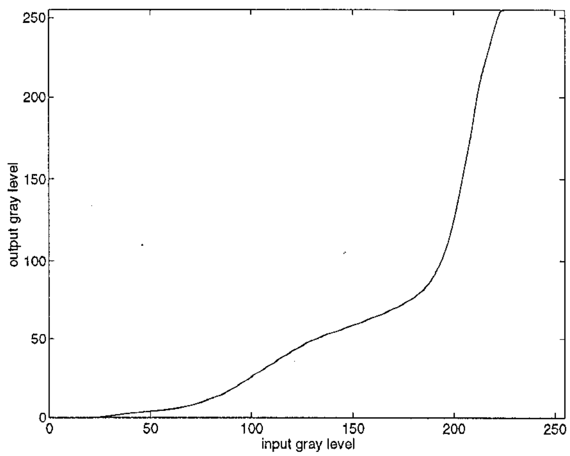

Figure 6: The transform function associated with (3) for *F16*.

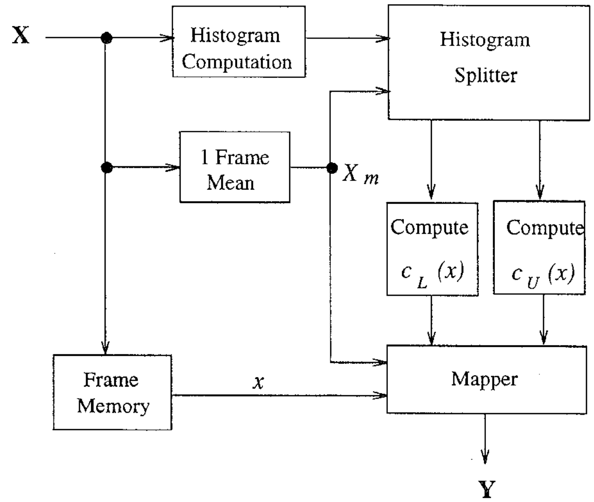

Figure 7: The functional block diagram of the BBHE for H/W realization.

range (X_0, X_m) whereas $f_U(\mathbf{X}_U)$ equalizes the subimage $\mathbf{X}_U$ over the range (X_{m+1}, X_{L-1}). As a consequence, the input image $\mathbf{X}$ is equalized over the entire dynamic range (X_0, X_{L-1}) with the constraint that the samples less than the input mean are mapped to (X_0, X_m) and the samples greater than the mean are mapped to (X_{m+1}, X_{L-1}).

The functional block diagram for realizing the proposed algorithm in H/W is shown in Fig. 7, in which the histogram computation unit counts and stores the respecitve numbers of occurrences n_k for $k = 0, 1, \cdots, L-1$, the histogram splitter then splits the number of occurrences as $(n_0, \cdots, n_m)$ and $(n_{m+1}, \cdots, n_{L-1})$, the respective and independent cumulative density functions $c_L(x)$ and $c_U(x)$ are then computed based on $(n_0, n_1, \cdots, n_m)$ and $(n_{m+1}, \cdots, n_{L-1})$, respectively, and where the mapper outputs $Y(i,j)$ as

$$Y(i,j) = \begin{cases} X_0 + (X_m - X_0)c_L(x), & \text{if } x \leq X_m \\ X_{m+1} + (X_{L-1} - X_{m+1})c_U(x), & \text{else} \end{cases} \tag{19}$$

which is based on the equation (16). Note that the computations of the histograms and mean typically need to be done during one frame period; thus, a frame memory to store the image being processed is necessary as shown in Fig. 7. However, it is also possible to reject the frame memory if we note that there usually exists high correlation in video signal between adjacent frames. This is also claimed in [5].

4. ANALYSIS ON THE BRIGHTNESS CHANGE BY THE BBHE

Suppose that $\mathbf{X}$ is a continuous random variable, i.e., $L = \infty$, then the output of the histogram equalization, $\mathbf{Y}$ is also regarded as a random variable. It is well known that the histogram equalization produces an image whose gray levels have a uniform density, i.e.,

$$p(x) = 1/(X_{L-1} - X_0) \tag{20}$$

for $X_0 \leq x \leq X_{L-1}$ [2]. Thus, it is easy to show that the mean brightness of the output image of the histogram equalization is the middle gray level since

$$\begin{aligned} E(\mathbf{Y}) &= \int_{X_0}^{X_{L-1}} xp(x)dx && (21) \\ &= \int_{X_0}^{X_{L-1}} \frac{x}{X_{L-1} - X_0} dx && (22) \\ &= \frac{X_0 + X_{L-1}}{2}, && (23) \end{aligned}$$

where $E(\cdot)$ denotes a statistical expectation. It should be emphasized here that the output mean of the histogram equalization has nothing to do with the input image. That is, it is always the middle gray level no matter how much the input image is bright/dark. Clearly, this property is not desirable in many applications.

Turning our attention to the mean change by the BBHE, suppose that $\mathbf{X}$ is a random variable which has a symmetric distribution around its mean X_m.

If we note that the subimages are equalized independently, the mean brightness of the output of the BBHE can be expressed as

$$\begin{aligned} E(\mathbf{Y}) &= E(\mathbf{Y}|\mathbf{X} \le X_m)Pr(\mathbf{X} \le X_m) \\ &\quad + E(\mathbf{Y}|\mathbf{X} > X_m)Pr(\mathbf{X} > X_m) \\ &= \frac{1}{2}\{E(\mathbf{Y}|\mathbf{X} \le X_m) \\ &\quad + E(\mathbf{Y}|\mathbf{X} > X_m)\} \end{aligned} \tag{24}$$

where we used $Pr(\mathbf{X} \le X_m) = Pr(\mathbf{X} > X_m) = \frac{1}{2}$ since $\mathbf{X}$ is assumed to have a symmetric distribution around X_m. With the similar discussion used to obtain (22), it can be easily shown that

$$E(\mathbf{Y}|\mathbf{X} \le X_m) = (X_0 + X_m)/2 \tag{25}$$

and

$$E(\mathbf{Y}|\mathbf{X} > X_m) = (X_m + X_{L-1})/2. \tag{26}$$

The use of (24) and (25) in (23) results in

$$E(\mathbf{Y}) = \frac{1}{2}(X_m + X_G), \tag{27}$$

where

$$X_G = \frac{X_0 + X_{L-1}}{2}) \tag{28}$$

is the middle gray level, which implies that the mean brightness of the equalized image by the BBHE locates in the middle of the input mean and the middle gray level. Note that the output mean of the BBHE is a function of the input mean brightness X_m. This fact clearly indicates that the BBHE preserves the brightness compared to the case of typical histogram equalization where the output mean is always the middle gray level.

5. SIMULATION RESULTS

To demonstrate the performance of the proposed algorithm, simulation results of the BBHE for the given images shown in Figs. 3 and 4 are presented in Fig. 8. Observe that the brightness of the original images are preserved well compared to the results of the histogram equalization shown in Figs. 3 and 4. Also observe that the BBHE results in more natural enhancement around the cloud than the typical histogram equalization. The contrasts around the letters on the tail-wing of the *F16* are enhanced whereas the typical histogram equalization is failed as discussed previously. The output histogram of the BBHE for the image *F16* is depicted in Fig. 9. The simulation results clearly show that the proposed algorithm outperforms the typical histogram equalization in points that it preserves the mean brightness of a given image while enhancing the contrast, and consequentially it results in more natural enhancement.

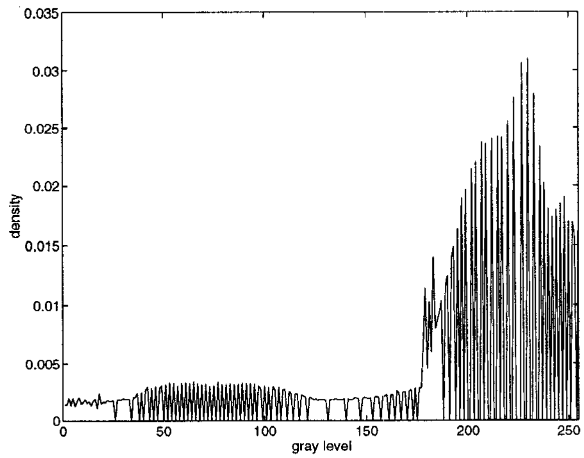

Figure 9: The histogram of F16 after enhanced by the BBHE.

6. CONCLUSION

In this paper, a newly developed contrast enhancement algorithm referred to as the *rightness preserving bi-histogram equalization* (BBHE) is proposed. The BBHE is a novel extension of a typical histogram equalization, which utilizes independent histogram equalizations over two subimages obtained by decomposing the input image based on its mean. The ultimate goal behind the BBHE is to preserve the mean brightness of a given image while enhancing the contrast of a given image. Analysis on the output mean of the BBHE for a given analog image having symmetric distribution is also established mathematically, which indicates that the BBHE is capable of preserving the mean brightness of a given image. Simulation results also demonstrate the brightness-preserving function of the BBHE while enhancing contrasts. Hence, many applications can be made possible by utilizing the proposed algorithm in the field of consumer electronics, such as TV, VTR, or, camcorder. In the view point of H/W implementation, however, the proposed algorithm requires more complicated H/W than the typical histogram equalization. For effective use of the proposed algorithm in applications, an effort to

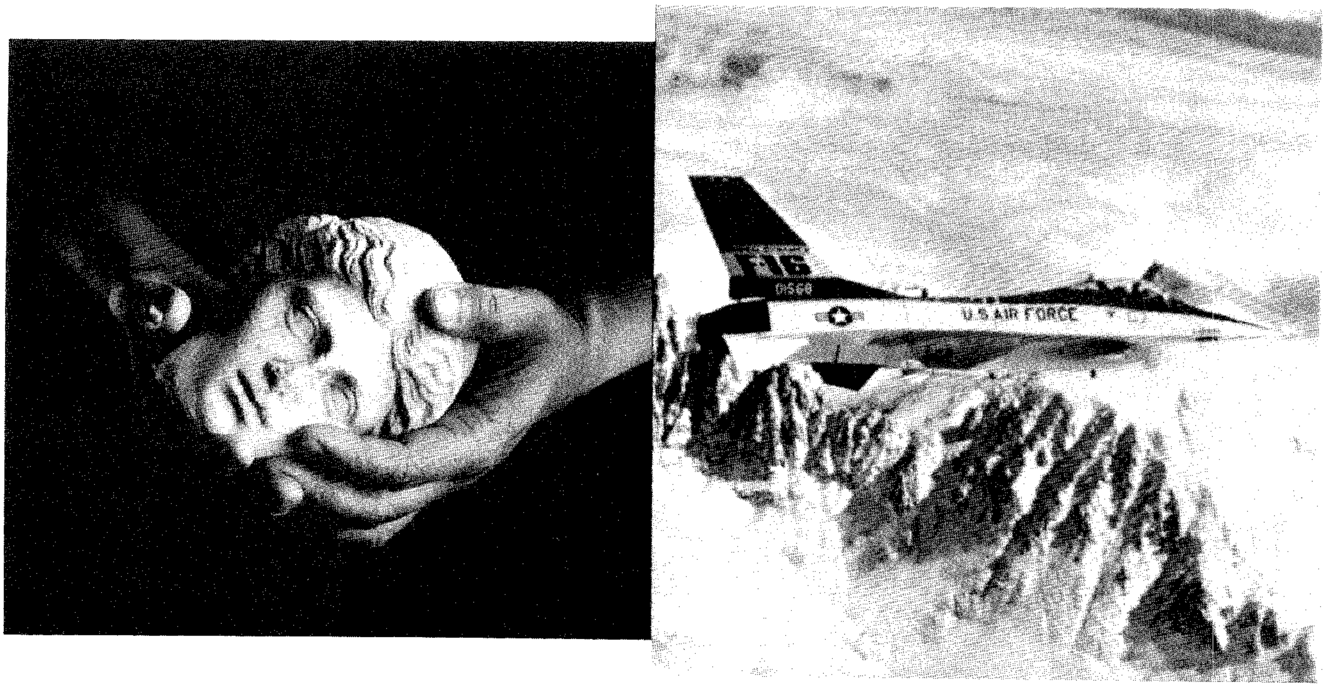

Figure 8: The results of the BBHE for the original images shown in Figs. 3 and 4

reduce the complexity should be made such as the method introduced in [6] which makes use of quantized probability density functions.

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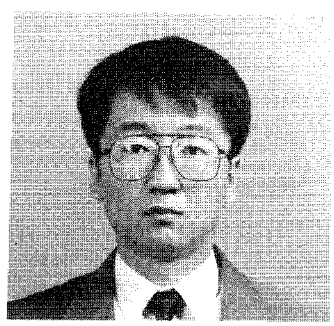

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