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A Novel Wavelet Denoising Method Used for Droplet Volume Detection in the Microfluidic System

Shuxiang Guo[1,3], Fang Wu[1]
[1]Tianjin Key Laboratory for Control Theory & Applications in Complicated Systems
Tianjin University of Technology
Binshui Xidao 391, Tianjin, China
wf8023zly@163.com

Wei Wei[1,2], Jian Guo[1,2]
[2]Biomedical Robot Laboratory
School of Electrical Engineering
Tianjin University of Technology
Binshui Xidao 391, Tianjin, China
weiwei_zhaohui@163.com

Yuehui Ji[1,2], Yunliang Wang[1,2]
[3]Mech. Systems Eng. Depart.
Kagawa University
2217-20, Hayashi-cho, Takamatsu, 761-0396, Japan
guoshuxiang@hotmail.com

***Abstract* – Microdroplet is found increasing use in the production of nanoparticles, chemical reactions and drug research and development. However, only some simple theory of droplet information is studied, automate droplet is the direction in the future. Size of droplet is detected in order to control the flow of the microfluid in automation droplet system. Image collected by image acquisition system has severe noise and denoising is the most important step. This paper describes a new wavelet threshold function to improve the wavelet threshold denoising. This approach successfully denoises the noise in the image. Compared with traditional wavelet threshold denoising, this approach has enormous improvements in objective evaluation of denoising such as Peak Signal Noise Ration (PSNR). With the demand of constant accurate flow in microfluidic system, the approach to measure droplet is in urgent need. The obtained results are in good agreement with the demand. The method is used to detect the radius of droplets in the microfluidic system. If dust or spot images are directly processed with noisy bring out error result even not able to be detected. Better results are achieved after processed by the approach in this paper. That boots application of microfluidic system in field of pharmacy, microchemistry, biochemistry and bioanalysis.**

Index Terms - Microfluidic system, Wavelet denoising, Automate droplet， Image processing

I. INTRODUCTION

In the early 1990s, the concept of micro total analysis systems (μ-TAS) or lab-on-a-chip (LOC) is proposed by Manz. Then, microfluidics has been developing rapidly based on the disciplines of chemistry, biology, Micro-Electro-Mechanical Systems (MEMS) and so on. Compared with the macroscopic devices, microfluidics has some highly beneficial properties such as small quantities of reagents, short time for analysis, low-cost and small devices footprints [1]. In earlier studies, researchers focus on manipulation of the continuous flow in microchannels, including sampling, mixing, reaction, separation and detection [2]-[6]. But the continuous flow has many limitations, for example, big quantities of reagents, complex structure of micropumps and microvalves, easy to cause the cross contamination and remaining laminar even for fluids with low viscosities [7]. Therefore, the manipulation of discrete droplets becomes the central issue of international research in recent years. Compared with traditional continuous flow system, microdroplet systems have a series of potential advantages such as small reagents and samples, short time mixing and easy to control. It is widely used for the production of nanoparticles, chemical reactions, drug delivery ect. [7].

Because of these potential advantages as introduced above, more and more researchers pay attention to microdroplet system, the major research is droplet generation and control. Several methods have been explored, including T-junctions, electro-wetting-on-dielectric (EWOD), thermocapillary and dielectrophoresis and pneumatic pressure [8]-[12]. Nguyen et al. has analyzed the generation rate of droplets in the T-shaped microchannel in theory, and fourth power is proportional to the generation rate of droplets and the average velocity of the continuous phase. This laid the foundation for control of droplets accurately [8]. Dubois et al. has used EWOD to control droplets. The biggest advantages of these methods are precise manipulation of individual droplets, including separation, transmission and mixing [9]. Darhuber et al. has designed a microfluidic device for the actuation of liquid droplets on a solid surface by means of integrated microheater arrays. Samples are transmitted, mixed and reacted in automation [10]. Singh et al. has used dielectrophoresis to control droplets move, separation and mixing [11]. These researches are concentrating on how to generate and control droplets. But they have a fatal weak point that droplets are difficult to achieve precise control. Control over the size and distribution of such droplets is the critical element in such micro- and nano-emulsions [7]. In this paper image processing is used to detect droplets in order to control the size of droplets in the microfluidic system.

Image processing begins with a digital capturing of the image collected by digital microscope system. The digital microscope system has two acquisition frame rate which are 15F/s and 28F/s. Images have serious smear due to the frame rate would not meet the demand to collect images of high-speed movement droplets. Denoising is a key to the image processing of this image according to this feature of the image and the microfluidic system is required to capture images in real-time. The goal of denoising is to remove the noise while retaining as much as possible the important signal features. The choice of an appropriate denoising method is very important. A series of experiments are conducted using different method to choose an appropriate method for denoising. These methods include median filter, average filter, wiener filter and so on. Results are detected by the parameter Peak Signal Noise Ratio (PSNR). Wavelet denoising is chose as a result of the advantage of good result and timeliness.

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Existing methods do not resolve local structures well enough. This is necessary when dealing with signals that contain structures of different scales and amplitudes such as neurophysiological signals. We arrange our signals such that the signals and any noise overlap as little as possible in the frequency domain and linear time-invariant filtering will approximately separate them. But this linear filtering approach cannot separate noise from signal where their Fourier spectra overlap. The wavelet transform performs a correlation analysis. So the output is expected to be maximal when the input signal most resembles the mother wavelet. If a signal has its energy concentrated in a small number of wavelet dimensions, its coefficients will be relatively large compared to any other signal or noise that its energy spread over a large number of coefficients. This means that shrinking the wavelet transform will remove the low amplitude noise or undesired signal in the wavelet domain, and an inverse wavelet transform will then retrieve the desired signal with little loss of details. Wavelet denoising can not only eliminate the noise in the signal, but also can effectively protect the edges of the image information. Mallat is the first person to propose the famous denoising method based on wavelet transform [12]. Subsequently, there are a lot of wavelet denoising method are described in papers. Donoho and Johnstone have demonstrated WaveShrink method that approximate optimal in the sense of minimum mean square error and can achieve good visual effects [13]. Then they proposed denoising method of soft and hard threshold function in 1995. Wavelet denoising threshold is the most widely method is studied by researchers and threshold and the threshold function are two of the most critical elements of this method. Based on this, researchers put forward new threshold and threshold function in the process of wavelet denoising threshold and a good denoising effect is obtained. Donoho put forward a unified threshold under normal Gaussian noise model [13]. Assuming the wavelet coefficients obey the generalized Gaussian distribution, Chang proposed the BsyesShrink threshold [14]. Anamika Bhardwaj has used the wavelet transform and Haar transform to propose a novel image enhancement approach. This method can not only enhance details of an image but also preserve edge of image. The Optimal threshold is chose by normal shrink method [15]. Liqiang Wei has constructed a new threshold function, it has derivative of higher order to overcome the constant deviation of soft threshold is overcame [16]. In past studies, there are exist two weak points:

1) Hard threshold function is discontinuous, which makes the image distortion like ringing and Pseudo-Gibbs phenomena.

2) Edge fog is appeared after processing by soft threshold method. In this paper, a soft-hard threshold denoising method is described for wavelet denoising, the result better than the hard or soft threshold denoising.

II. Algorithm Implementation

A. The Basic Principle of Wavelet Transform

Wavelet can be simply described as a function that the average value is zero in a limited time range. It is a great breakthrough after Fourier transformation and put forward by the French geophysicist Morlet. Wavelet transform has been widely used in various engineering fields since mathematical theory of wavelet transform is improved by Inrid Daubechies and wavelet decomposition and reconstruction algorithm are structured by Stephane Mallat. For example, voice signal processing, medical electronic signal processing, image information processing.

Wavelet transform theory is described in below [17]. Assuming $\psi(t) = L^2(R)$, $L^2(R)$ is Finite energy signal space， $\psi(\omega)$ is the Fourier transform of $\psi(t)$ and $\psi(\omega)$ is satisfied with $C_4 = \int_R \frac{\psi^2(\omega)}{|\omega|} d\omega < \infty$. Wavelet base depends on a and τ is expresses as:

$$\psi_{a,\tau}(t) = a^{-\frac{1}{2}}\psi(\frac{t-\tau}{a}), a > 0, \tau \in R \tag{1}$$

where $\psi(t)$ is mother wavelet, a is size factor, τ is shift factor.

There are two typical wavelet transform that continuous wavelet transform (CWT) and discrete wavelet transform (DWT). The continuous wavelet transform is defined as follows:

$$W(a,\tau) =< x(t), \psi_{a,\tau}(t) >= \frac{1}{\sqrt{a}} \int_R x(t)\psi^*(\frac{t-\tau}{a})dt \tag{2}$$

where $x(t)$ is transformed function. The discrete wavelet transform is defined as:

$$W_x(j,k) = \int_R x(t)\psi^*_{j,k}(t)dt \tag{3}$$

where $\psi_{j,k}(t) = \frac{1}{\sqrt{2^j}}\psi(\frac{t}{2^j} - k)$.

B. The Basic Principle of Wavelet Threshold Denoising

Image denoising is the process with which we reconstruct a signal from a noisy one. During image processing, wavelets are used for instance for edges detection, watermarking, texture detection, compression, denoising, and coding of interesting features for subsequent classification [18]. Wavelet denoising, which is one of the simple noise reduction methods, was proposed by D. L. Donoho and I. M. Johnstone in 1994. Because of its simple algorithm and small computation quantity, denoising by threshold can obtain the widespread application. The process of wavelet denoising can be summarized as three steps.

1) The noisy images are decomposed by wavelet, the appropriate basis functions and layers are selected to conduct the wavelet decomposition and the wavelet coefficients are obtained.

2) The decomposed high-frequent coefficient of all layers is processed using threshold to obtain new wavelet coefficient. Shrink coefficients by thresholding (hard/soft).

3) The images are restructured according to the decomposed low-frequent coefficient and threshold high-frequent coefficient.

Threshold processing of the wavelet thresholding coefficients is the most critical step in wavelet denoising. The result of denoising is directly affected by the selected threshold. The current threshold is divided into global threshold and local threshold, global threshold is unified for layers of wavelet coefficients and local threshold is mutative according to the case of wavelet coefficients surrounding the current coefficient [19]. In this paper, global threshold is chosen. According to D. Donoho's method， global threshold estimate λ is given by:

$$\lambda = \delta\sqrt{2\log N} \tag{4}$$

$$\delta = \frac{Median(|\omega|)}{0.6745} \tag{5}$$

where λ is the threshold, δ is the standard deviation of Gaussian noise, N is the number of the wavelet coefficients, ω is the wavelet high-frequency diagonal coefficients.

There are two basic problems in wavelet threshold processing, one is threshold and another is threshold function. In the range of wavelet thresholding, the energy of the Besov space signal is concentrated in some limited coefficients, but noise energy is distributed throughout the wavelet thresholding. After wavelet transform, coefficients of the signal is bigger than the coefficient of the noise, so an appropriate number is found as the threshold. The wavelet coefficients are reserved or shrank to zero by a fixed quantity when the wavelet coefficients are bigger than the threshold, and 0 otherwise. The new wavelet coefficients are used to reconstruct image after denoising. There are two classic threshold functions, that is, soft threshold and hard threshold.

Soft threshold [20] can be expressed as follows:

$$\hat{w}_{j,k} = \begin{cases} w_{j,k}, |w_{j,k}| > \lambda \\ 0, |w_{j,k}| \le \lambda \end{cases} \tag{6}$$

where $w_{j,k}$ is the wavelet coefficients of wavelet transform with noise signal, $\hat{w}_{j,k}$ is the wavelet coefficients after hard threshold function processing.

Hard threshold can be described as follows:

$$\hat{w}_{j,k} = \begin{cases} \mathrm{sgn}(w_{j,k})(|w_{j,k}| - \lambda), |w_{j,k}| > \lambda \\ 0, |w_{j,k}| \le \lambda \end{cases} \tag{7}$$

where $\hat{w}_{j,k}$ is the wavelet coefficients after soft threshold function processing. sgn is the sign function, can be expressed as:

$$\mathrm{sgn}(x) = \begin{cases} 1, x > 0 \\ 0, x < 0 \end{cases} \tag{8}$$

B. The New Wavelet Threshold Function

Hard and soft threshold function has been generally applied in practice and good results are achieved in good agreement with theory. Soft thresholding provides smoother results in comparison with the hard thresholding. But Soft threshold method, part of amplitude is subtracted when it is bigger than the threshold value of the amplitude of the wavelet coefficients and the wavelet coefficients are shrank for a certain degree. So edge fog is appeared after processing by this method. The shrink phenomenon of the wavelet coefficients is not appeared in hard threshold function. Hard threshold, however, provides better edge preservation in comparison with the soft one. But hard threshold function is discontinuous at the point of threshold and Pseudo-Gibbs phenomenon is emerged. A hard-soft threshold function is proposed, it can be written as:

$$\hat{w}_{j,k} = \begin{cases} 0, & |w_{j,k}| \le n_1\lambda \\ \mathrm{sgn}(w_{j,k})\sqrt{(|w_{j,k}| - n_1\lambda)(n_2\lambda - |w_{j,k}|)}, & n_1\lambda < |w_{j,k}| \le n_2\lambda \\ w_{j,k}, & |w_{j,k}| > n_2\lambda \end{cases} \tag{9}$$

where $\hat{w}_{j,k}$ is the wavelet coefficient after the hard-soft threshold function processing, n_1 and n_2 are regulation and control parameters. Here, $n_2 > 1$, $0 < n_1 < 1$. When $n_1\lambda < |w_{j,k}| \le n_2\lambda$, take the appropriate value of n_1, n_2 make the following equation is established.

$$|w_{j,k}| - \lambda \le \sqrt{(|w_{j,k}| - n_1\lambda)(n_2\lambda - |w_{j,k}|)} \le |w_{j,k}| \tag{10}$$

Equation (10) means that it is a threshold between soft threshold and hard threshold.

This function can not only retain information as better as the hard threshold function, but also has good edge information like the soft threshold function. Compared with hard or soft threshold function, the threshold function has superiority and flexibility. n_1 and n_2 are changed in different image and different wavelet coefficients are achieved.

III. The Microfluidic System

A. Introduce of the microfluidic system

In order to verify the effectiveness of the algorithm, it is used to process image is obtained by the microfluidic system, as shown in Fig. 1 [21]. The microfluidic system is made up of microfluidic system and digital microscope system. The element of microfluidic system is air pump, micropumps, micro-chip, droplet collection device and some other devices if experiment needed. The air pump provides air pressure to the micropump which controls the velocity of microfluid. The micropump is set the pressure according to the velocity of the microliquid and the maximum pressure is 10bar. Microchip offers the path for microfluid. Its length, width and shape are set based on the mixture time and portfolio. In this experiment, the microchannel is Y-shaped and the breadth is 190μm. The microchip has three inlets and they are connected to the pressure pump by means of flexible Teflon tubes. In the Y-type interface, the shear force of the continuous phase act on the dispersed phase. The droplet size is very small when the dispersed phase comes from the front end channel. The shear force is not big enough to overcome the internal Laplace force. The size of droplet becomes larger along with the accumulation of droplet and the shear force increasing while the internal Laplace force decreasing. The shear force can be overcome the Laplace force when the droplet size increases to a certain extent and made the droplet separate oneself from the continuous phase. Droplet is formed in a dispersed phase of oil and a continuous water phase. Collecting device is used for droplet collection that used to calculate the volume of the droplet to verify accuracy of measurement and other function according to the needs. Microfluid will be injected into next device through Teflon if further step is required.

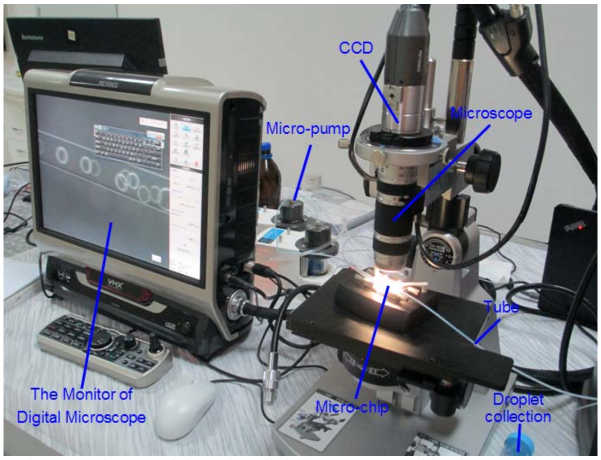


Fig. 1 A picture of the microfluidic system used in the experiment

The digital microscope system is combined with monitor of microscope system, microscope and CCD (Charge Coupled Device) camera. The monitor of microscope system is used to obtain images, save images, process images and some other functions. The size of microchannel at micro- and nano-scale, it is observed by microscope. The microscope contains six objective lenses which are 20X, 30X, 50X, 100X, 150X and 200X to meet with different needs. The droplet images are recorded using CCD camera. The CCD camera is integrated above objective lenses and connected with controller by camera cable. CCD combine with microscope changes the situation of former type optical microscope. When images are collected, the micro-chip is illuminated by halogen lamp and amplified by microscope. Images are shown on the screen and save. Then it can be used in the next experimental step.

There is some of dust present on-the-scene, the camera lens of the image acquisition and the surface of microchip are covered by dust or spot. Dust or spot is enough big for affect the quality of image due to the function of microscope. There is a lot of noise in the image if images are obtained at that time. Dust or spot imaging after microscope amplified, like salt and pepper noise that appears on the image. Dust or spot images are directly processed with noisy bring out error result even not able to be detected.

B. The control of droplets size

The closed-loop control of the microfluidic system is shown as Fig. 2. The actual size of droplets is detected by image processing. A desired droplet size is set before experiment. Compared with actual value and desired value, if the difference existence, micropump will be adjusted until the size of droplets as the desired value.

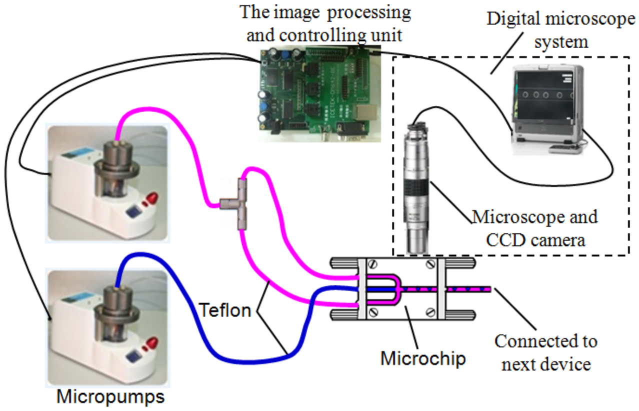


Fig. 2 The closed-loop control of the microfluidic system

IV. Results and Discussions

A. The results of image denoising

Some results are demonstrated the performance of the algorithm in this section. Superiority and effectiveness of improved threshold function in image denoising are illustrated by experiments. The experiments are conducted on microdroplet image of size 1200*1200 which is corrupted by Gaussian white noise of standard deviation 0.02 (Fig. 3). Hard threshold noise filter, soft threshold noise filter and soft-hard threshold noise filter is used in the experiment. Fig.4 shows the results of images after denoising by three methods.

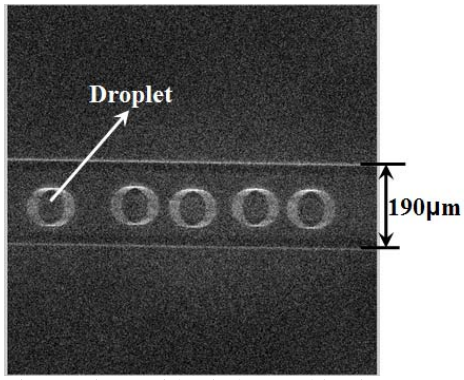
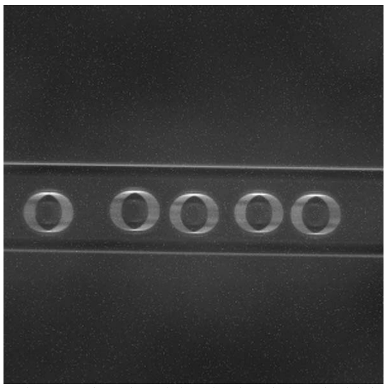
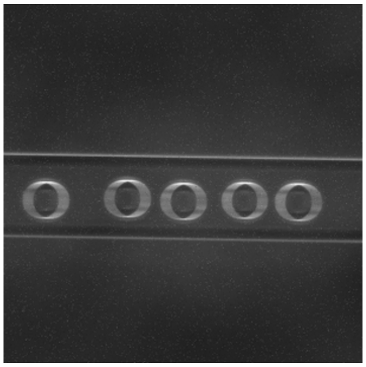
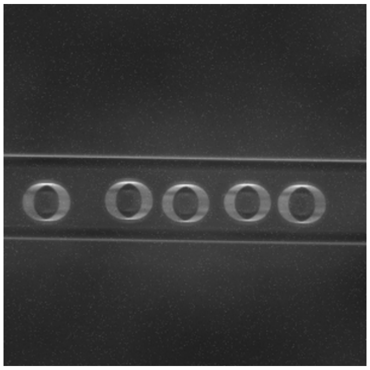


Fig. 3 A picture of droplet image with noise


(a) The picture after denoising by hard threshold function



(b) The picture after denoising by soft threshold function



(c) The picture after denoising by hard-soft threshold

Fig.4 The picture of image processed by wavelet thresholding

It is hard to say what kind of denoising algorithm is the most suitable for a particular occasion due to any denoising algorithm has advantages and disadvantages. In fact, the performance of the denoising algorithm depends entirely on the applications. Commonly, objective evaluation and subjective evaluation method are used to evaluate the effect of denoising. Objective evaluation refers to propose a quantitative parameters and indicators to describe the image quality such as PSNR (Peak Signal Noise Ration). They are expressed as:

$$MSE = \frac{1}{M \times N} * \sum_{i=1}^{M} \sum_{j=1}^{N} (f(i,j) - \hat{f}(i,j))^2 \quad (11)$$

$$PSNR = 10 \lg \frac{(L-1)^2}{MSE} \quad (12)$$

where $f(i,j)$ is the pixel of original image. $\hat{f}(i,j)$ is the pixel of the image after denoising, L is the gray level of image. In general, the value is 0-255. The size of image is $M \times N$.

TABLE I

COMPARISON OF DIFFERENT DENOISING

Method / Parameter	Hard Threshold	Soft Threshold	Hard-Soft Threshold
PSNR	69.7480	70.3149	73.5111

Table I clearly shows that the hard or soft threshold function can not do better than hard-soft threshold function while removing the noise. So, the proposed methods in this paper can preserve most satisfying image details.

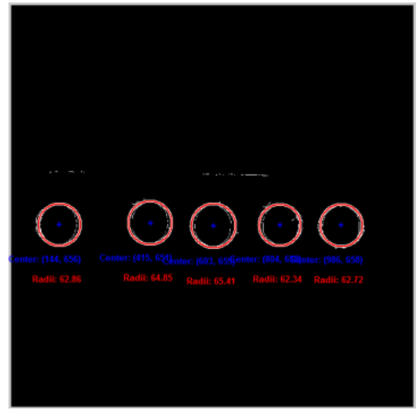


Fig. 5 The picture of detection droplet size

B. *The results of detection*

The droplet size data are shown in Fig. 5 for denoising by hard-soft threshold. In the experiments at a fixed parameter of edge detection, the droplet size is closed to true value when the image denoising by hard-soft threshold function. Increasing the parameter can make error in result. The result of detect can reveal the radius of droplet and the volume of microfluid is calculated by radius of droplet.

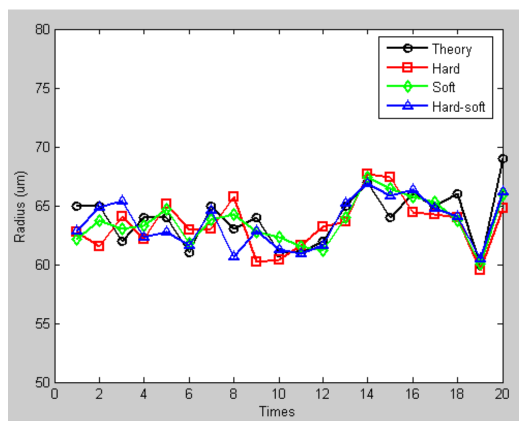


Fig. 6 The radius of droplet measured by different wavelet threshold function

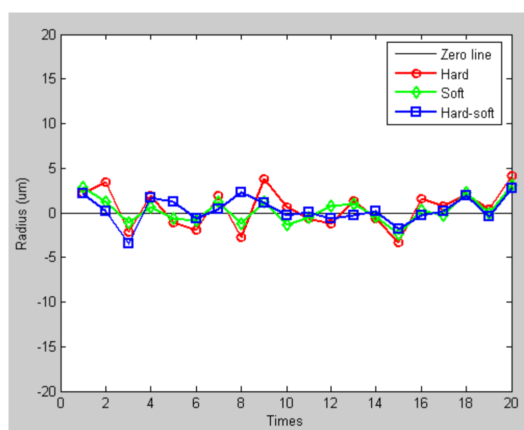


Fig. 7 The deviation of radius between theoretical and measured with different wavelet threshold function

In the experiment, radius of droplet is measured for 20 times and measurement result data are recorded. Fig. 6 shows the radius of droplet is measured by hard threshold function, soft threshold function and hard-soft threshold function. The hard-soft threshold function is approximate to the theory compared with others. The difference between measured by different threshold function and theoretical is very small (Fig. 7). From Fig. 6 and Fig. 7, the function can be used for denoising and edge detection of droplet is close to the true value of droplets. Therefore, the approach can used to measure the volume of droplets in the microfluidic system.

V. CONCLUSION

In this paper, based on some previous studies a simple hard-soft threshold function is proposed to remove noise of image. This method can address the issue of image is acquired in dust environments that not directly used in detection. Simulations of this approach and comparison are carried out. Results are concluded as follows:

1) A novel wavelet denoising method used hard-soft threshold was proposed to solve the problem that hard threshold function is discontinuous and edge fog was appeared after processing by soft threshold. The image denoise algorithm of hard-soft thresholding could provide smoothness and better image details. The wavelet soft-hard thresholding denoise algorithm produce better PSNR result compared with other traditional denoise approaches. Image after hard-soft thresholding used to detect edge of droplet was better than hard or soft thresholding from radius data.

2) A microfluidic system detecting droplet size was proposed. The microfluidic system used closed-loop control. Micropumps were adjusted by comparing the difference between the actual value and the detected value.

3) The experimental results showed that this approach could be used in the fields of pharmacy, biochemistry and production of nanoparticles.

The future work will be concentrated on improved control algorithm in order to increase the system response speed. Some other methods are used to improve the accuracy of detected droplet radius.

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REFERENCES

[1] George M. Whitesides, “The Origins and the Future of Microfluidics” Nature, Vol.442, No.7101, pp.368-373, 2006.

[2] Bo Yao, Guoan Luo, Xue Feng, et al, “A Microfluidic Device Based on Gravity and Electric Force Driving for Flow Cytometry and Fluorescence Activated Cell Sorting”, Lab on a Chip, Vol.4, No.6, pp.603-607, 2004.

[3] H. M. Xia, S. Y. M. Wan, C. Shu, et al, “Chaotic Micromixers Using Two-layer Crossing Channels to Exhibit Fast Mixing at Low Reynolds Numbers” Lab on a Chip, Vol.5, No.7, pp.748-755, 2005.

[4] Piotr Garstecki, Michael J. Fuerstman, Howard A. Stone, et al, “Formation of Droplets and Bubbles in a Microfluidic T-junction-Scaling and Mechanism of Break-up”, Lab on a Chip, Vol.6, No.3, pp.437-446, 2006.

[5] Yuli Wang, Hsuan-Hong Lai, Mark Bachman, et al, “Covalent Micropatterning of Poly (Dimethylsiloxane) by Photografting through a Mask” Analytical Chemistry, Vol.77, No.23, pp.7539-7546, 2005.

[6] Kazuhiko Tsukagoshi, Naoya Jinno, Riichiro Nakajima, “Development of a Micro Total Analysis System Incorporating Chemiluminescence Detection and Application to Detection of Cancer Markers” Analytical Chemistry, Vol.77, No.6, pp.1684-1688, 2005.

[7] Erik Miller, Mario Rotea, Jonathan P. Rothstein, “Microfluidic Device Incorporating Closed Loop Feedback Control for Uniform and Tunable Production of Micro-droplets” Lab on a Chip, Vol.10, No.10, pp.1293-1301, 2010.

[8] Nam-Trung Nguyen, Sumantri Lassemono, Franck Alexis Chollet, “Optical Detection for Droplet Size Control in Microfluidic Droplet-based Analysis Systems”, Sensors and Actuators B: Chemical, Vol.117, No.2, pp.431-436, 2006.

[9] Philippe Dubois, Gilles Marchand, Said Gmouh, et al, “Reaction Rates as a Function of Scale within Ionic Liquids: Microscale in Droplet Microreactors versus Macroscale Reactions in the Case of the Grieco Three−Component Condensation Reaction”, Chemistry-a European Journal, Vol.13, No.19, pp.5642-5648, 2007.

[10] Anton A. Darhuber, Joseph P. Valentino, Sandra M. Troian, et al, “Thermocapillary Actuation of Droplets on Chemically Patterned Surfaces by Programmable Microheater Arrays”, Microelectromechanical Systems, Vol.12, No.6, pp.873-879, 2003.

[11] Pushpendra Singh, Nadine Aubry, “Transport and Deformation of Droplets in a Microdevice Using Dielectrophoresis”, Electrophoresis, Vol.28, No.4, pp.644-657, 2007.

[12] Stephane G. Mallat, “A Theory for Multiresolution Signal Decomposition: the Wavelet Representation”, IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol.11, No.7, pp.674-693, 1989.

[13] David L. Donoho, Iain M. Johnstone, “Ideal Spatial Adaptation by Wavelet Shrinkage” Biometrika, Vol.81, No.3, pp.425-455, 1994.

[14] N. Ibáñez-Escriche, VaronaL., J. Casellas, et al. “Bayesian threshold analysis of direct and maternal genetic parameters for piglet mortality at farrowing in Large White, Landrace, and Pietrain populations”, Journal of Animal Science, Vol.87, No.1, pp.80-87, 2009.

[15] Anamika Bhardwaj, Manish K. Singh, “A Novel approach of medical image enhancement based on Wavelet transform” International Journal of Engineering Research and Applications, Vol.2, No.3, pp.2356-2360, 2012.

[16] Liqiang Wei, Yanghong Tan, "Research of Wavelet Image Denoising Based on New Thresholding Functions”, Science Technology and Engineering, Vol.7, No.9, pp.2114-2117, 2007

[17] Yucai Dong, Hongtao Shi, Junzhi Luo, et al. “Application of Wavelet Transform in MCG-signal Denoising”, Modern Applied Science, Vol.4, No.6, pp.20-24, 2010.

[18] Akhilesh Bijalwan, Aditya Goyal, Nidhi Sethi, “Wavelet Transform Based Image Denoise Using Threshold Approaches” International Journal of Engineering, Vol.1, No.5, pp.218-221, 2012.

[19] Xiaoxi Chen, Yanjie Wang, Lian Liu, “Deep Study on Wavelet Threshold Method for Image Noise Removing”, Laser & Infrared, Vol.42, No.1, pp.105-110, 2012.

[20] Min Han, Yuhua Liu, Jianhui Xi, et al, “Noise Smoothing for Nonlinear Time Series Using Wavelet Soft Threshold”, IEEE Signal Processing Letters, Vol. 14, No.1, pp.62-65, 2007.

[21] Wei Wei, Shuxiang Guo, Fang Wu, Yuehui Ji, Yunliang Wang, “Image Processing-based Measurement of Volume for Droplets in the Microfluidic System”, Proceedings of the 2013 IEEE International Conference on Complex Medical Engineering, pp.518-522, 2013.