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Noise-robust low-contrast retinal recognition using compression-based joint wavelet transform correlator

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ABSTRACT

A new method is proposed for recognizing noise corrupted low-contrast retinal images that employs joint wavelet transform correlator with compressed reference and target. Noise robustness is achieved by correlating wavelet-transformed retinal target and reference images. Simulation results show that besides being robust to noise, its recognition performance can become independent upon compression qualities when low spatial-frequency components of joint power spectrum are enhanced by appropriately dilated wavelet filter.

1. Introduction

Over the past decades, human retina has played important roles in the fields of medicine and security. This is because retinal blood vessels are useful to diagnose systemic diseases associated with hypertension, diabetes, aging or other ocular abnormalities [1]. Besides its location at the back of the eyes, spatial distribution of retinal vessels is indeed unique. Hence, the retinal images offer the best biometric solution to prevent counterfeiting in advanced security systems [2–5]. One of the useful methods for the retinal diagnosis and identification is the correlation-based pattern recognition. Individual identification can be done by correlating retinal target and reference templates which may associate with retinal images of users [6–9]. In the case of the ocular diagnosis, the templates may consist of the retinal images of individual patient recorded at different times [10,11].

Recently, we have proposed and verified experimentally the use of compression-based joint transform correlator (CBJTC) for retinal recognition [12,13]. Our works have distinguishing feature compared to a conventional JTC in which joint photographic experts group (JPEG) algorithm is utilized to compress both retinal target and reference. The reasons for this interest are that firstly, development of tele-ophthalmology for remote area requires small file size of retinal images captured by fundus cameras. This requirement is achievable by means of the JPEG algorithm [14,15]. Secondly, noise suppression ability of the JPEG compression has been verified to be useful for improving the CBJTC detection performance. Thirdly, the JTC has been widely employed for real-time implementation of pattern recognition [16–21].

However, our studies found that when the retinal target images have low contrast, the recognition improvement is not significant such that the CBJTC performance never exceeds the conventional JTC which has poor discrimination property [17]. This may be caused by the fact that the noise cannot be totally removed by the JPEG compression. Since retinal fundus images suffer inherently from poor contrast caused by narrow vessel widths [14,22] and noise due to characteristic of digital sensors [23,24], these problems need to be urgently solved.

The present work proposes a novel recognition method for the noisy low-contrast retinal images by incorporating wavelet transform (WT) into the CBJTC. This optical architecture is known as the compression-based joint wavelet transform correlator (CBJWTC). The retinal recognition performance is improved by cross-correlating two wavelet-transformed images whose particular features are enhanced [25]. Feature enhancement of the two images is simultaneously performed by modulating its joint power spectrum (JPS) with appropriately dilated wavelet filters. To assess the improvement of the recognition performance, the present work employs the same retinal images as the ones used in the previous works. Quantitative assessment of the recognition performance is done through computer simulations.

2. Theoretical background

2.1. JPEG compression of retinal images

The JPEG algorithm is a useful method for reducing file size of still digital images, yielding high compression ratio. To reduce file

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size of digital images, the JPEG algorithm discards permanently redundant information in the following steps [26]. The first step is to divide the image into segments consisting of 8×8 pixels. These segments are transformed into 63 ac and 1 dc frequency spectral components by utilizing 2D discrete cosine transform. The second one is to discard high frequency components which correspond to fine details of the input image. This is done by quantizing these frequency components with a predefined table whose values are determined by a quality factor (QF). In general compression softwares, the QF is a default function and can be selected by users. This quantization process results in preservation and approximation of the low- and the high-spectral components, respectively. Next, the resultant coefficients are rounded to integers. For small QF, the ac components may become zeros. Therefore, the JPEG algorithm causes lossy compression. A run-length-encoding combined with Huffman coding are finally used to reduce further the remaining redundant coefficients. As a consequence, blocking artifacts may become observable at high compression ratios.

2.2. Correlation of wavelet-transformed signals

The WT of a spatial pattern $g(x,y)$ is defined as [27]

$$W_g(a, b_x, b_y) = \iint_{-\infty}^{+\infty} g(x, y) h^*_{ab_x b_y}(x, y)\,dx\,dy \tag{1}$$

which is a cross-correlation of the pattern $g(x,y)$ and a set of wavelets

$$h_{ab_x b_y}(x, y) = \frac{1}{a} h\left(\frac{x - b_x}{a}, \frac{y - b_y}{a}\right) \tag{2}$$

dilated by the factor a. Since the wavelet has a characteristic similar to a band-pass filter, its frequency response can be changed by the dilation factor. When the dilation is small, amplitude and center frequency of the wavelet filter become high, while its bandwidth broadens. A large dilation factor reduces the amplitude and center frequency response together with narrowing filter bandwidth. Therefore, different image features can be enhanced by varying the dilation of the wavelet.

By taking this property into account, the cross-correlation of the wavelet-enhanced reference and target signals, $W_r(a,b_x,b_y)$ and $W_t(a,b_x,b_y)$ [28]

$$c(a, x, y) = \iint_{-\infty}^{+\infty} W_t(a, b_x, b_y) W_r^*(a, b_x - x, b_y - y)\,db_x\,db_y \tag{3}$$

can be used for pattern recognition with higher discrimination property compared to the conventional correlations. This equation can be expressed in the frequency domain as

$$c(a, x, y) = \iint_{-\infty}^{+\infty} R^*(f_x, f_y) T(f_x, f_y) \left|H_a(f_x, f_y)\right|^2 \exp\left[-i2\pi(xf_x + yf_y)\right] df_x\,df_y, \tag{4}$$

where $R(f_x,f_y)$, $T(f_x,f_y)$ and $H_a(f_x,f_y)$ represent the frequency spectra of the reference, the target and the dilated wavelet, respectively. Eq. (4) reveals that the JTC can perform the wavelet transform correlation by Fourier transforming the wavelet-modulated JPS.

2.3. Joint wavelet-transform correlation of compressed signals

An optical implementation of the CBJWTC is schematically shown in Fig. 1 with a set of the wavelet filters $|H_a(f_x,f_y)|^2$ and the JPEG-compressed retinal references $r_c(x,y)$ are prepared in a computer system. The compressed images of the noisy target and the reference are displayed onto an electrically-addressed spatial light modulator (EASLM) installed in the front focal plane of a lens L with a focal length f. A mathematical expression of the joint image with a spatial separation d is given by [11]

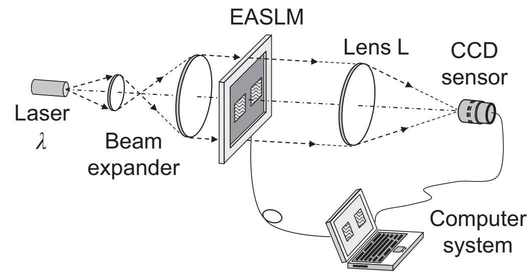

Fig. 1. Schematic setup for implementing low-contrast retinal recognition by using the CBJWTC.

$$f(x, y) = t_c(x + d, y) + n_c(x + d, y) + r_c(x - d, y). \tag{5}$$

In Eq. (4), $n_c(x,y)$ stands for the compressed Gaussian noise which corrupts the target. A perpendicular illumination of the EASLM by using the plane wave with the wavelength λ generates the spectrum $F(f_x,f_y)$ in the back focal plane. The resultant JPS

$$\begin{aligned}
\left|F(f_x, f_y)\right|^2 = {} & \left|T_c(f_x, f_y)\right|^2 + \left|N_c(f_x, f_y)\right|^2 + \left|R_c(f_x, f_y)\right|^2 \\
& + T_c(f_x, f_y) N_c^*(f_x, f_y) + T_c^*(f_x, f_y) N_c(f_x, f_y) \\
& + T_c(f_x, f_y) R_c^*(f_x, f_y) \exp(j4\pi d f_x) \\
& + T_c^*(f_x, f_y) R_c(f_x, f_y) \exp(-j4\pi d f_x) \\
& + N_c(f_x, f_y) R_c^*(f_x, f_y) \exp(j4\pi d f_x) \\
& + N_c^*(f_x, f_y) R_c(f_x, f_y) \exp(-j4\pi d f_x)
\end{aligned} \tag{6}$$

is recorded by using a CCD sensor. Here, $T_c(f_x,f_y)$, $N_c(f_x,f_y)$ and $R_c(f_x,f_y)$ denote the spectra of the target, the noise and the reference images, respectively. The spatial frequencies at coordinates (f_x,f_y) in the back focal plane are determined by $f_x = x'/\lambda f$ and $f_y = y'/\lambda f$. To enhance features of the two images, the filter $|H_a(f_x,f_y)|^2$ is employed for modulating digitally the captured JPS

$$\begin{aligned}
C(a, f_x, f_y) = {} & \left|H_a(f_x, f_y)\right|^2 \left|F(f_x, f_y)\right|^2 \\
= {} & \left|H_a(f_x, f_y)\right|^2 \Big\{ \left|T_c(f_x, f_y)\right|^2 + \left|N_c(f_x, f_y)\right|^2 + \left|R_c(f_x, f_y)\right|^2 \\
& + T_c(f_x, f_y) N_c^*(f_x, f_y) + T_c^*(f_x, f_y) N_c(f_x, f_y) \\
& + T_c(f_x, f_y) R_c^*(f_x, f_y) \exp(j4\pi d f_x) \\
& + T_c^*(f_x, f_y) R_c(f_x, f_y) \exp(-j4\pi d f_x) \\
& + N_c(f_x, f_y) R_c^*(f_x, f_y) \exp(j4\pi d f_x) \\
& + N_c^*(f_x, f_y) R_c(f_x, f_y) \exp(-j4\pi d f_x) \Big\}
\end{aligned} \tag{7}$$

By displaying the modulated JPS $C(a,f_x,f_y)$ onto the EASLM, its Fourier transform gives the correlation output. The wavelet correlation corresponds to the last four terms of Eq. (7)

$$\begin{aligned}
c(a, x', y') = {} & W_{tC}(a, x', y') * W_{rC}(a, x', y') * \delta(x' \pm 2d) \\
& + W_{nC}(a, x', y') * W_{rC}(a, x', y') * \delta(x' \pm 2d)
\end{aligned} \tag{8}$$

where * stands for the symbol of the correlation operation. When the image separation is satisfied by the required distance d of the JTC [29], Eq. (8) will not be affected by the other terms of Eq. (7). In Eq. (8), the first term is the desired wavelet correlation corresponding to Eq. (3). The second one associates to the unwanted