SDALA: SIMULTANEOUS DYNAMIC RANGE COMPRESSION AND LOCAL CONTRAST ENHANCEMENT ALGORITHM

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ABSTRACT

This paper presents a novel simultaneous dynamic range compression and local contrast enhancement algorithm, termed as SDALA, to resolve low dynamic range (LDR) image enhancement problem. The proposed SDALA is able to combine with any differentiable intensity transfer function, which greatly increases the applicability of the proposed method. Moreover, the proposed method can separately control the level of enhancement on the overall lightness and contrast achieved at the output. Experimental results validate the performance of the proposed method by comparing with two existent methods, both quantitatively and visually.

Index Terms**—**Low dynamic range image enhancement, dynamic range compression, local contrast enhancement

1. INTRODUCTION

In recent years, digital video cameras have been widely used in several applications. Although video capture becomes an easy task, the images taken from a camera usually suffer from certain defects, such as noises, low dynamic range, poor contrast, and color distortion, etc. This paper addresses two common defects: low dynamic range and poor contrast.

Several existing methods have provided functions of dynamic range compression and local contrast enhancement, and most of them solve both problems separately by using two different algorithms [1-2]. In [1], Tao *et al*. proposed an adaptive and integrated neighborhood-dependent approach for nonlinear enhancement (AINDANE) which is comprised of two separate processes, namely, adaptive luminance enhancement and adaptive contrast enhancement. The adaptive luminance enhancement is employed to compress the dynamic range of the image, and the adaptive contrast enhancement is applied to restore the contrast after luminance enhancement. The authors also developed a similar but efficient nonlinear image enhancement algorithm to enhance the image quality for improving the performance of face detection [2]. However, the common drawback of these two methods is that the two-stage procedure may induce undesired artifacts in each stage and could not produce satisfactory outputs.

This paper presents a single-stage procedure to resolve LDR image enhancement problem. A novel general form of SDALA that is able to combine with any monotonically increasing and continuously differentiable intensity transfer function, such as the typical gamma curve, is proposed. Based on this general form, the proposed method can simultaneously accomplish dynamic range compression and local contrast enhancement. In the experiments, the performance of the proposed method is validated by comparing with two recently published methods, both quantitatively and visually.

2. THE GENERAL FORM OF SDALA

This section presents the derivation of the proposed method to simultaneously enhance image contrast and dynamic range. A local contrast preserving condition is first introduced. The general form of SDALA is then derived based on this condition. A brief discussion on the property of SDALA is also presented.

2.1. Image Enhancement with Local Contrast Preservation

Since human vision is very sensitive to spatial frequency, the visual quality of an image highly depends on the local image contrast which is commonly defined by using Michelson or Weber contrast formula [3]. Let $I_{in}(x,y)$ and $I_{avg}(x,y)$, respectively, denote the input luminance level and the corresponding local average one of each pixel (x,y). The Weber contrast formula is then given by

$$Contrast_{Weber}(x,y) = [I_{avg}(x,y)]^{-1}[I_{in}(x,y) - I_{avg}(x,y)], \quad (1)$$

where $Contrast_{Weber} \in [-1,+\infty)$ is the local contrast value of the input luminance image. Based on the Weber contrast value (1), the local contrast preserving condition of a general image enhancement processing is described as follows [4]

$$[g_{avg}(x,y)]^{-1} g_{out}(x,y) = [I_{avg}(x,y)]^{-1} I_{in}(x,y), \quad (2)$$

where $g_{out}(x,y)$ and $g_{avg}(x,y)$, respectively, denote the output luminance level and the corresponding local average one of each pixel (x,y). Operating on expression (2) by $g_{avg}(x,y)$ gives

$$g_{out}(x,y) = [I_{avg}(x,y)]^{-1} g_{avg}(x,y) \times I_{in}(x,y), \quad (3)$$

where $g_{avg}(x,y)$ usually is a function of $I_{in}(x,y)$. Therefore, expression (3) presents a basic form in the spatial domain for image enhancement with local contrast preservation.

2.2. The Proposed Method

In traditional dynamic range compression methods, the remapped luminance image, $y_T(x,y)$, is usually obtained from a fundamental intensity transfer function such that

$$y_T(x,y) = T[I_{in}(x,y)], \quad (4)$$

where $T[\bullet] \in C^1$ is an arbitrary monotonically increasing and continuously differentiable intensity mapping curve. According to expression (4), the output local average luminance level of each pixel can be approximated by using the first-order Taylor series expansion such that

$$g_{avg}(x,y) = T[I_{in}(x,y)] + T'[I_{in}(x,y)] \times [I_{avg}(x,y) - I_{in}(x,y)], \quad (5)$$

where $T'[I_{in}(x,y)] = dT[X]/dX|_{X=I_{in}(x,y)}$. By substituting (5) into (3), the basic formula of dynamic range compression with local contrast preservation is obtained as follows.

$$g_{out}(x,y) = \bar{I}_{in}(x,y) \times y_T(x,y) + [1 - \bar{I}_{in}(x,y)] \times y_{lcp}(x,y), \quad (6)$$

where $g_{out}(x,y)$ denotes the enhanced output luminance level of each pixel, $y_{lcp}(x,y) = T'[I_{in}(x,y)] \times I_{in}(x,y) \geq 0$ is the component of local contrast preservation, and $\bar{I}_{in}(x,y) = I_{in}(x,y)/I_{avg}(x,y)$ for $I_{avg}(x,y) \neq 0$ is a weighting coefficient which ranges from 0 to 256. Expression (6) shows that when $\bar{I}_{in}(x,y) \cong 0$ the local contrast preservation component $y_{lcp}(x,y)$ dominates the enhanced output $g_{out}(x,y)$. On the other hand, when $\bar{I}_{in}(x,y) \cong 1$ the output in (6) is close to the fundamental intensity mapping result $y_T(x,y)$. Otherwise, the enhanced output $g_{out}(x,y)$ is a linear combination between the fundamental intensity mapping component $y_T(x,y)$ and the local contrast preservation component $y_{lcp}(x,y)$.

In order to achieve local contrast enhancement, one of the common used enhancement schemes is the linear unsharp masking (LUM) algorithm, which enhances the local contrast of output image by amplifying high-frequency components such that [5]

$$g_{out}^{LUM}(x,y) = I_{in}(x,y) + \lambda I_{high}(x,y), \quad (7)$$

where $I_{high}(x,y) = I_{in}(x,y) - I_{avg}(x,y)$ denotes the high-frequency components of input image, and λ is a nonnegative scaling factor that controls the level of local contrast enhancement. Based on the concept of LUM algorithm, we modify the output local average luminance (5) into an unsharp masking form such that

$$g_{avg}(x,y) = T[I_{in}(x,y)] + \alpha T'[I_{in}(x,y)] \times [I_{avg}(x,y) - I_{in}(x,y)], \quad (8)$$

where $\alpha = \{-1, 1\}$ is a two-valued parameter that determines the property of contrast enhancement. When $\alpha = 1$, expression (8) is equivalent to (5) that provides local contrast preservation for the output local average luminance. In contrast, when $\alpha = -1$, expression (8) becomes a LUM equation with $\lambda = T'[I_{in}(x,y)] \geq 0$ to achieve local contrast enhancement of output local average luminance. Based on this observation, the general form for simultaneous dynamic range compression and local contrast enhancement algorithm is then obtained by substituting (8) into (3) with a normalization factor such that

$$g_{out}(x,y) = \left\{ \begin{array}{l} f_n^{-1}(x,y) \times \{\bar{I}_{in}(x,y) \times y_T(x,y) \\ \qquad + [1 - \bar{I}_{in}(x,y)] \times y_{lce}(x,y)\} \end{array} \right\}_0^1, \quad (9)$$

where $y_{lce}(x,y) = \alpha \times y_{lcp}(x,y)$ denotes the component of local contrast enhancement for each pixel, $f_n \in [\varepsilon, 1]$ denotes a normalization factor to normalize the output, and ε is a small positive value to avoid dividing by zero. The operator $\{x\}_a^b$ means that the value of x is bounded to the range $[a, b]$. In expression (9), the parameter α is set to 1.0 for the purpose of local contrast preservation and is set to -1.0 for the purpose of local contrast enhancement. Therefore, expression (9), referred to as the general form of SDALA, provides the capability to achieve dynamic range compression and local contrast enhancement simultaneously.

3. AN EXAMPLE STUDY

We take the conventional power-law transformation as an example to explain how the proposed method works. The simplest power-law transformation, normally termed as gamma tone-mapping curve, has the basic form

$$y_T(x,y) = T[I_{in}(x,y)] = [I_{in}(x,y)]^{\gamma}, \quad (10)$$

where γ is a nonzero and positive constant, and the value of $I_{in}(x,y)$ ranges from 0 to 1. In general, the gamma curve with $\gamma < 1$ maps a narrow range of dark input values into a wider range of output values to achieve the dynamic range compression result. However, it is difficult to preserve the local contrast in the bright region due to a compressed range of bright output values.

In order to overcome this drawback, we apply the proposed SDALA to the conventional power-law transformation to realize the function of simultaneous dynamic range compression and local contrast enhancement. The differential function of the power-law transformation (10) is given by

$$T'[I_{in}(x,y)] = \gamma [I_{in}(x,y) + \varepsilon]^{(\gamma-1)}, \quad (11)$$

where ε is a small positive value to avoid dividing by zero when $I_{in}(x,y)$ is equal to zero. According to expression (11), the local contrast enhancement component is then computed such that

$$y_{lce}(x,y) = \alpha \times \gamma [I_{in}(x,y) + \varepsilon]^{(\gamma-1)} \times I_{in}(x,y), \quad (12)$$

where $\alpha = \{-1, 1\}$ is determined according to the purpose of the application. Since the output luminance image is calculated by the weighted linear combination between the results obtained from expressions (10) and (12), the weighting coefficient used in this study is calculated as follows.

$$\bar{I}_{in}(x,y)=[I_{in}(x,y)\otimes F_{LPF}(x,y)]^{-1}I_{in}(x,y), \quad (13)$$

where the operator $\otimes$ denotes the 2D convolution operation, and $F_{LPF}(x,y)$ denotes a spatial low-pass filter kernel function and is subject to the condition $\iint F_{LPF}(x,y)dxdy=1$. Finally, the SDALA output for the power-law transformation (10), denoted by $g_{gamma}(x,y)$, can be obtained by substituting (10) into (9) such that

$$g_{gamma}(x,y)=\left\{\begin{array}{l} f_n^{-1}(x,y)\times\{\bar{I}_{in}(x,y)\times[I_{in}(x,y)]^{\gamma} \\ \qquad +[1-\bar{I}_{in}(x,y)]\times y_{lce}(x,y)\}\end{array}\right\}_0^1, \quad (14)$$

where $y_{lce}(x,y)$ and $\bar{I}_{in}(x,y)$ are given by (12) and (13), respectively. The normalization factor f_n is calculated by

$$f_n(x,y)=\left\{\bar{I}_{in}^{\max}(x,y)+[1-\bar{I}_{in}^{\max}(x,y)]\times\alpha\times\gamma\right\}_{\varepsilon}^{1}, \quad (15)$$

where $\bar{I}_{in}^{\max}(x,y)=I_{in}^{\max}/I_{avg}(x,y)$ for $I_{avg}(x,y)\neq 0$ is the weighting coefficient with respect to the maximum input luminance value $I_{in}^{\max}$. In this study, the value of $I_{in}^{\max}$ is equal to 1.0.

4. EXPERIMENTAL RESULTS

In the experiments, the quantitative method depending on the statistics of visual representation [6] is employed in order to quantitatively evaluate the performance of enhancement algorithms. The following experiments focus on three issues, which include an examination of the properties of the proposed method, the quantitative comparison with recently published approaches, and the visual comparison with the results produced by these methods.

4.1. Properties of the Proposed Method

For the proposed method, the parameter α in (12) is set to -1.0 for the purpose of local contrast enhancement. Moreover, the local average of the image $I_{avg}(x,y)$ in (13) is computed from a Gaussian low-pass filter given by

$$F_{LPF}(x,y)=Ke^{-(x^2+y^2)/(Sigma)^2}, \quad (16)$$

where K is a scalar to normalize the sum of filter coefficients to 1, and *Sigma* denotes the standard deviation of Gaussian kernel. From (14) and (16), the proposed method thus controls the level of image enhancement depending on two parameters: γ (termed as *Gamma* in Figs. 1, 2) and *Sigma*. Since the value of these two parameters may drastically influence enhancement performance, it is interesting to study how they affect the enhancement results of the proposed method. Fig. 1 represents the evolution of the image quality as parameter γ increasing from 0.4 to 1.2 with *Sigma* = 16 and 32. In Fig. 1, the square symbol denotes the enhanced result by using gamma correction (10), and the diamond and triangle symbols denote the corresponding SDALA output (14) with *Sigma* = 16 and 32, respectively. From Fig. 1, it is clear that the proposed method significantly improves the enhancement results obtained from the typical gamma correction method. Moreover, the parameters γ and *Sigma* are respectively able to control the overall lightness and contrast of the enhanced output. Therefore, the proposed method provides capability to simultaneously enhance the overall lightness and contrast of the enhanced output.

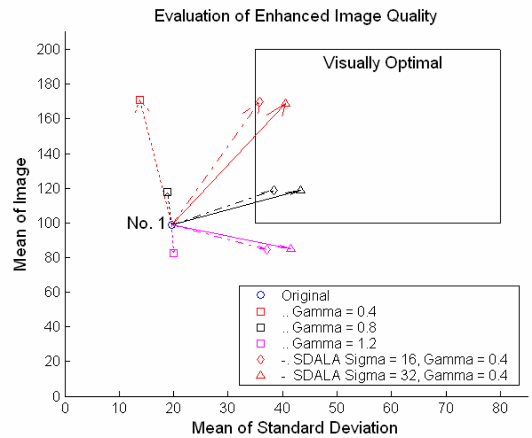

Fig. 1. Experiment results of tweaking γ from 0.4 to 1.2 by using gamma correction (10) and the SDALA output (14).

Table I. Parameter setting for each compared method

Compared Method	Parameter Setting
AINDANE [1]	*Sigma* = 32 for Gaussian filter
WDRC [7]	4th order Daubechies wavelet, d = 2.0 for contrast enhancement

4.2. Quantitative Comparison with Other Methods

The enhancement results of the proposed method are compared with those using two recently published approaches methods: the AINDANE method [1] and wavelet-based dynamic range compression (WDRC) [7]. Table I tabulates the parameter setting for each compared method used in the experiments. For the proposed method, the value for γ is fixed as 0.4, and the values for *Sigma* are both 16 and 32.

Fig. 2 illustrates the quantitative evaluation of image quality before and after enhancement processing. Note that the performance of the proposed algorithm was tested on a large number of images; however, only three evaluation results are presented in Fig. 2 in order to clarify the comparison results. As can be seen in Fig. 2, the proposed method provides more overall contrast on the enhanced output compared to AINDANE method and more overall lightness enhancement compared to WDRC method. This implies that the proposed method is able to produce the results represented with more satisfactory image quality.

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

Fig. 3. Enhancement results of test image No. 1. (a) Original picture; Enhanced by (b) AINDANE method, (c) WDRC method, the proposed SDALA with $\gamma = 0.4$ and (d) *Sigma* = 16; (e) *Sigma* = 32.

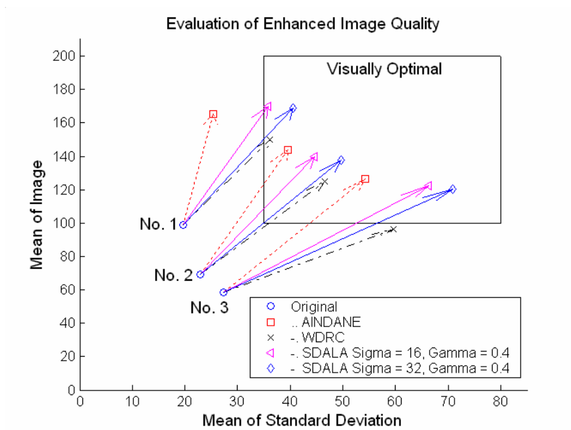

Fig. 2. Quantitative evaluation of image quality before and after enhancement processing.

4.3. Visual Comparison

Fig. 3(a) shows the test image No. 1 used in the experiments. Figs. 3(b), 3(c), 3(d), and 3(e) are the enhanced results obtained from AINDANE method, WDRC method, and the proposed SDALA with *Sigma* = 16 and 32, respectively. Obviously, the AINDANE method does not produce satisfactory image quality for Fig. 3(a) due to insufficient image contrast, and thus the quantitative evaluation of Fig. 3(b) lies outside the visually optimal region shown in Fig. 2. On the other hand, the WDRC method and the proposed method both produce satisfactory image quality; however, the proposed method provides more overall lightness and contrast on the enhanced output as Fig. 2 indicated.

5. CONCLUSION AND FUTURE WORK

This paper proposed a novel LDR image enhancement algorithm which simultaneously accomplishes dynamic range compression and local contrast enhancement. One merit of the proposed method is that it can combine with any monotonically increasing and continuously differentiable intensity transfer function, such as the typical gamma curve, to achieve dynamic range compression with local contrast preservation/enhancement for LDR images. Moreover, the proposed method possesses the adjustability to separately control the level of enhancement on the overall lightness and contrast achieved at the output. Therefore, the proposed method provides a useful lightness-contrast enhancement solution due to the flexible adjustability.

6. ACKNOWLEDGMENT

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7. REFERENCES

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