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Mammogram Enhancement Using Alpha Weighted Quadratic Filter

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***Abstract*—Mammograms are widely used to detect breast cancer in women. The quality of the image may suffer from poor resolution or low contrast due to the limitations of the X-ray hardware systems. Image enhancement is a powerful tool to improve the visual quality of mammograms. This paper introduces a new powerful nonlinear filter called the alpha weighted quadratic filter for mammogram enhancement. The user has the flexibility to design the filter by selecting all of the parameters manually or using an existing quantitative measure to select the optimal enhancement parameters. Computer simulations show that excellent enhancement results can be obtained with no apriori knowledge of the mammogram contents. The filter can also be used for automatic segmentation.**

I. Introduction

BREAST cancer is the leading cause of death in women between the ages of 35 and 55. The National Cancer Institute estimates that one out of eight women in the United States will develop breast cancer at some point during her lifetime [1]. Early detection of breast cancer is an important and effective method to reduce mortality since treatments of breast cancer in the early stages are more successful. Mammography is the most common technique used by radiologists in the screening and diagnosis of breast cancer. It is seen as the most reliable method for early detection of breast carcinomas [2].

However, due to the limitations of the X-ray hardware systems, screened mammograms may present poor characteristics such as poor resolution or low contrast. In mammograms exhibiting these characteristics, the distinction between the normal tissue and the malignant disease is not readily discernable and makes accurate diagnosis extremely difficult [3]. The situation is exasperated since radiologists routinely interpret large numbers of mammograms and can misdiagnose a condition [4]. Digital enhancement of mammograms allows a more confident interpretation of difficult cases without resorting to follow-up patient examinations and secondary procedures, as well as allowing quicker diagnoses of routine cases [5].

Technologies for mammographic enhancement are mainly based on 1) the acquisition process or 2) the post process in medical imaging systems. Enhancement methods based on the acquisition process intend to collect more image data to improve the quality of the medical image. For example, X-ray machines may extend the X-ray data collection time to obtain better screened mammograms. However, this method significantly increases the overall acquisition time, the amount of radiation that a patient is exposed to and hardware costs [6].

Enhancement approaches based on the post process utilize image enhancement techniques to analyze and recognize breast cancer, evaluate the effectiveness of treatment, and predict the development of breast cancer by improving the visual quality of mammograms without affecting the acquisition process or increasing the hardware costs.

Previous methods for mammogram enhancement utilized different image enhancement techniques such as histogram equalization [7], fuzzy enhancement [8], adaptive density-weighted contrast enhancement [9], wavelet-based enhancement [10] and many others. Some of them have been manipulated to enhance the contrast of the mammograms [2, 3]. These methods enhance only the local contrast or regions of interest (ROI) of mammograms.

Since nonlinear filtering is known for its ability to preserve edges while simultaneously removing noise, it is a desirable technique that can be used to enhance mammographic images and also other types of medical images. Examples include utilizing the topological derivative and anisotropic diffusion [6], adaptive filtering [11] and also quadratic filters [12]. However, their effectiveness for image enhancement is still limited for enhancing fine details or processing images that have dark regions of illumination.

The goal of this work is to enhance the global contrast of mammograms as well as their local contrast to achieve better visibility of mammographic images for the human observers (radiologists). By introducing the new alpha weight coefficients to the traditional quadratic filter, the filter can overcome the aforementioned limitations. The new filter, called the alpha weighted quadratic filter (AWQF), can effectively improve the visual quality of mammograms by enhancing their contrast and also the fine details and dark regions in mammograms.

The rest of this paper is organized as followed. Section II introduces and analyzes the AWQF. An algorithm to implement the AWQF is presented in Section III. The simulation results are shown in Section IV and a conclusion is discussed in Section V.

II. Alpha Weighted Quadratic Filter

In this section, we first review the definition of the quadratic filter. A new alpha weighted quadratic filter is then

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introduced. Its properties are also discussed.

A. Quadratic Filter

A quadratic filter is the second order of the polynomial (or Volterra) filter. Its 1D format is characterized by the following equation:

$$y(n) = \sum_{j,k=-M}^{M} w(j,k)x(n-j)x(n-k) \tag{1}$$

where $N = 2M + 1$ is the mask size and $w(\bullet)$ is coefficients.

Similar to the polynomial filter, the quadratic filter is also known to be a complex nonlinear filter. Its implementation requires a large number of coefficients to be determined in the design of the filter.

Assuming the mask size is $N \times N$, $N = 2M + 1$, the 2D format of quadratic filter is defined as,

$$\begin{aligned} y(m,n) &= \sum_{i,j=-M}^{M} \sum_{k,l=-M}^{M} w(i,j,k,l)x(m-i,n-j)x(m-k,n-l) \\ \text{Or} \quad y_n &= \sum_{j,k=1}^{N^2} w_{jk} x_j x_k \end{aligned} \tag{2}$$

A study of the quadratic filter was addressed in [13].

B. Alpha Weighted Quadratic Filter

The Alpha Weighted Quadratic Filter (AWQF) is an extension of the quadratic filter which is defined as following,

$$y(n) = \sum_{i,j=-M}^{M} w(i,j)x^{\alpha(i)}(n-i)x^{\alpha(j)}(n-j) \tag{3}$$

where $w(\bullet)$ and $\alpha(\bullet)$ are coefficients.

Similarly, its 2D format is defined as following,

$$\begin{aligned} y(m,n) &= \sum_{i,j=-M}^{M} \sum_{k,l=-M}^{M} w(i,j,k,l)x^{\alpha(i,j)}(m-i,n-j)x^{\alpha(k,l)}(m-k,n-l) \\ \text{Or} \quad y_n &= \sum_{j,k=1}^{N^2} w_{jk} x_j^{\alpha_j} x_k^{\alpha_k} \end{aligned} \tag{4}$$

The AWQF is also a complex nonlinear filter and requires a large number of coefficients. The users have difficulty designing an AWQF for practical applications because all its coefficients have to be determined. On the other hand, more coefficients offer the AWQF more power and more design flexibility to meet more specific and complex requirements in real world applications.

To make the AWQF independent of the orientation of the objects or features of the input image, the AWQF is designed into an isotropic image operator. Thus, the number of the AWQF's coefficients can be reduced.

For example, if mask size is 3×3, $N = 3$ (i.e. $M = 1$), the mask contains nine image pixels.

$w_1 x_1^{\alpha_1}$	$w_2 x_2^{\alpha_2}$	$w_3 x_3^{\alpha_3}$
$w_4 x_4^{\alpha_4}$	$w_5 x_5^{\alpha_5}$	$w_6 x_6^{\alpha_6}$
$w_7 x_7^{\alpha_7}$	$w_8 x_8^{\alpha_8}$	$w_9 x_9^{\alpha_9}$

Based on symmetric and isotropic properties, the weight coefficient matrix of the first order terms and alpha weight matrix can be minimized as follows:

$$W_1 = \begin{pmatrix} w_1 & w_2 & w_1 \\ w_2 & w_5 & w_2 \\ w_1 & w_2 & w_1 \end{pmatrix} \qquad \alpha = \begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_1 \\ \alpha_2 & \alpha_5 & \alpha_2 \\ \alpha_1 & \alpha_2 & \alpha_1 \end{pmatrix} \tag{5}$$

Similar to the weight coefficient matrix of the second order terms,

$$W_2 = \begin{pmatrix} w_{11} & w_{12} & w_{13} & w_{12} & w_{22} & w_{12} & w_{13} & w_{12} & w_{11} \\ w_{12} & w_{15} & w_{16} & w_{24} & w_{25} & w_{24} & w_{16} & w_{15} & w_{12} \\ w_{13} & w_{16} & w_{19} & w_{16} & w_{28} & w_{16} & w_{19} & w_{16} & w_{13} \\ w_{12} & w_{24} & w_{16} & w_{15} & w_{25} & w_{15} & w_{16} & w_{24} & w_{12} \\ w_{22} & w_{25} & w_{28} & w_{25} & w_{55} & w_{25} & w_{28} & w_{25} & w_{22} \\ w_{12} & w_{24} & w_{16} & w_{15} & w_{25} & w_{15} & w_{16} & w_{24} & w_{12} \\ w_{13} & w_{16} & w_{19} & w_{16} & w_{28} & w_{16} & w_{19} & w_{16} & w_{13} \\ w_{12} & w_{15} & w_{16} & w_{24} & w_{25} & w_{24} & w_{16} & w_{15} & w_{12} \\ w_{11} & w_{12} & w_{13} & w_{12} & w_{22} & w_{12} & w_{13} & w_{12} & w_{11} \end{pmatrix} \tag{6}$$

To preserve the gray input level, the following conditions should be satisfied,

$$\begin{aligned} &1)\ 4w_1 + 4w_2 + w_5 = 1 \\ &2)\ 4\alpha_1 + 4\alpha_2 + \alpha_5 = 1 \\ &3)\ 4w_{11} + 16w_{12} + 8w_{13} + 8w_{15} + 16w_{16} \\ &\quad + 4w_{19} + 4w_{22} + 8w_{24} + 8w_{25} + 4w_{28} + w_{55} = 0 \end{aligned} \tag{7}$$

According to the distance between two elements of the AWQF which are two pixels of the input image, the AWQF can be classified into three types:

1) Type Zero AWQF: This type of the AWQF consists of all the second order terms in which the distance of two elements is zero, namely two elements have the same locations. For mask size 3×3, the filter is,

$$\begin{aligned} y_n &= w_{55} x_5^{2\alpha_5} + w_{11}(x_1^{2\alpha_1} + x_3^{2\alpha_1} + x_7^{2\alpha_1} + x_9^{2\alpha_1}) \\ &\quad + w_{22}(x_2^{2\alpha_2} + x_4^{2\alpha_2} + x_6^{2\alpha_2} + x_8^{2\alpha_2}) \end{aligned} \tag{8}$$

2) Type One AWQF: The type one AWQF includes all the second order terms in which the distance of two elements is one. In other words, two elements are two adjacent pixels. For mask size 3×3, the filter becomes,

$$\begin{aligned} y_n &= w_{12}(x_1^{\alpha_1} x_2^{\alpha_2} + x_1^{\alpha_1} x_4^{\alpha_2} + x_2^{\alpha_2} x_3^{\alpha_1} + x_3^{\alpha_1} x_6^{\alpha_2} + x_4^{\alpha_2} x_7^{\alpha_1} \\ &\quad + x_6^{\alpha_2} x_9^{\alpha_1} + x_7^{\alpha_1} x_8^{\alpha_2} + x_8^{\alpha_8} x_9^{\alpha_9}) + w_{15}(x_1^{\alpha_1} x_5^{\alpha_5} + x_3^{\alpha_1} x_5^{\alpha_5} \\ &\quad + x_5^{\alpha_5} x_7^{\alpha_1} + x_5^{\alpha_5} x_9^{\alpha_1}) + w_{25}(x_2^{\alpha_2} x_5^{\alpha_5} + x_4^{\alpha_2} x_5^{\alpha_5} + x_5^{\alpha_5} x_6^{\alpha_2} \\ &\quad + x_5^{\alpha_5} x_8^{\alpha_2}) + w_{24}(x_2^{\alpha_2} x_4^{\alpha_2} + x_2^{\alpha_2} x_6^{\alpha_2} + x_4^{\alpha_2} x_8^{\alpha_2} + x_6^{\alpha_2} x_8^{\alpha_2}) \end{aligned} \tag{9}$$

2) Type Two AWQF: It is comprised of the second order terms in which the distance of two elements is two. For mask size 3×3, the filter is,

$$\begin{aligned} y_n &= w_{13}(x_1^{\alpha_1} x_3^{\alpha_1} + x_1^{\alpha_1} x_7^{\alpha_1} + x_3^{\alpha_1} x_9^{\alpha_1} + x_7^{\alpha_1} x_9^{\alpha_1}) + w_{19}(x_1^{\alpha_1} x_9^{\alpha_1} \\ &\quad + x_3^{\alpha_1} x_7^{\alpha_1}) + w_{28}(x_2^{\alpha_2} x_8^{\alpha_2} + x_4^{\alpha_2} x_6^{\alpha_2}) + w_{16}(x_1^{\alpha_1} x_6^{\alpha_2} + x_1^{\alpha_1} x_8^{\alpha_2} \\ &\quad + x_2^{\alpha_2} x_7^{\alpha_1} + x_2^{\alpha_2} x_9^{\alpha_1} + x_3^{\alpha_1} x_4^{\alpha_2} + x_3^{\alpha_1} x_8^{\alpha_2} + x_4^{\alpha_2} x_9^{\alpha_1} + x_6^{\alpha_2} x_7^{\alpha_1}) \end{aligned} \tag{10}$$

III. THE AWQF IMPLEMENTATION ALGORITHM

There are a large number of coefficients in the AWQF. This makes the AWQF quite expensive to implement. For example, there are 99 coefficients in the AWQF if mask size is 3×3. Seventeen coefficients still remain even if we use symmetric and isotropic properties to reduce the number of its coefficients. For a larger mask size, the number of coefficients will significantly increase.

In this section, we introduce a new algorithm to simplify the AWQF implementation for a large mask size. The algorithm is described as follow:

1) If mask size is 3×3, the input image is directly filtered by the AWQF.
2) If mask size is 5×5, we select 9 image pixels from the 5×5 mask window to generate a new 3×3 window as shown in Fig. 1, and then apply the AWQF.

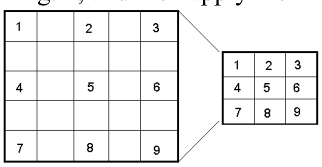

Fig. 1. Generating a new 3×3 window.

3) If the mask size is greater than 5×5, we apply the AWQF to the 3×3 sub-windows in the four corners of the mask window. The final output of the AWQF is the mean value of the results from these four sub-windows.

The algorithm strives to simplify the AWQF design by using a smaller mask window in such a way that the users need only focus on designing the AWQF with a mask size 3×3. The number of the AWQF's coefficients is minimized.

IV. PERFORMANCE MEASURE AND SIMULATION RESULTS

To quantitatively evaluate the AWQF's enhancement performance, the user has the flexibility to use any measure approach for establishing a qualitative metric of mammogram enhancement. They can also optimize the AWQF's coefficients using the measure results to obtain better enhanced mammograms. In this paper, we utilize the logarithmic Michelson contrast measure by entropy (LogAMEE) [14] as an example of the enhancement measure methods to design the AWQF.

To further simplify implementation and reduce the number of the coefficients of the AWQF, we assume $w_1 = w_2 = h$, $\alpha_1 = \alpha_2 = h$, $w_{15} = w_{25} = w_{16} = h$, $w_{12} = 4h$, $w_{11} = w_{22} = -h$ and $-1 < h < 1$. According to constraints in equation (7) and definition of three types of the AWQF, we then have $w_{19} = 2w_{13} = -4h$, $w_5 = \alpha_5 = 1 - 8h$, $w_{55} = 8h$ and $w_{24} = 2w_{12} = -h$. A mammogram containing breast cancer shown in Fig. 3(a) is used as the test image.

The LogAMEE of enhanced mammograms using the AWQF with different parameters is plotted in Fig. 2. We can see the maximum value of LogAMEE is located at $h = 0.1$. The best enhancement result of the test image using the AWQF can be obtained at this point [14]. The enhanced image based on this parameter is shown in Fig.3 (b). The global contrast of the original image is significantly improved.

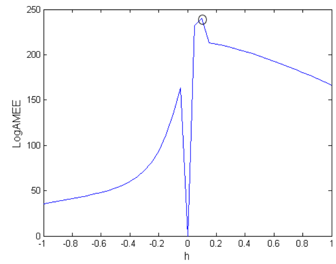

Fig. 2. LogAMEE of the mammogram enhancement with breast cancer when parameter h changes. The maximum of the graph depicts the value of h for achieving the optimal enhanced image.

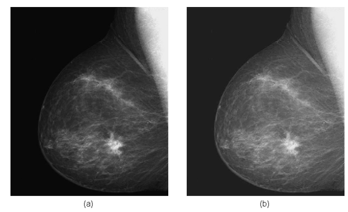

Fig. 3. Mammogram enhancement based on the LogAMEE measure result. (a) Original mammogram; (b) Enhanced mammogram with $h = 0.1$.

The users also have the flexibility to design the AWQF by manually selecting all its coefficients. We have utilized the three types of the AWQF to enhance 20 mammograms and 16 selected regions by manually changing coefficients of the AWQF.

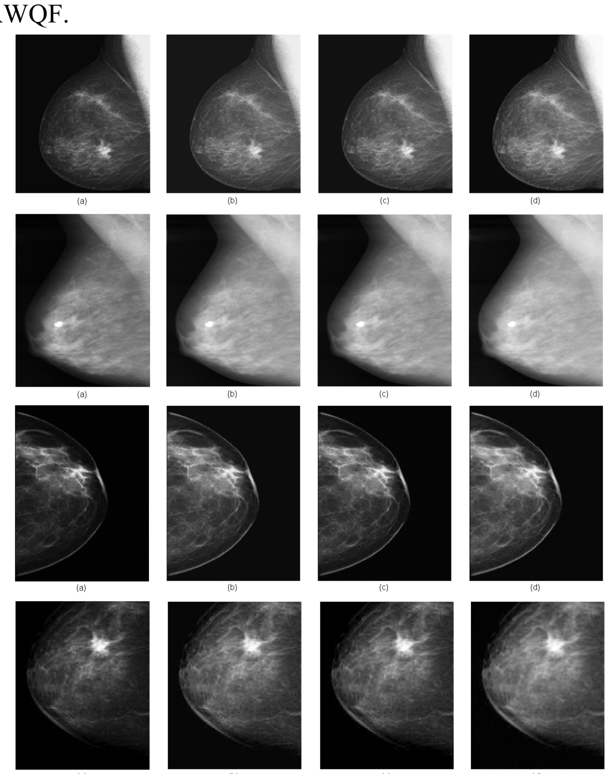

Fig. 4. Enhanced results of four mammograms using different types of the AWQF with different coefficients. (a) Original mammograms (b) Enhanced mammograms using the type zero AWQF; (c) Enhanced mammograms using the type one AWQF; (d) Enhanced mammograms using the type two AWQF.

Fig. 4 shows several enhanced results of four selected mammograms using three types of the AWQF by manually selecting their coefficients. The contrast and fine details of the original mammograms have been enhanced. The visual quality of enhanced mammograms is much better than that of their original ones. Different types of the AWQF show specific performance for enhancing different mammograms.

Fig. 5 provides the enhancement results of selected regions of some mammograms using the AWQF. The AWQF enhances not only the fine details and objects (breast cancer cells) but also the dark regions in the mammograms. These further show that the AWQF can also enhance the local contrast and fine details.

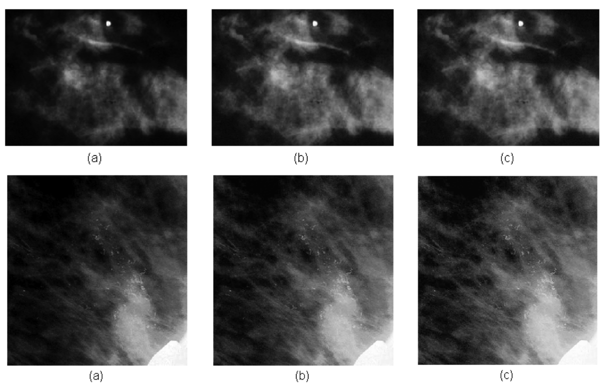

Fig. 5. Selective region enhancement using different types of the AWQF with different coefficients and window sizes. (a) Original regions; (b) Enhanced region using the type zero AWQF; (c) Enhanced region using the type one AWQF.

Fig. 6 compares the enhancement performance between the AWQF and the histogram equalization method. The AWQF shows better enhancement performance because it enhances contrast of mammograms and make cancer cells and fine details in the mammogram more recognizable as shown in Fig. 6(c). However, the histogram equalization spreads out the cancer cells and the boundary of the mammogram which is shown in Fig. 6(b).

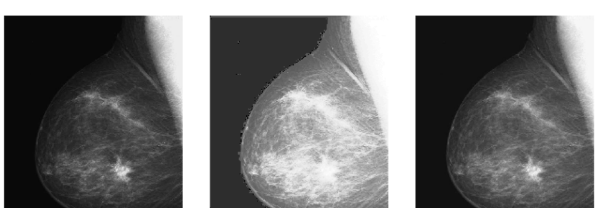

Fig. 6. Comparison of the mammogram enhancement. (a) Original image; (b) Enhanced image using the Histogram Equalization; (c) Enhanced image using the AWQF.

V. Conclusion

We have introduced a new type of nonlinear filter called the alpha weighted quadratic filter in this paper. This filter has been shown to effectively enhance the overall contrast of mammograms and also improve the local fine details and dark regions in mammograms. Compared to the histogram equalization method, the AWQF shows better performance for enhancing mammograms.

To evaluate the performance of the AWQF for mammogram enhancement, the LogAMEE as an example of measure approaches was used to evaluate the enhanced results. The simulation results show that the AWQF's coefficients can be optimized by the measure approaches to obtain a better enhanced mammogram. The users can also design the AWQF by manually selecting its parameters to achieve better enhanced results, meeting requirements in practical applications.

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