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Retinal vessel enhancement based on multi-scale top-hat transformation and histogram fitting stretching

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ABSTRACT

Retinal vessels play an important role in the diagnostic procedure of retinopathy. A new retinal vessel enhancement method is proposed in this paper. Firstly, the optimal bright and dim image features of an original retinal image are extracted by a multi-scale top-hat transformation. Then, the retinal image is enhanced preliminarily by adding the optimal bright image features and removing the optimal dim image features. Finally, the preliminarily enhanced image is further processed by linear stretching with histogram Gaussian curve fitting. The experiments results on the DRIVE and STARE databases show that the proposed method improves the contrast and enhances the details of the retinal vessels effectively.

1. Introduction

Retinal images are widely used by the ophthalmologists for disease diagnosis, and retinal blood vessels provide considerable information on pathological changes caused by many kinds of pathologies such as Age-related Macular Degeneration, Diabetic Retinopathy, and Retinopathy of Prematurity. However, the quality of retinal vessel image is usually poor due to the non-perfect imaging environment. The purpose of retinal vessel enhancement is to highlight the vessel structure [1–4]. The existing techniques for vessel enhancement include *histogram equalization* (HE) [5], *contrast limited adaptive histogram equalization* (CLAHE) [6], mathematical morphology [7,8], Gabor filter [9,10], etc. The HE method is one of the most popular methods for retinal image contrast enhancement, but some retinal vessel details are lost due to the decreasing of gray levels in the enhanced image. To overcome such weakness, the CLAHE technique is developed [11]. However, the CLAHE technique shows no obvious enhancement when the histogram of the original retinal image is narrow. It is also easy to introduce artificial boundaries at the regions where there is an abrupt change in gray levels. Oh et al. [12] proposed a medical image enhancement method based on morphological filter and differential evolution algorithm. In this method, the corresponding target image must be input in advance, which restricts its application to a large extent. Bai et al. [13] proposed an image enhancement technique based on multi-scale top-hat transformation. The method can enhance the image details better than some other methods, but it does not perform well in improving the image contrast. Fraz et al. [9] applied the 2D Gabor wavelet transformation for retinal vessel enhancement. This method can detect the retinal vessels in multiple scales and directions, but some parameters used in it are sensitive, such as the parameters σ, λ, ψ and γ.

The gray levels of retinal vessel image are centralized, and its histogram is similar to a normal distribution. Based on this observation, a novel retinal vessel enhancement method by using multi-scale top-hat transformation and histogram fitting stretching is proposed in this paper. Firstly, we extract the optimal bright and dim image features from the original retinal image using multi-scale top-hat transformation. Then, the retinal image is enhanced preliminarily by adding the optimal bright image features and removing the optimal dim image features. Finally, according to the characteristics of the histogram of the retinal image, the preliminarily enhanced image is processed by linear stretching with histogram Gaussian curve fitting. The experimental results on the DRIVE and STARE databases show that the contrast of the retinal images can be well enhanced and the retinal vessels are highlighted by using the proposed technique.

2. Algorithm description

2.1. Multi-scale top-hat transformation

Mathematical morphology is widely used for image processing. Most of the morphological operations are defined based on dilation and erosion. Let $f(x,y)$ be a grayscale image with the size of $M \times N$, and $b(u,v)$ be a structuring element, the dilation and

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erosion of $f(x, y)$ by $b(u, v)$, denoted by $f \oplus b$ and $f\Theta b$, respectively, are defined as

$$f \oplus b = \max_{u,v}(f(x-u,\ y-v)+b(u,\ v)) \tag{1}$$

$$f\Theta b = \min_{u,v}(f(x+u,y+v)-b(u,v)) \tag{2}$$

On the basis of dilation and erosion, the opening and closing of $f(x,y)$ by $b(u,v)$, denoted by $f \circ b$ and $f \bullet b$, respectively, are defined, as

$$f \circ b = (f\Theta b) \oplus b \tag{3}$$

$$f \bullet b = (f \oplus b)\Theta b \tag{4}$$

Applying opening and closing operations, the top-hat transformations of $f(x,y)$ by $b(u,v)$ are defined as

$$WTH(x,\ y) = f - f \circ b \tag{5}$$

$$BTH(x,\ y) = f \bullet b - f \tag{6}$$

where $WTH(x,\ y)$ is called white top-hat transformation, which is used to extract the bright regions of the image, and $BTH(x,\ y)$ is called black top-hat transformation, which is used to extract the dim regions of the image. The performance of top-hat transformation mostly depends on the structuring element. To avoid the unsatisfactory enhanced result caused by the inappropriate structuring element, we utilize multi-scale top-hat transformation in this paper to preliminarily enhance the retinal image.

Assume

$$B = \{B_0, \cdots, B_i, \cdots, B_n\} \tag{7}$$

is a structuring element sequence, where B_0 is the initial selected structuring element, $B_i = \underbrace{B_0 \oplus B_0 \cdots \oplus B_0}_{i\ \ times}$ and $1 \le i \le n$. The top-hat transformations of the grayscale image f by structuring element B_i can be defined as

$$WTH_i(x,y) = f - f \circ B_i \tag{8}$$

$$BTH_i(x,y) = f \bullet B_i - f \tag{9}$$

The optimal bright and dim image regions, denoted by f_w^r and f_b^r, respectively, are defined as

$$f_w^r = \arg\max_{WTH_i(x,y)} \left\{ \frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} WTH_i(x,y),\ \ 1 \le i \le n \right\} \tag{10}$$

$$f_b^r = \arg\max_{BTH_i(x,y)} \left\{ \frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} BTH_i(x,y),\ \ 1 \le i \le n \right\} \tag{11}$$

The multi-scale image details, denoted by $DWTH_i$ and $DBTH_i$, are defined as

$$DWTH_i = WTH_{i+1} - WTH_i \tag{12}$$

$$DBTH_i = BTH_{i+1} - BTH_i \tag{13}$$

Similarly, we also defined the optimal bright and dim image details, denoted by f_w^d and f_b^d, respectively, as

$$f_w^d = \arg\max_{DWTH_i(x,y)} \left\{ \frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} DWTH_i(x,y),\ \ 1 \le i \le n \right\} \tag{14}$$

$$f_b^d = \arg\max_{DBTH_i(x,y)} \left\{ \frac{1}{M \times N} \sum_{x=1}^{M} \sum_{y=1}^{N} DBTH_i(x,y),\ \ 1 \le i \le n \right\} \tag{15}$$

The optimal bright and dim image features, denoted by f_w and f_b, respectively, are defined as

$$f_w = f_w^r + f_w^d \tag{16}$$

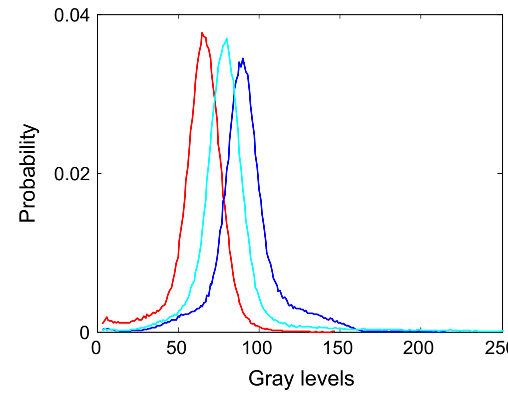

Fig. 1. The histogram of three preliminarily enhanced retinal images randomly chosen from the DRIVE database.

$$f_b = f_b^r + f_b^d \tag{17}$$

The preliminary retinal image enhancement can be achieved by adding the optimal bright image features and removing the optimal dim image features, as shown in the following equation:

$$f_{en} = f + f_w - f_b = f + (f_w^r + f_w^d) - (f_b^r + f_b^d) \tag{18}$$

where f_{en} is the preliminarily enhanced image

2.2. Histogram fitting stretching

Multi-scale top-hat transformations can effectively improve the contrast of the thin vessels, but the contrast of the whole image is not well improved. Our experiment below shows that the histogram of the preliminarily enhanced retinal image is basically in line with normal distribution. Therefore, we can further enhance it by the linear stretching based on Gaussian curve fitting [14], which can effectively improve the contrast of the whole image by transforming the grayscale range of the original image into a relatively larger range.

Fig. 1 shows the histogram of three preliminarily enhanced retinal images, where the corresponding original images are the green channels of three randomly chosen images from the DRIVE database [15]. It can be seen that the histogram of the preliminarily enhanced retinal image is similar to normal distribution. Note that the black background pixels of the preliminarily enhanced retinal images are not taken into account in Fig. 1.

The purpose of the image stretching is to improve the image contrast, which transforms the gray levels of the original image into a relatively larger range by a transformation function. If the transformation function is a linear single-valued function, this method is called gray linear stretching, which can be performed by

$$I' = \frac{I'_{max} - I'_{min}}{I_{max} - I_{min}}(I - I_{min}) + I'_{min} \tag{19}$$

where I and I' are the gray levels before and after the gray linear stretching, respectively, I'_{max} and I'_{min} are the maximum and minimum gray levels after the gray linear stretching, and I_{max} and I_{min} denote the selected gray-scale range in the original image before the gray linear stretching.

As the histogram of the preliminarily enhanced retinal image satisfies the normal distribution, in order to determine the stretched gray-scale range $[I_{min},\ I_{max}]$, and to get a better enhancement result, we fit gray histogram of preliminarily enhanced image by a Gaussian function

$$P(x) = ce^{-(x-a)^2/b^2} \tag{20}$$

where the parameter a represents the center of the normal distribution, c is the peak, and b controls the width of the curve. In this paper, the Least Square Algorithm is used to fit the gray