A FAST DYNAMIC RANGE COMPRESSION WITH LOCAL CONTRAST PRESERVATION ALGORITHM FOR LOW DYNAMIC RANGE IMAGE ENHANCEMENT

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ABSTRACT

This paper presents a new fast dynamic range compression format with a local-contrast-preservation (FDRCLCP) algorithm to efficiently resolve low dynamic range (LDR) image enhancement problem for natural color images. The proposed FDRCLCP algorithm can combine with any continuously differentiable intensity transfer function to achieve LDR image enhancement. In combination with the FDRCLCP algorithm, a new intensity-transfer function that achieves satisfactory dynamic-range compression while preventing over enhancement in dark regions of the image is proposed. Experimental results validate that the proposed method provides better visual representation in comparison with two existing methods.

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

1. INTRODUCTION

It is well known that human vision system can capture a scene with a wide dynamic range through various adaptive mechanisms [1, 2]. In contrast, current digital cameras can only capture images with a limited dynamic range. The captured image thus may result in poor visibility due to overexposure in bright regions and underexposure in dark regions. This problem motives the development of an image enhancement process to handle high dynamic range scenes by compressing the dynamic range of captured images. This process is commonly known as dynamic range compression.

Various dynamic range compression techniques have been proposed. To achieve better visual quality and preserve visual details, current dynamic range compression methods are usually combined with a local contrast enhancement algorithm. For instance, Tao *et al*. proposed an AINDANE (Adaptive and Integrated Neighborhood Dependent Approach for Nonlinear Enhancement) algorithm which involves two separate processes: adaptive luminance enhancement and adaptive contrast enhancement [3]. The former compresses dynamic range of the input image, and the latter restores local contrast after range compression. The authors also extended their work to color image enhancement using an illuminance-perception based adaptive dynamic range compression process [4]. Monobe *et al*. proposed a spatially variant dynamic range compression algorithm with local contrast preservation based on the concept of local contrast range transform [5]. Although these methods perform well in LDR image enhancement, the image enhancement procedure usually requires high computational costs with a large memory and leads to an inefficient algorithm. To improve computational efficiency, Unaldi *et al*. proposed a fast and robust WDRC (Wavelet-based Dynamic Range Compression) algorithm with local-contrast enhancement [6]. The processing time of WDRC algorithm is notably reduced since it fully operates in wavelet domain. Recently, Tsai *et al.* proposed a SDRCLCE (Simultaneous Dynamic Range Compression and Local Contrast Enhancement) algorithm, which improves computational efficiency via parallel processing [7]. However, this method requires computing the derivative function of a given intensity-transfer function and thus may lead to an inefficient algorithm when employing a complicated intensity-transfer function.

This paper presents a fast dynamic range compression format with a local-contrast-preservation (FDRCLCP) algorithm to efficiently resolve LDR image enhancement problem. A novel general form of FDRCLCP algorithm that can be applied to any continuously differentiable intensity-transfer function is proposed. Moreover, the proposed method does not require computing the derivative function of the intensity-transfer function. This helps leading to an efficient algorithm and achieving real-time performance in practical applications. The performance of the proposed method is validated in the experiments by comparing with two existing methods, both quantitatively and visually.

2. THE GENERAL FORM OF FDRCLCP

This section presents the derivation of the proposed method to efficiently achieve dynamic range compression with local-contrast preservation to enhance LDR images. It first introduces a local contrast-preserving condition. The general form of the FDRCLCP algorithm is then derived based on this condition.

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2.1. Image Enhancement with Local Contrast Preserving Condition

Since human vision is very sensitive to spatial frequency, the visual quality of an image depends greatly on local image contrast, commonly defined by either the Michelson or Weber contrast formula [8]. This paper utilizes the Weber contrast formula to derive the condition of local image contrast preservation.

Let $L_{in}(x,y)$ and $\overline{L}_{in}(x,y)$, 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 [8]

$$C_W(x,y) = [\overline{L}_{in}(x,y)]^{-1}[L_{in}(x,y) - \overline{L}_{in}(x,y)], \quad (1)$$

where $C_W \in [-1,+\infty)$ is the local contrast value of the input luminance image. Based on the Weber contrast formula (1), the local contrast preserving condition of a general image enhancement processing can then be described as follows [5]

$$\frac{L_{out}(x,y)}{\overline{L}_{out}(x,y)} = \frac{L_{in}(x,y)}{\overline{L}_{in}(x,y)}, \quad (2)$$

where $L_{out}(x,y)$ and $\overline{L}_{out}(x,y)$, respectively, denote the output luminance level and the corresponding local average one of each pixel (x,y). Operating on equation (2) by $\overline{L}_{out}(x,y)$ gives

$$L_{out}(x,y) = \frac{\overline{L}_{out}(x,y)}{\overline{L}_{in}(x,y)} L_{in}(x,y), \quad (3)$$

where $\overline{L}_{out}(x,y)$ usually is a function of $L_{in}(x,y)$. Therefore, equation (3) presents a basic formula in the spatial domain to enhance an image while preserving local contrast.

2.2. General Form of FDRCLCP Algorithm

This subsection applies basic form (3) to dynamic range compression with local-contrast preservation for LDR image enhancement. In traditional dynamic range compression methods, the remapped luminance image, denoted by $L_T(x,y)$, usually comes from a fundamental intensity transfer function

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

where $T[\bullet]: \Re \to \Re$ is an intensity-mapping function assumed to be continuously differentiable at $L_{in}(x,y)$. According to equation (4), the best affine approximation to T near $L_{in}(x,y)$ can be approximated by using the first-order Taylor expansion such that

$$T[X] \cong T[L_{in}(x,y)] + T'[L_{in}(x,y)][X - L_{in}(x,y)], \quad (5)$$

where $T'[L_{in}(x,y)] = dT[X]/dX\big|_{X=L_{in}(x,y)}$. Let Ω_{xy} denote a neighborhood of specified size, centered at (x, y). The value of input local average luminance of the pixels in Ω_{xy} can be computed by

$$\overline{L}_{in}(x,y) = \sum_{(i,j)\in\Omega_{xy}} w_{i,j} L_{in}(x+i, y+j), \quad (6)$$

where $w_{i,j}$ for $(i,j) \in \Omega_{xy}$ are the weights satisfying $\sum_{(i,j)\in\Omega_{xy}} w_{i,j} = 1$. Suppose that

$$\overline{L}_{out}(x,y) = \sum_{(i,j)\in\Omega_{xy}} w_{i,j} L_T(x+i, y+j). \quad (7)$$

Then letting $X = \overline{L}_{in}(x,y)$ and substituting (6) into (5) yields

$$\begin{aligned} T[\overline{L}_{in}(x,y)] &\cong T[L_{in}(x,y)] + \\ &\quad T'[L_{in}(x,y)][\sum_{(i,j)\in\Omega_{xy}} w_{i,j} L_{in}(x+i,y+j) - L_{in}(x,y)] \\ &\cong \sum_{(i,j)\in\Omega_{xy}} w_{i,j} T[L_{in}(x+i,y+j)] = \sum_{(i,j)\in\Omega_{xy}} w_{i,j} L_T(x+i,y+j). \end{aligned} \quad (8)$$

Observing (7) and (8) finds that the following relationship is satisfied

$$\overline{L}_{out}(x,y) \cong T[\overline{L}_{in}(x,y)]. \quad (9)$$

By substituting (9) into (3), a basic formula to efficiently achieve dynamic range compression with local-contrast preservation yields

$$L_{out}(x,y) = \frac{T[\overline{L}_{in}(x,y)]}{\overline{L}_{in}(x,y)} L_{in}(x,y), \quad (10)$$

where $L_{out}(x,y)$ denotes the enhanced output luminance level of each pixel. Based on equation (10), the general form for fast dynamic range compression with the local-contrast preservation algorithm emerges as follows:

$$L_{out}(x,y) = \left\{ \frac{T[\overline{L}_{in}(x,y)]}{\overline{L}_{in}(x,y)} L_{in}(x,y) \right\}_0^1, \quad (11)$$

where operator $\{L\}_a^b$ means that the value of L is bounded to range $[a, b]$. Equation (11) implies that if T is a continuously differentiable function, then the input-output mapping ratio can be fully determined by the given intensity-transfer function T and the value of input local average luminance. This feature simplifies the enhancement process and helps achieving real-time performance. Here, equation (11) gives the general form of the FDRCLCP algorithm.

Note that the local contrast range transform (LCRT) formula proposed in [5] is also derived from the local contrast-preserving condition (2), implying that the proposed method produces similar results with the LCRT formula. However, there are two main differences between the proposed FDRCLCP formula (11) and the LCRT formula. First, the LCRT formula adopts a linear approximated power function associated with the mapping function T, the derivative function of T, the input value L_{in} and the local average value $\overline{L}_{in}$ with high computational costs and a large memory requirement, leading to an inefficient algorithm. By contrast, the proposed FDRCLCP formula adopts a linear approximated ratio function associated only with the function T and the local average value $\overline{L}_{in}$, leading to an efficient algorithm in practical application. Secondly, the LCRT formula requires the derivative function of T that dramatically increases computational costs when using a complicated mapping function T. By contrast, the proposed method only requires the mapping function T to determine the input-output mapping ratio. When implemented, the computation of the proposed method is more efficient than the LCRT formula, and is thus better suited to meet the requirements of real-time applications.

3. AN EXAMPLE STUDY

We take the AINDANE algorithm, previously mentioned in Introduction, as an example to explain how the proposed method works. The AINDANE algorithm is a well-known method in color image enhancement. This section first gives a brief introduction to this algorithm and then presents how the proposed FDRCLCP formula applied on it.

3.1. The AINDANE Algorithm

The AINDANE algorithm consists of two processes: adaptive luminance enhancement and adaptive contrast enhancement. Let $L_{in} \in [0,1]$ be the normalized luminance component of an input color image. The adaptive luminance enhancement process first compresses the dynamic range of an input luminance image using the following nonlinear transfer function

$$T_1[L_{in}(x,y)] = \frac{1}{2}\left\{ \begin{array}{r} L_{in}^{(0.75z+0.25)}(x,y) + L_{in}^{(2-z)}(x,y) + \\ 0.4(1-z)[1-L_{in}(x,y)] \end{array} \right\}, \quad (12)$$

where the parameter z is determined by an intensity level L related to the darkness of the input luminance image such that

$$z = \begin{cases} 0, & \text{for } L \le 50 \\ \dfrac{L-50}{100}, & \text{for } 50 < L \le 150 \\ 1, & \text{for } L > 150. \end{cases}$$

The adaptive contrast enhancement process next enhances the contrast of the range-compressed luminance image using a center-surround contrast enhancement technique as follows:

$$L_{out}^{AINDANE}(x,y) = T_1[L_{in}(x,y)]^{\left(\frac{\bar{L}_{in}(x,y)}{L_{in}(x,y)}\right)^P}, \quad (13)$$

where the parameter P is related to the global standard deviation σ_g of the input luminance image such that

$$P = \begin{cases} 3, & \text{for } \sigma_g \le 3 \\ \dfrac{27-2\sigma_g}{7}, & \text{for } 3 < \sigma_g < 10 \\ 1, & \text{for } \sigma_g \ge 10. \end{cases}$$

Because the AINDANE algorithm only processes the luminance component of the input image, it requires combining with a linear color restoration process to deal with color image enhancement. The existing linear color restoration process usually works in RGB color space. Let $\mathbf{P}_{in}^{RGB} = [R_{in} \quad G_{in} \quad B_{in}]^T$ and $\mathbf{P}_{out}^{RGB} = [R_{out} \quad G_{out} \quad B_{out}]^T$, respectively, denote the input and output color value of each pixel in RGB color space. Then, the linear color restoration process for each input RGB color pixel can be expressed as:

$$\mathbf{P}_{out}^{RGB}(x,y) = \alpha(x,y)\mathbf{P}_{in}^{RGB}(x,y), \quad (14)$$

where $\alpha(x,y)$ is a nonnegative color-mapping ratio given by

$$\alpha(x,y) = \frac{L_{out}^{AINDANE}(x,y) + \varepsilon}{L_{in}(x,y) + \varepsilon}, \quad (15)$$

where ε is a small positive value to avoid dividing by zero. Eq. (14) is able to preserve color information of the original image for minimal color shifts in the enhanced result.

3.2. Application of FDRCLCP Formula into the AINDANE Algorithm

Since the intensity-transfer function given by (12) is continuously differentiable, the proposed FDRCLCP formula (11) can be applied to this function accordingly. That is, substituting (12) into (11) yields the FDRCLCP output as follows:

$$\begin{aligned} L_{out1}^{FDRCLCP}(x,y) &= \left\{ \frac{T_1[\bar{L}_{in}(x,y)]}{\bar{L}_{in}(x,y)} L_{in}(x,y) \right\}_0^1 \\ &= \left\{ \frac{1}{2}\left\{ \begin{array}{r} [\bar{L}_{in}(x,y)+\varepsilon]^{(0.75z+0.25-1)} + \bar{L}_{in}^{(1-z)}(x,y) + \\ 0.4(1-z)\{[\bar{L}_{in}(x,y)+\varepsilon]^{-1} - 1\} \end{array} \right\} L_{in}(x,y) \right\}_0^1, \end{aligned} \quad (16)$$

where ε is previously defined in (15). The computation of local average $\bar{L}_{in}(x,y)$ can be achieved by convolution with a spatial low-pass filter such that

$$\bar{L}_{in}(x,y) = L_{in}(x,y) \otimes F_L(x,y), \quad (17)$$

where the operator $\otimes$ denotes the 2D convolution operation, and $F_L(x,y)$ denotes a spatial low-pass filter kernel function and is subject to the condition $\sum_x \sum_y F_L(x,y) = 1$. To obtain better enhancement results, another method with acceptable computing performance is to use a combined-scale Gaussian filter [6] defined as

$$F_L(x,y) = \frac{1}{n}\sum_{i=1}^{n} K_i e^{-(x^2+y^2)/(2^{i-1}\sigma)^2}, \quad (18)$$

where n is the number of scales, K_i is the scalar of ith filter to normalize the sum of filter coefficients to 1, and σ denotes the standard deviation of the small-scale Gaussian kernel. Here, we use n=3. Note that the proposed FDRCLCP formula is able to enhance local contrast of the image without an extra contrast enhancement process (Fig. 1). This is the main advantage of the proposed FDRCLCP output (16) over the AINDANE output (13).

4. THE PROPOSED LDR IMAGE ENHANCEMENT ALGORITHM

The AINDANE method usually performs well in LDR image enhancement; however, it may over-enhance dark regions of the image. Fig. 2(a) shows the intensity mapping curve processed by the nonlinear transfer function (12) and explains how this problem occurred by the AINDANE method. From Fig. 2(a), one can see that when z<1 the nonlinear transfer function (12) remaps a zero-value input to a nonzero-value output. According to

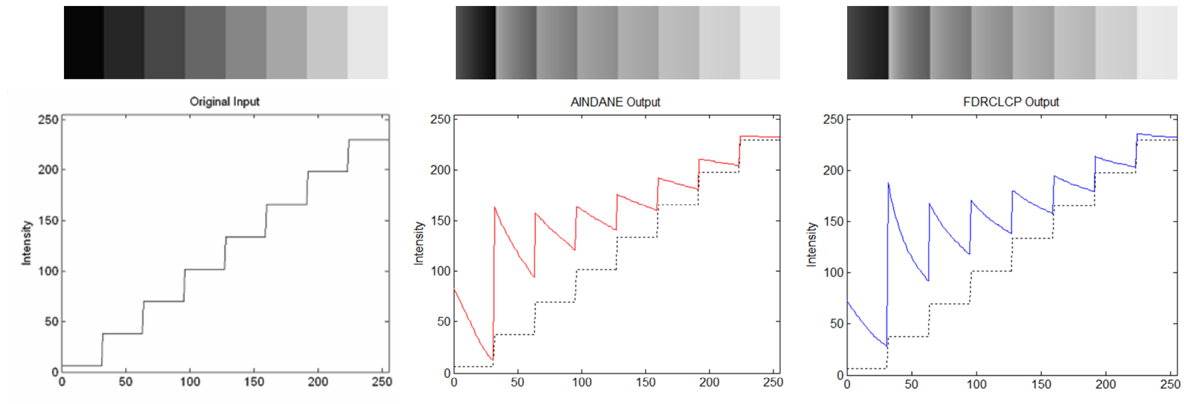

Fig. 1. Top row: (a) original grayscale image, enhanced result of (b) the AINDANE output (13) and (c) the proposed FDRCLCP output (16). Bottom row: the corresponding pixel data of scan lines.

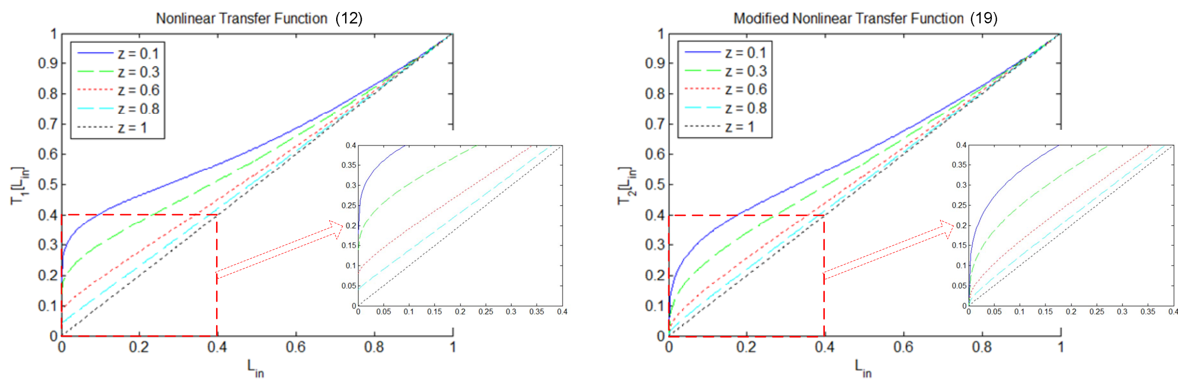

Fig. 2. The intensity mapping curve processed by (a) the nonlinear transfer function (12) and (b) the modified nonlinear transfer function (19) with φ=0.25.

(15), this feature leads to a large color-mapping ratio for a dark pixel and thus usually produces color artifacts in the dark region of the image. This problem highlights the importance to design a new intensity-transfer function that achieves satisfactory dynamic-range compression while preventing over enhancement in the dark region of the image.

4.1. A New Intensity-Transfer Function

Observing the intensity-transfer function (12) finds that the over enhancement problem mentioned above is caused by the third term in the braces. Hence, a modification on this term to guarantee that the output equals to zero when L_{in}=0 is proposed as follows:

$$T_2[L_{in}(x,y)] = \frac{1}{2}\left\{ \begin{array}{l} L_{in}^{[(1-\varphi)z+\varphi]}(x,y) + L_{in}^{(2-z)}(x,y) + \\ \quad 0.4(1-z)L_{in}^{\varphi}(x,y)(1-L_{in}(x,y)) \end{array} \right\}, \tag{19}$$

where the parameter $\varphi \in (0,1)$ controls the level of dynamic-range compression achieved at the output. That is, a smaller (larger) value of φ provides more (less) dynamic-range compression for dark pixels. Fig. 2(b) illustrates the intensity mapping curve processed by the modified nonlinear transfer function (19) with φ=0.25. From Fig. 2(b), it is clear that the proposed transfer function (19) satisfies a zero-input, zero-output condition for all $z \in [0,1]$. This property helps achieving an acceptable dynamic-range compression result with less color artifacts and will be validated in the experiment section.

4.2. Application of FDRCLCP Formula into the New Intensity-Transfer Function

The modified nonlinear transfer function (19) satisfies the continuously differentiable condition; therefore, the proposed algorithm is derived by applying the proposed FDRCLCP formula (11) to this function such that

$$\begin{aligned} L_{out2}^{FDRCLCP}(x,y) &= \left\{ \frac{T_2[\bar{L}_{in}(x,y)]}{\bar{L}_{in}(x,y)} L_{in}(x,y) \right\}_0^1 \\ &= \left\{ \frac{1}{2}\left\{ \begin{array}{l} (\bar{L}_{in}(x,y)+\varepsilon)^{[(1-\varphi)z+\varphi-1]} + \bar{L}_{in}^{(1-z)}(x,y) + \\ 0.4(1-z)[\bar{L}_{in}(x,y)+\varepsilon]^{(\varphi-1)}[1-\bar{L}_{in}(x,y)] \end{array} \right\} L_{in}(x,y) \right\}_0^1 . \end{aligned} \tag{20}$$

For the enhancement of color images, the linear color restoration process (14) is employed, but using $L_{out2}^{FDRCLCP}$ instead of $L_{out}^{AINDANE}$ in (15).

5. EXPERIMENTAL RESULTS

The following experiments focus on two issues, which include an examination of the properties of the proposed method and comparisons with two existing enhancement approaches, both quantitatively and visually.

5.1. Properties of the Proposed Method

From (17), (18) and (20), the proposed method controls the level of image enhancement depending on two parameters: φ and σ. To study how these two parameters affect the enhancement results of the proposed method, the quantitative method depending on the statistics of visual representation [9] is employed in this experiment. Fig. 3 represents the evolution of the image quality as parameter φ increasing from 0.25 to 0.5 with $\sigma = 16$ and 32. In Fig. 3, the square symbol denotes the enhanced result by using the proposed nonlinear intensity-transfer function (19), and the triangle and diamond symbols denote the corresponding FDRCLCP output (20) with $\sigma = 16$ and 32, respectively. Fig. 3 shows that the proposed method significantly improves image contrast of the enhancement results obtained from the proposed intensity-transfer function (19). Moreover, the parameters φ and σ respectively control the overall lightness and contrast of the enhanced output. This means that the proposed method provides capability to separately enhance the overall lightness and contrast of the enhanced output.

5.2. Quantitative and Visual Comparisons

The enhancement results of the proposed method are compared with those using two existing approaches: the AINDANE method [3] and WDRC method [6]. Table I tabulates the parameter setting for each compared method used in the experiments. The values $\sigma = 16$ and $\varphi = 0.35$ are used as the default value for the proposed method. Note that, to provide a fair comparison all competing methods use the same multiple scales defined in (18) and the RGB color restoration process given by (14).

Figs. 4, 5 and 6 present the enhanced results of three LDR images. A visual comparison shows that the AINDANE and WDRC methods both produce high-range compression results, but with notable color artifacts. The proposed method, however, produces satisfactory results in range compression and contrast enhancement with slight color artifacts. The proposed method also produces a significant improvement on the visual quality of a typical LDR image captured from a video stream. In Fig. 6, each compared method produces an unnatural image with unwanted artifacts, caused by over-enhancing the dark regions of the image. On the other hand, the proposed method produces significant improvement in the resulting image by enhancing fine details in dark regions with fewer artifacts.

Table II tabulates the quantitative measure of image quality before and after enhancement processing. In Table II, the symbols $\overline{L}$ and $\overline{\sigma}$ respectively represent the mean of luminance image and the mean of regional standard deviation. It is clear from Table II that both competing methods produce better quantitative measures of image lightness and local contrast than the proposed method does; however, as can be seen in Figs. 4-6, the proposed method produces better improvement in visual quality with less color artifacts compared to these two methods.

6. CONCLUSION AND FUTURE WORK

This paper proposes a fast dynamic range compression with local-contrast preservation algorithm for digital color images. The algorithm can combine with any continuously differentiable intensity-transfer function to achieve LDR image enhancement. This property greatly increases the applicability of the proposed method. It also proposes a new nonlinear intensity-transfer function, inspired by the AINDANE method, to produce a satisfactory dynamic-range compression result with less color artifacts. By combining the FDRCLCP algorithm with the proposed nonlinear intensity-transfer function, the proposed method is able to separately adjust the level of enhancement on image lightness and local contrast. This improves the flexibility of the proposed method in practical application. In the future, extension to real-time video processing will be further investigated.

7. ACKNOWLEDGMENT

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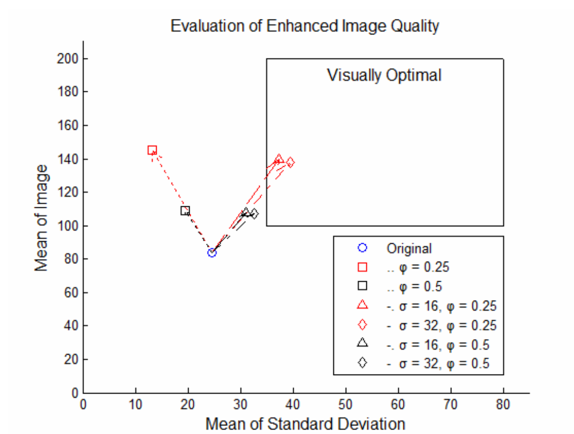


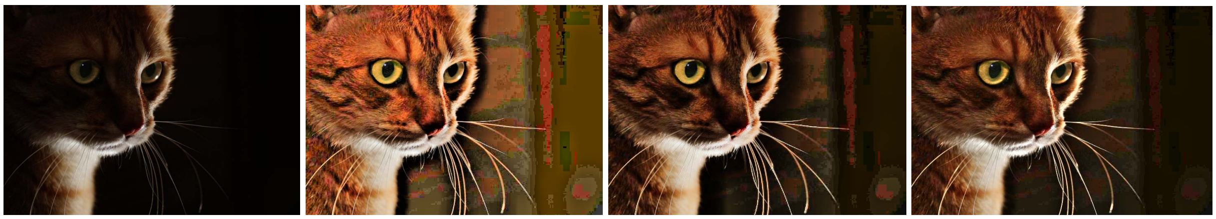
Fig. 3. Experiment results of tweaking φ from 0.25 to 0.5 by using the proposed nonlinear intensity-transfer function (19) and the FDRCLCP output (20).

Table 1. Parameter setting for each compared method used in the experiments

Compared Method	Parameter Setting
AINDANE [3]	Multi-scale with $\sigma = 16$
WDRC [6]	Multi-scale with $\sigma = 16$, 4th order Daubechies wavelet, d = 1.2 for contrast enhancement
Proposed Method	Multi-scale with $\sigma = 16$, $\varphi = 0.35$ for dynamic-range compression

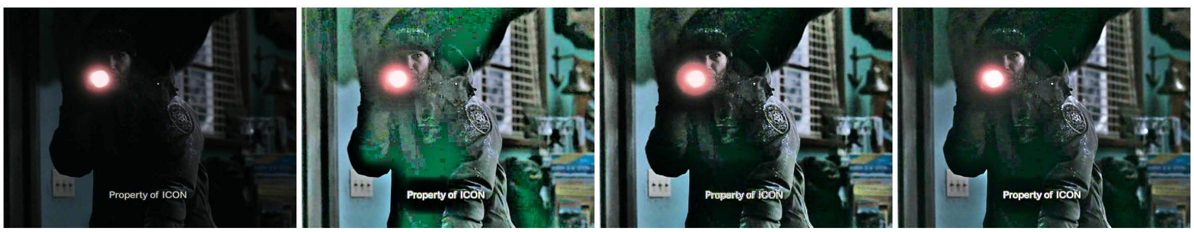
(a) (b) (c) (d)

Fig. 4. (a) Original image. Enhanced result produced by (b) the AINDANE output (13), (c) WDRC method, and (d) the proposed FDRCLCP output (20).



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

Fig. 5. (a) Original image. Enhanced result produced by (b) the AINDANE output (13), (c) WDRC method, and (d) the proposed FDRCLCP output (20).



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

Fig. 6. (a) Original image. Enhanced result produced by (b) the AINDANE output (13), (c) WDRC method, and (d) the proposed FDRCLCP output (20).

Table II. Quantitative measure of enhanced images

	Method		State-of-the-Art Methods				The Proposed Method			
	Original Image		AINDANE [3]		WDRC [6]		The Proposed Intensity-Transfer Function (19)		FDRCLCP Output (20)	
Image	$\overline{\sigma}$	$\overline{L}$	$\overline{\sigma}$	$\overline{L}$	$\overline{\sigma}$	$\overline{L}$	$\overline{\sigma}$	$\overline{L}$	$\overline{\sigma}$	$\overline{L}$
Fig. 4	4.9999	9.4869	42.7916	96.5785	32.7358	54.5106	15.9705	48.6185	20.6220	42.1954
Fig. 5	14.1927	27.5564	39.31934	121.9041	35.1483	71.9610	14.8653	80.2303	28.5542	70.8493
Fig. 6	14.2348	22.8800	46.30196	104.0488	45.9073	75.1087	16.7822	72.3407	33.0436	66.2912

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