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A variational-based fusion model for non-uniform illumination image enhancement via contrast optimization and color correction

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Non-uniform illumination images are of limited visibility due to under-exposure, over-exposure, or a combination of these two factors. Enhancing these images is a very challenging task in image processing. Although there are numerous enhancement methods to improve the visual quality of images, many of these methods produce undesirable results with regard to contrast and saturation improvements. In order to improve the visibility of images without over-enhancement or under-enhancement, a variational-based fusion method is proposed for adaptively enhancing non-uniform illumination images. First, a hue-preserving global contrast adaptive enhancement algorithm obtains a globally enhanced image. Second, a hue-preserving local contrast adaptive enhancement method produces a locally enhanced image. Finally, an enhanced result is obtained by a variational-based fusion model with contrast optimization and color correction. The final result represents a trade-off between global contrast and local contrast, and also maintains the color balance between the globally enhanced image and the locally enhanced image. This method produces visually desirable images in terms of contrast and saturation improvements. Experiments were conducted on a dataset that included different kinds of non-uniform illumination images. The results demonstrate that the proposed method outperforms the compared enhancement algorithms both qualitatively and quantitatively.

1. Introduction

The advent of digital cameras makes it very convenient to obtain images. However, some images contain poor visual details, which results from the limitations of imaging devices or environmental illuminations. To improve the visibility of images, many enhancement methods [1–8] have been proposed. Enhancement methods are able to improve the visual quality of images, so they have been widely applied to various fields of imaging, such as photography [9], medical imaging [10], and remote-sensing imaging [11]. Since image enhancement methods can improve the visibility of images, they are often used for pre-processing images in some other computer vision applications and image processing problems, including object segmentation [12], face recognition [13], and high dynamic range image rendering [14]. Moreover, these kinds of image enhancement methods are also applied in post-processing images and videos.

Images captured in uniform illumination environments can be enhanced well in terms of contrast improvements. However, most of the enhancement algorithms fail in processing non-uniform illumination images. Some existing methods [1–3,5,8,15] either under-enhance dark regions or over-enhance bright regions of images. Generally speaking, enhancement methods are categorized into two types: global enhancement algorithms and local enhancement algorithms. Usually, global enhancement methods produce over-enhanced results in the bright regions of images, while local enhancement algorithms obtain under-enhanced results in the dark regions of images. An example is shown in Fig. 1, from which we can see that the global enhancement method Histogram Equalization (HE) [15] over-enhances the bright regions and the local method Contrast-Limited Adaptive Histogram Equalization (CLAHE) [16] under-enhances the dark regions.

Inspired by the idea of exposure fusion [17], Tian and Cohen [18] proposed an enhancement method that combines globally enhanced images and locally enhanced images. This method improves the contrast both in dark regions and bright regions of images. Following the enhancement framework in [18], we consider a variational method [19] in the fusion model to improve more visibility of images. Specifically, a hue-preserving global contrast adaptive enhancement method is applied to the original non-uniform

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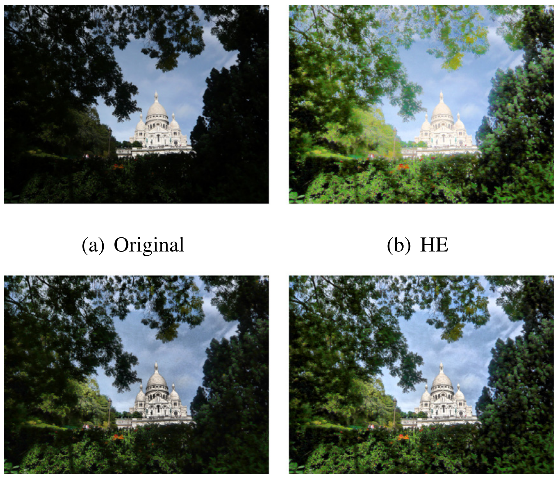

(a) Original (b) HE (c) CLAHE (d) Proposed

Fig. 1. Enhancement results by the global method Histogram Equalization (HE), local method Contrast-Limited Adaptive Histogram Equalization (CLAHE), and the proposed method. The bright regions (white building) are over-enhanced by HE. The dark regions (under-exposed tree) are under-enhanced by CLAHE. The bright regions and dark regions are both enhanced well by the proposed method.

illumination color images. Then, a hue-preserving local contrast adaptive enhancement method is applied to the original images. Finally, the enhanced results are obtained via a variational-based fusion algorithm considering contrast optimization [20,21] and color correction [22,23].

The main contributions of this paper include presenting an adaptive global contrast enhancement method, considering hue preservation in the enhancement framework, and developing a variational-based fusion model via contrast optimization and color correction.

This paper is an extended version of our previous work [18]. Compared with [18], a variational-based fusion model considering contrast optimization and color correction is proposed in this work. The proposed variational-based fusion method produces better results than [18] in terms of contrast improvement. The rest of this paper is organized as follows. The related work is briefly summarized in Section 2. The detailed description of the proposed method is presented in Section 3. Numerical experiments and performance evaluations are shown in Section 4. Finally, we give the conclusions and the future work in Section 5.

2. Related work

The proposed image enhancement method combines the results of a global enhancement method and a local enhancement method, with a variational-based image fusion framework. In this section, we will introduce some related techniques, including global enhancement methods, local enhancement methods, and image fusion models.

2.1. Global enhancement methods

Global image enhancement methods conduct the same operation on the same pixel value regardless of the corresponding neighboring pixel distribution. The simplest method is a piece-wise linear transformation [15], which defines a poly-line as the mapping function. In order to obtain more visibility of images, some global enhancement methods use various curves to map the considered images. For example, power-law functions, log functions, and gamma functions are often used for non-linear mappings, which produce better results than linear mappings. Global histograms of images can also be used for enhancements. Histogram Equalization (HE) [15] is a widely used technique for image contrast enhancement. HE modifies the original histograms of images to an approximate uniform histogram, which stretches pixel value range of images. The traditional HE might produce over-enhanced results. To avoid this problem, some improved histogram equalization methods are proposed. Arici et al. [5] proposed a general histogram equalization framework for image contrast enhancement via optimizing cost functions. Tian and Cohen [24] presented a naturalness preservation histogram-based enhancement method using structure measure and statistical naturalness measure.

2.2. Local enhancement methods

Contrast-Limited Adaptive Histogram Equalization (CLAHE) [16] is another traditional histogram-based enhancement algorithm. CLAHE considers histogram equalization in each local region. This kind of local enhancement methods [25–28] can obtain more details of images, and preserve the image naturalness. Inspired by the retinex theory [29], there are many retinex-based contrast enhancement algorithms. Considering a Gaussian kernel to build the relationship between the center pixel and surrounding pixels, Jobson et al. [30] proposed a classic retinex-based enhancement method. Recently, Petro et al. [31] improved the multiscale retinex model for image enhancement. In order to obtain better visual quality, Kimmel et al. [32] introduced a variational model to the retinex enhancement via a quadratic programming optimization. Moreover, Morel et al. [33] explored some new alternative kernels for the retinex model, which are suitable for different kinds of enhancement applications. Banić and Lončarić [6] proposed a fast retinex implementation for brightness adjustment and color correction, which avoids some disadvantages of traditional retinex enhancement methods. Provenzi et al. [4] combined color correction and local contrast improvement for color image enhancement. Palma-Amestoy et al. [20] proposed a variational framework for color image enhancement, which was inspired by the basic phenomenology of color perception. Recently, Pierre et al. [21] proposed a hue-preserving variational contrast enhancement method, which enables users to control the contrast improvement levels.

2.3. Image fusion

Image fusion is a technique of combining useful information from different images, that describe the same scene. The fused result contains better visibility than any of the input images. The fusion can be conducted on various levels, such as signal-level, pixel-level, feature-level, and symbol-level [34]. No matter which level is selected, the fusion result should meet the following two conditions: (1) the fused image preserves as much information as possible from the input images; (2) the fused image does not contain new artifacts or noise. Mertens et al. [17] proposed a practical pixel-level exposure fusion method for generating high dynamic range images. The result maintains useful information in each image sequence by using weighted blending. Ma et al. [35] proposed a feature-level robust exposure fusion model for avoiding ghosting effects. Wang et al. [36] proposed a variational method for fusing multi-focus images. A family of weight functions using the local average modulus of gradients and the power transform was adopted in Wang et al.'s method. Fu et al. [37] proposed a fusion method for combining three illumination components. This method can obtain good results for weakly-illuminated images. Inspired by the human visual system, Ying et al. [38] proposed a multi-exposure fusion method for low-light image enhancement, which produced enhanced results with small lightness distortion.