Defa Hu[1],
Zhuang Wu[2]

1 – Hunan University of Commerce, Changsha, Hunan, China
2 – Capital University of Economics and Business, Beijing, China

COMBINATIONAL IMAGE ENHANCEMENT METHOD BASED ON WAVELET DOMAIN

Дефа Ху[1],
Чжуан У[2]

1 – Хунаньський університет комерції, м. Чанша, провінція Хунань, КНР
2 – Столичний університет економіки та бізнесу, м. Пекін, КНР

КОМБІНАЦІЙНИЙ МЕТОД ПОЛІПШЕННЯ ЯКОСТІ ЗОБРАЖЕННЯ НА ОСНОВІ ВЕЙВЛЕТ-ДОМЕНА

Purpose. The image enhancement technique is to highlight the interesting features or suppress the unnecessary features of the image, and it is a basic image processing technique. The article presents a series of study about how to enhance degra-ded image and get desirable effect. The combinational image enhancement measures based on wavelet domain have been developed, which are very helpful for image enhancement, improve the degraded image contrast greatly, and effectively enhance the overall image quality.

Methodology. The high-frequency and low-frequency components in the original image were separated by wavelet decomposition. Different methods were employed to enhance the image detail components of different frequency scopes and highlight the details of different scales. The low-frequency and high-frequency components were combined through the wavelet reconstruction to obtain the final enhanced image so as to improve the visual effect of the image.

Findings. A new wavelet domain algorithm was proposed for image enhancement. It adjusts the lightness of the image, expands the dynamic grayscale scope of the image, and enhances the contrast. The method carries out the self-adaptive enhancement of an image by some appropriate correction in the degraded image clarity.

Originality. The image enhancement method based on wavelet domain has been analysed systematically. The traditional wavelet analysis method was improved according to the different collected information loss level of the degraded image.

Practical value. The research results greatly enhance the details of the image, improve the overall clarity; and the best effect is achieved when the algorithm is used to improve degraded images. The algorithm can improve the degraded image contrast greatly, effectively enhance the overall image quality without losing the image information during the processing.

Keywords*: image enhancement, wavelet decomposition, wavelet reconstruction, degraded image, visual clarity, image contrast*

Introduction. Generally, the image quality degrades in the process of the image transmission and transfer, such as imaging, reproduction, scanning, transmission and display. Image enhancement is to highlight the important information of the image, weaken or erase the unnecessary information and enhance or sharpen certain image features like edge, outline or contrast according to specific needs [1]. Proper enhancement processing of images obtained by different approaches can turn the original image which is fuzzy or even indistinguishable into a useful image, which is clear and contains a great amount of useful information. It allows extruding the interesting feature information of the image, improving the subjective visual quality of the image and increasing the articulation of the image [2]. Being a part of digital image processing, the image enhancement is the pre-processing phase and it is a significant step in the entire processing.

In recent years, numerous domestic and international scholars have made plenty of research on the image enhancement methods, including histogram equalization algorithm, grayscale transformation processing, spatial smoothing technique, frequency-domain low-pass filtering, frequency-domain high-pass filtering and digital image sharpening technique [3]. The image enhancement is a contradictory process since it intends not only to realize image denoising but also to enhance the edges. However, whilst using filtering to reduce noises, it blurs the image edge to some extent or while enhancing the image edge, it generates noises. It is quite difficult to solve the conflicts between noise filtering and edge enhancement with traditional methods. Although the traditional histogram equalization algorithm has been a classic image enhancement technique, its enhanced image will lose details and amplify noises [4]. Wavelet is a recently-development time-frequency analysis tool and it has the capability of time-frequency localization and multi-resolution analysis, making it suitable for the field of signal processing. As a novel mathematical tool, wavelet transform has manifested significant advantages in image processing. After performing multi-scale wavelet analysis on the image, the signals with different frequencies emerge in the sub-band image of different scales, which can enhance the interesting part in a better manner [5].

This article firstly illustrates the categories and methods of image enhancement. Then it analyses wavelet analysis, including multi-scale and multi-resolution analysis. On the above research basis, it proposes the combinational image enhancement method based on wavelet domain. Finally, it verifies the effectiveness of the developed algorithm through a simulation experiment.

Image enhancement and histogram equalization. Majority of original images have unclear details and low contract because their grayscales are distributed in the relatively narrow scope. The low-pass filtering reduces the image noises through the filtering equipment, which allows the signals with lower frequency than the cut-off frequency to pass and stops those with higher frequency than the cut-off frequency. The high-pass filtering enhances such high-frequency signals as the edges, makes full use of the lightness information of the image, makes fuzzy images become clear and greatly improves the image quality through relevant local operation to the pixel neighborhood or pint-by-point operation on the image [6].

Histogram equalization performs non-linear stretching on the image and reallocates the image pixel value to make the number of pixel values almost the same within a certain grayscale scope. With probability theory as the foundation, it uses grayscale operation to realize histogram transform so as to accomplish the purpose of image enhancement.

The image gray histogram is a one-dimensional discrete function

$$p_f(f_k) = \frac{n_k}{n} k = 0,1,\cdots,l-1 \quad ,$$

where f_k is kth gray scale in the image $f(x,k)$, n_k is pixels number which has a gray value f_k in the image $f(x,k)$, n is the total number of pixels in the image [7].

In other words, the above transform generates the image, the gray scale of which is quite equalized and which covers the entire scope $[0,1]$. The result of the grayscale equalization is an image with expanded dynamic range, which has high contract. This transform function is merely a cumulative distribution function (CDF). Typical histogram shapes are shown in Fig.1.

In general, certain transform on the gray histogram of an image can make its grayscale distribution even or basically even. If the histogram contour line of an image is approximate to a normal distribution, it means the image lightness is close to a random distribution. Such image can be processed with statistical methods and it has proper contrast. If the histogram peak position inclines to the side with bigger gray value, then the image is lighter; if it tends to the other side, the image is darker and the steep and narrow peak changes suggest the gray value of the image is too centralized. Traditional image enhancement algorithms are based on the statistic of the entire image. Under this circumstance, when calculate the transform of the entire image, the low-frequency information, high-frequency information and noises have also been transformed. Therefore, while enhancing the image, the image noises have also been enhanced, thus causing declination of information entropy [8].

Theory of wavelet analysis. ***Wavelet transform and diversity of wavelet function.*** The core of wavelet analysis is the construction of the wavelet function and multi-scale analysis. The main properties of the wavelet function are rapid decay and oscillatory and its sub-functions are mutually orthogonal. The concept of orthogonality here is not the verticality in narrow sense, but the failure to represent Nth subwavelet with any $N-1$ th wavelet. The shape and size of the wavelet function are changeable. For high-frequency signals, it can only last a short time. In small scale, the time window narrows down and the frequency window broadens, making it in favor of detail description while for low-frequency signals, it lasts a long time. In large scale, the time window broadens and the frequency window narrows down, making it good for overall description of the signal.

Wavelet is a function or a signal $\psi(x)$ in the function space of $L^2(R)$, which meets the following condition:

$$C_\psi = \int_{R^+} \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty.$$

Where ω is the frequency. $\hat{\psi}(\omega)$ is the Fourier transform of $\psi(x)$ and $\psi(x)$ becomes the wavelet mother function.

For the real-number pair (a,b), the parameter a is a nonzero real number and the function

$$\psi(a,b)(x) = \frac{1}{\sqrt{|a|}} \psi\left(\frac{x-b}{a}\right) \quad .$$

It is called the continuous wavelet function, which is generated from the wavelet mother function $\psi(x)$ and which depends on the parameter pair (a,b) and it is called wavelet for short. Here, a is the scaling factor and b is the shift factor.

The continuous wavelet transform W on signal $f(x)$ is defined as

$$W_f(a,b) = \frac{1}{\sqrt{|a|}} \int_R f(x)\psi\left(\frac{x-b}{a}\right) dx = \langle f(x), \psi_{a,b}(x) \rangle .$$

Here, a is the scaling factor and b is the shift factor. $\psi(x)$ is the wavelet mother function. R is vector space.

Its inverse transform and reconstructed signal is

$$f(x) = \frac{1}{C_\psi} \iint_{R\times R^*} W_f(a,b)\psi\left(\frac{x-b}{a}\right) dadb \cdot$$

Here, a is the scaling factor and b is the shift factor. $\psi(x)$ is the wavelet mother function. R is vector space.

The discrete wavelet transform W of signal $f(x)$ is defined as

$$W_f(2^j, 2^j k) = 2^{-j/2} \int_{-\infty}^{+\infty} f(x)\psi(2^{-j}x - k)dx ,$$

where $\psi(x)$ is the Fourier transform. j and k are wavelet coefficient.

Its inverse transform and reconstructed signal is

$$f(t) = \lambda \sum_{j=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} W_f(2^j, 2^j k)\psi_{(2^j, 2^j k)}(x) \cdot$$

Here, λ is a constant which is irrelevant to signal. $\psi(x)$ is the Fourier transform. j and k are wavelet coefficient [9].

Orthogonal multi-wavelets. Assume that $\psi(t)$ is a quadratically integrable function, namely $\psi(t) \in L^2(R)$, if its Fourier transform $\hat{\psi}(\omega)$ meets the condition.

$$C_\psi = \int_R \frac{|\hat{\psi}(\omega)|^2}{|\omega|} d\omega < \infty \quad . \qquad (1)$$

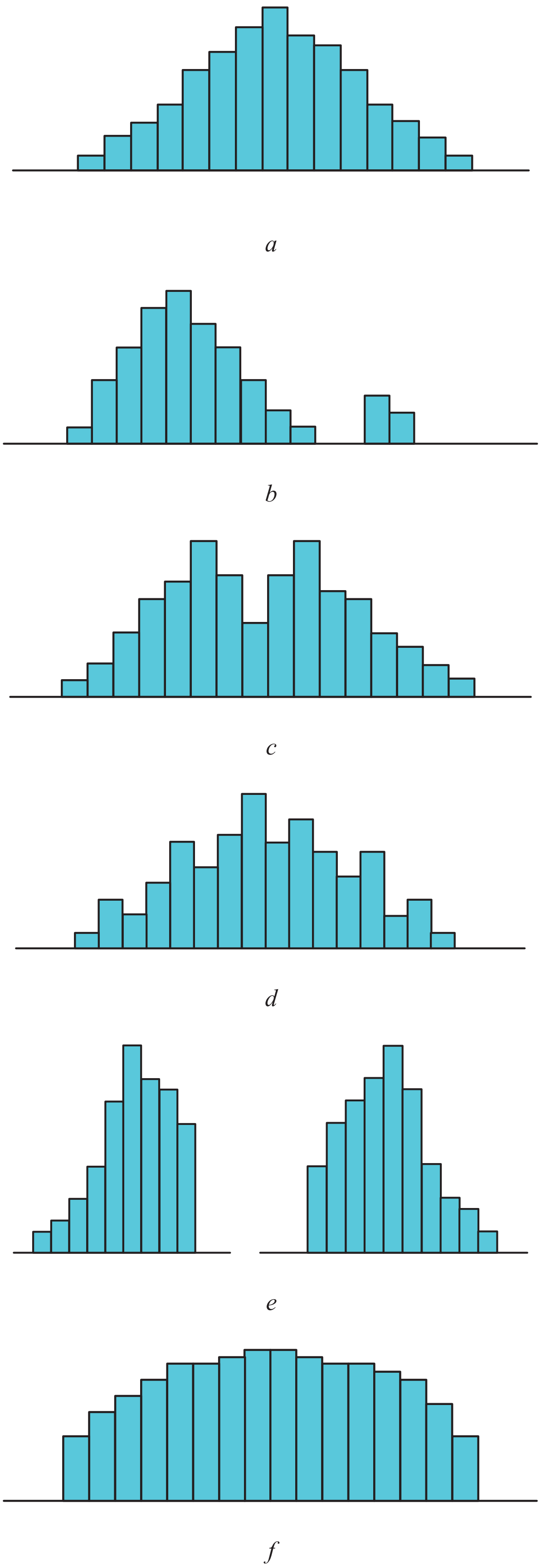

Fig. 1. Typical histogram shapes: a –normal distribution; b – skewed distribution; c – double-peaked (or bimodal) distribution; d –plateau distribution; e –dog food distribution; f –truncated (or heart-cut) distribution

Then $\psi(t)$ is called a basic wavelet, ω is the frequency, mother wavelet and we called the equation (1) the admissible condition of the wavelet function. There are N wavelet function $W(t)=[w_1(t), w_2(t), \ldots, w_N(t)]^T$ corresponding to scaling function. Translate the wavelet function to get $w_1(t-k)$, . $w_2(t-k), \ldots, w_N(t-k)$ and generate a space W_0. If $\left\langle w_i(\cdot-k), w_j(\cdot-l)\right\rangle = \delta_{i,j}\delta_{k,l}$ where $0 \le i, j \le N-1$, $W(t)$ is called orthogonal multi-wavelet function [10].

The multi-scale analysis idea in the wavelet analysis can observe the signals gradually from coarsely to finely and it has strong flexibility in local time-frequency analysis. It can automatically adjust to narrow "time window" and broad "frequency window" with the increase of frequency and to broad "time window" and narrow "frequency window" with the decrease of frequency to meet the needs of practical analysis.

For a high frequency signal, the duration is short, the time window is narrow, and the frequency window is wide, which is good to study for the signal details. For a low frequency signal, the duration is long, the time window is wide, the frequency is narrow, which is good to study for the whole situation of the signal. Fig.2 shows the changes of the wavelet window function in time-frequency.

The wavelet is composed of a family of wavelet basis functions, which can describe the local characteristics of signal time and frequency domain. The window shape of the wavelet window function is variable. The wavelet analysis can be used to analyse the signal, and it can be used in any time or space domain.

Multi-scale decomposition and reconstruction of the wavelet. Mallat proposed a multi-scale concept when constructed orthogonal wavelet bases. It can decompose a signal into the space part and time part of the signal, without losing the information contained in the original signal, and can find the orthogonal basis, achieve the signal decomposition.

Any function $f(x) \in L(R)$ can be completely reconstructed according to the low frequency part and the high frequency part of the resolution. The expression of the multi-scale decomposition is:

$$f(x) = L_n + H_n + H_{n-1} + \ldots + H_2 + H_1 .$$

Where the x is the signal, L is the low frequency approximation, H is the high frequency detail part, and n is the decomposition level. Wavelet 3 level decomposition structure is shown in Fig. 3.

The wavelet analysis has the characteristics of time frequency localization and multi-resolution, it has the ability to represent the signal local features in a time domain and a frequency domain. By the wavelet transformation, the signal can be decomposed into different frequency channels. Wavelet analysis can find the information that represents the structure characteristics that are hidden in the data and cannot be identified by other analytical methods. The decomposed signal is single comparing to the original signal, so the stability of the decomposed signal is better than that of the original signal. Schematic diagram of wavelet decomposition and reconstruction is as shown in Fig. 4.

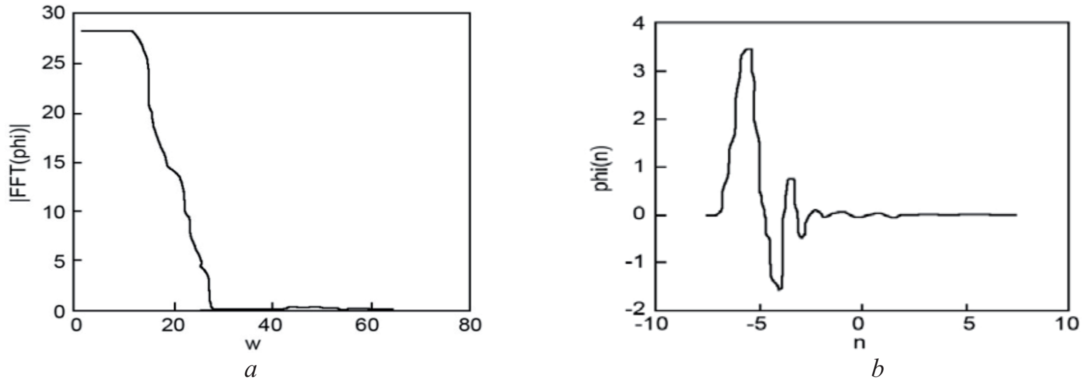

Fig. 2. DB scale function: a −graph of scale function; b −Fourier transform of scale function

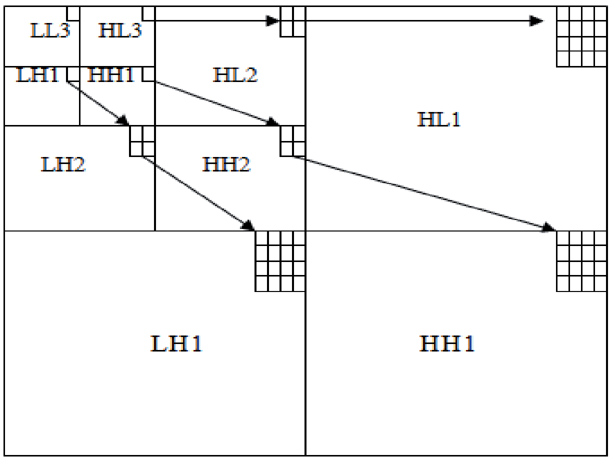

Fig. 3. Wavelet 3 level decomposition structure

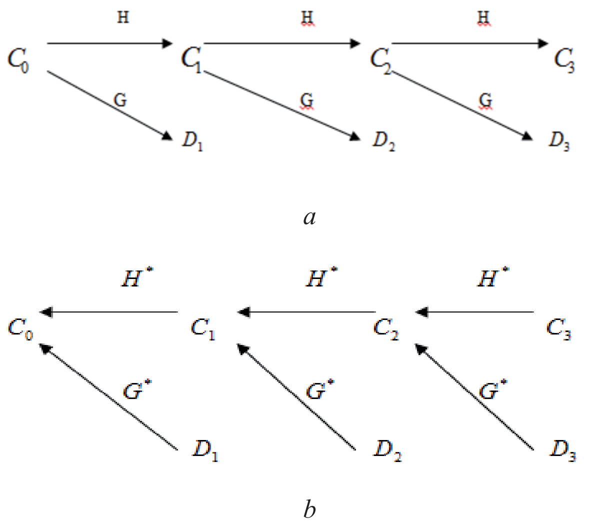

Fig. 4. Schematic diagram of the wavelet decomposition and reconstruction: a − decomposition algorithm; b − reconstruction algorithm

Implementation of the procedures on the image enhancement based on the wavelet transform. The wavelet transform is a novel mathematical tool and its multi-scale and multi-resolution inherent characteristics show the perfect reconstruction capacity and ensure that in the signal decomposition, there is no information missing or redundant information generated. Most of the image noises and details lie in the high-frequency part after wavelet decomposition; however, the overall visual sensation of the image is generally determined by the low-frequency information. Therefore, this research proposes a combination image enhancement method based on wavelet domain. Firstly, given that histogram equalization algorithm has some effect to enhance the overall contrast of the image, this research only performs histogram equalization on the low-frequency information and denoising processing on the high-frequency information with threshold value method. The wavelet transform can decompose the image into the sum of the approximate image and detailed image, which represent the different image structures, therefore, the structural information and detailed information of the original image can be easily extracted. Finally, the pixel-level integration of the low-frequency and high-frequency components is performed and the final enhanced image is obtained. In this way, it allows not only avoiding the implication of the noises and prevent the image details from missing in the combination of low-frequency grayscale but also reducing the noises in the high-frequency information.

In order to enhance the global features of the image simultaneously, the multi-scale enhancement algorithm was proposed. The method of enhancement based on the wavelet transform can be described as follows.

Step1. Make decomposition on the image with orthogonal wavelet transform and obtain sub-band wavelet coefficients. Divide the original image $f(x,y)$ into LL, LH, HL, HH . The low-frequency part is a fuzzy image, the noises of which are suppressed and the high-frequency part contains the detail information of the image and the image noises. Detail space W is composed of three wavelet functions of horizontal shift and stretching, their relationship can be described as

$$\begin{cases} \Psi^{LH}(x,y) = \alpha(x)\beta(y) \\ \Psi^{HL}(x,y) = \beta(x)\alpha(y) \\ \Psi^{HH}(x,y) = \beta(x)\beta(y) \end{cases},$$

where LH, HL, HH represent three sub bands in different directions. Ψ is signal wavelet function. $\alpha(x)$ is horizontal shift function. $\beta(y)$ is stretching function.

efficient k_j^{Ψ} of $D_j^{\Psi}(x, y)$ according to the image model. Make zero setting on the wavelet coefficient k_j^{Ψ} . $D_j^{\Psi}(x, y)$ is the image details of direction corresponding to the decomposition series j .

Step3. Make histogram equalization processing on low-frequency ban LL , make histogram equalization on the low-frequency component $f_L(x, y)$ and assume the low-frequency image after equalization is $\tilde{f}_L(x, y)$.

Step4. Perform simple weighted enhancement on the high-frequency part $f_H(x, y)$ and assume that the enhanced high-frequency image is $\tilde{f}_H(x, y)$, then

$$\tilde{f}_H(x, y) = \lambda \times f_H(x, y) .$$

Here, the parameter λ is the weighted coefficient of the high-frequency part.

LH, HL, HH and obtain the image after the wavelet reconstruction. Stretch the non-zero wavelet coefficient, namely $k_j^{\Psi} \bullet D_j^{\Psi}(x, y)$. Here, $D_j^{\Psi}(x, y) \geq 1$ is the gain factor at the position (x, y) with the scale as j and direction as k .

Step6. Make histogram equalization on the reconstructed and obtain the final image. Implement corresponding inverse wavelet transform on the processed wavelet coefficient $D_j^{\Psi}(x, y)$. The linear sum of the equalized low-frequency image $\tilde{f}_L(x, y)$ and the enhanced high-frequency image $\tilde{f}_H(x, y)$ is the final enhanced image $f(x, y)$, namely

$$f(x, y) = \tilde{f}_L(x, y) + \tilde{f}_H(x, y) .$$

Here, $f(x, y) \in L(R)$. $\tilde{f}_L(x, y)$ is low-frequency image. $\tilde{f}_H(x, y)$ is high-frequency image.

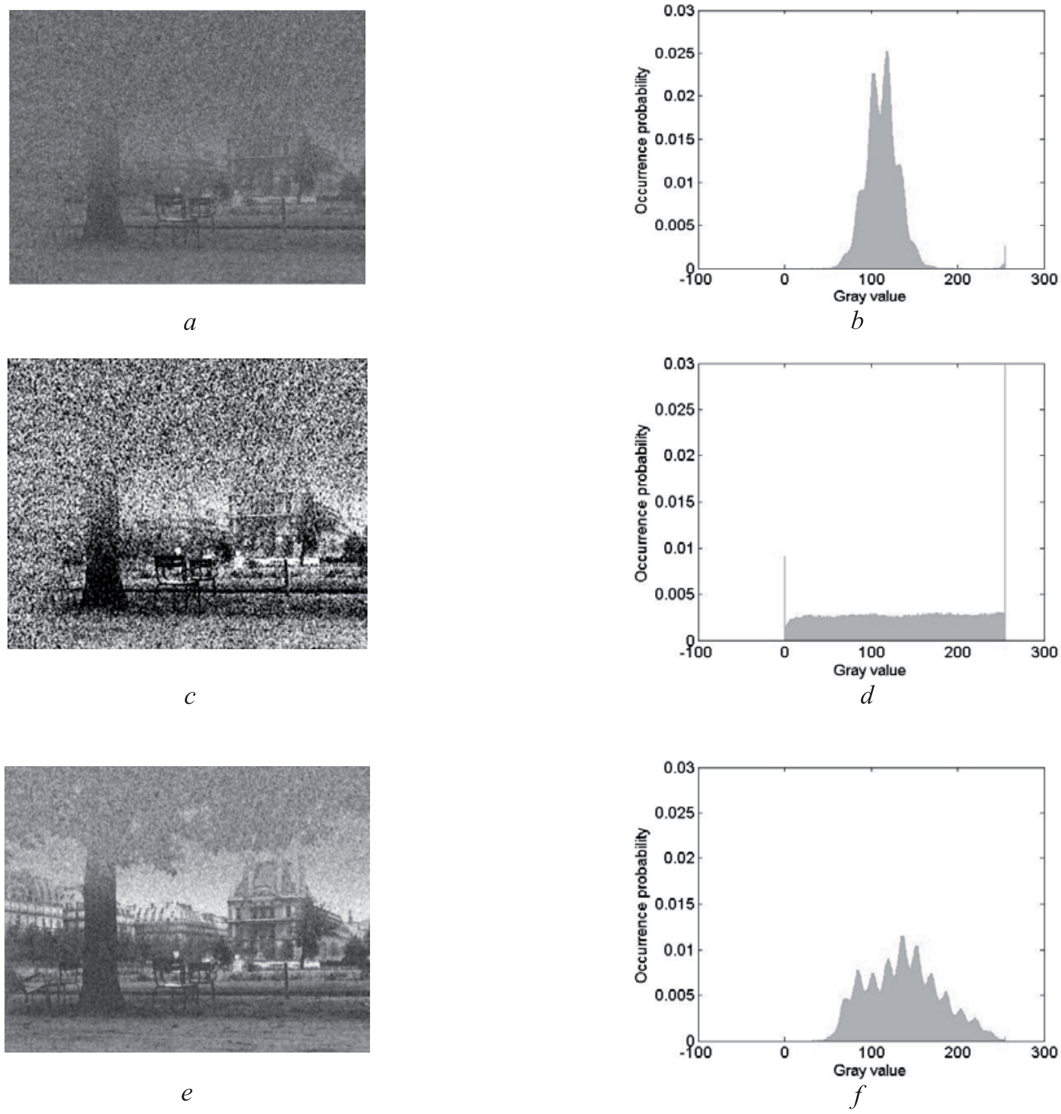

Fig. 5. The comparison of the degraded image enhancement results: a −original degraded image; b −histogram of (a); c − histogram equalization; d −histogram of (c); e – the new algorithm; f −histogram of (e)

Analysis of experimental result. With a degraded image as example, this research enhances the degraded image with the traditional histogram equalization method and the new algorithm, evaluates and analyses the experimental results, which are shown in Fig.5, *a–f.* It is easy to see from the above experimental results, the histogram of the degraded image is distributed too centralized with gray value among 50–200, that the image sense of depth with high fuzziness and that the scenery in the image is quite difficult to distinguish due to bad overall image quality. Histogram analysis is the basic method of image analysis and it improves the image quality by altering the histogram form on purpose. Comparing the image after histogram equalization and the original degraded image, some of the scenery can be told in the image, however, due to the defects of traditional histogram equalization, excessive combination of grayscale in the equalization and lack of remedial measures for the reduced gray scale, plenty of the detailed information in the original image. There are only some gray scales in the original image and some will be missing after processing, making the scenery edges in the image unclear. The enhanced image by the algorithm of this paper has even lightness, clear-cut details, better visual effects and greatly improved contrast.

Conclusion. It has been proposed the degraded image enhancement method based on wavelet domain, which can result in excellent image contrast and definition and realize ideal image enhancement effect. Compared with the traditional method, this algorithm is better in the processing effect whether from the subjective perception or objective evaluation index data analysis and it can obtain ideal image with high detailed information, high contrast and smoothness.

Acknowledgements. This work was supported by the Beijing Philosophical Social Science Project (No.14SHB015), the Beijing Municipal Education Commission Foundation of China (No.SM201410038013) and the National Natural Science Foundation of China (Grant No: 61202464).

References / Список літератури

1. João Miguel Pires Dias, Carlos Manta Oliveira and Luís A. da Silva Cruz (2014), "Retinal image quality assessment using generic image quality indicators", *Information Fusion*, vol.19, no.9, pp. 73–90.

2. Mingwei Sheng, Yongjie Pang, Lei Wan (2014), "Underwater images enhancement using MultiWavelet transform and median filter", *TELKOMNIKA Indonesian Journal of Electrical Engineering*, vol.12, no.3, pp. 2306–2313.

3. Artur Łoza, David R. Bull, Paul R. Hill and Alin M. Achim. (2013), "Automatic contrast enhancement of low-light images based on local statistics of wavelet coefficients", *Digital Signal Processing*, vol.23, no.6, pp. 1856–1866.

4. Bhandari, A.K., Soni, V., Kumar, A. and Singh, G.K. (2014), "Cuckoo search algorithm based satellite image contrast and brightness enhancement using DWT–SVD", *ISA Trans-actions*, vol.53, no.4, pp. 1286–1296.

5. Lei Wang, Nian-de Jiang and Xing Ning (2012), "Research on medical image enhancement algorithm based on GSM model for wavelet coefficients", *Physics Procedia*, vol. 33 no. 6, pp. 1298–1303.

6. Alex F. de Araujo, Christos E. Constantinou and João Manuel R.S. Tavares (2014), "New artificial life model for image enhancement", *Expert Systems with Applications*, vol. 41, no.13, pp. 5892–5906.

7. Claudia Defrasne (2014), "Digital image enhancement for recording rupestrian engravings: Applications to an alpine rockshelter", *Journal of Archaeological Science*, vol.50, no.10, pp. 31–38.

8. Muhammad Zafar Iqbal, Abdul Ghafoor, Adil Masood Siddiqui, Muhammad Mohsin Riaz and Umar Khalid. (2014), "Dual-tree complex wavelet transform and SVD based medical image resolution enhancement", *Signal Processing*, vol.105, no.12, pp. 430–437.

9. Mohammad Reza Yousefi, Reza Jafari, Hamid Abrishami Moghaddam. (2014), "Imposing boundary and interface conditions in multi-resolution wavelet Galerkin method for numerical solution of Helmholtz problems", *Computer Methods in Applied Mechanics and Engineering*, vol.276, no.1, pp. 67–94.

10. Andò, B., Baglio, S. and Pistorio, A. (2014), "A low cost multi-sensor strategy for early warning in structural monitoring exploiting a wavelet multiresolution paradigm", *Procedia Engineering*, vol.87, no. 8, pp. 1282–1285.

Мета. Методика поліпшення якості зображення використовується для того, щоб виділити елементи зображення, які представляють інтерес, або ж приховати непотрібні, що є базовою технікою обробки зображень. У роботі розглядається ряд досліджень, присвячених поліпшенню вицвілих зображень і досягненню бажаного результату. Були розроблені комбінаційні заходи з поліпшення якості зображень на основі вейвлет-домена, сприяючі покращенню зображення, що істотно підвищують як контрастність вицвілого зображення, так і його якість у цілому.

Методика. Короткохвильові й довгохвильові компоненты вихідного зображення були розділені за допомогою вейвлет-розложення. Поліпшення деталей елементів зображення, частот, що належать до різних діапазонів, і виділення деталей різного масштабу здійснювалося різними методами. У результаті поєднання короткохвильових і довгохвильових компонентів шляхом вейвлет-реконструкції було отримане підсумкове покращене зображення, і таким чином досягнуте поліпшення його зорового ефекту.

Результати. Розроблено новий алгоритм покращення якості зображень на основі вейвлет-домена, що коректує яскравість зображення, покращує його контрастність, розширює динамічний діапазон градацій сірого. Метод реалізує саморегульоване підвищення якості зображення завдяки відповідній корекції чіткості вицвілого зображення.

Наукова новизна. Проведено систематичний аналіз і дослідження методу покращення якості зображень на основі вейвлет-домена. Внесені належні зміни до класичного методу вейвлет-анализу відповідно до рівня втрати інформації для вицвілого зображення.

Практична значимість. Результати дослідження сприяють істотному підвищенню якості деталізації зображення, покращують його загальну чіткість, кращий ефект досягається при застосуванні алгоритму до вицвілих зображень. Алгоритм здатний значно поліпшити контрастність вицвілого зображення та підвищити якість такого зображення в цілому, без втрати інформації у процесі обробки.

Ключові слова: *поліпшення якості зображення, вейвлет-розложення, вейвлет-реконструкція, вицвіле зображення, візуальна ясність, контрастність зображення*

Цель. Методика улучшения качества изображения используется для того, чтобы выделить представляющие интерес элементы изображения или же скрыть ненужные, что является базовой техникой обработки изображений. В работе рассматривается ряд исследований, посвященных улучшению выцветших изображений и достижению желаемого результата. Были разработаны комбинационные меры по улучшению качества изображений на основе вейвлет-домена, способствующие улучшению изображения, существенно повышающие как контрастность выцветшего изображения, так и его качество в целом.

Методика. Коротковолновые и длинноволновые компоненты исходного изображения были разделены с помощью вейвлет-разложения. Улучшение деталей элементов изображения, принадлежащих к разным диапазонам частот, и выделение деталей разного масштаба осуществлялось различными методами. В результате совмещения коротковолновых и длинноволновых компонентов путем вейвлет-реконструкции было получено итоговое улучшенное изображение, и таким образом достигнуто улучшение его зрительного эффекта.

Результаты. Разработан новый алгоритм улучшения качества изображений на основе вейвлет-домена, который корректирует яркость изображения, улучшает его контрастность, расширяет динамический диапазон градаций серого. Метод реализует саморегулирующееся повышение качества изображения благодаря соответствующей коррекции четкости выцветшего изображения.

Научная новизна. Проведен систематический анализ и исследование метода улучшения качества изображений на основе вейвлет-домена. Внесены надлежащие изменения в классический метод вейвлет-анализа в соответствии с уровнем потери информации для выцветшего изображения.

Практическая значимость. Результаты исследования способствуют существенному повышению качества детализации изображения, улучшают его общую четкость, лучший эффект достигается при применении алгоритма к выцветшим изображениям. Алгоритм способен значительно улучшить контрастность выцветшего изображения и повысить качество такого изображения в целом, без потери информации в процессе обработки.

Ключевые слова: *улучшение качества изображения, вейвлет-разложение, вейвлет-реконструкция, выцветшее изображение, визуальная ясность, контрастность изображения*

Рекомендовано до публікації докт. техн. наук О.М. Алексєєвим. Дата надходження рукопису 21.11.14.