STEERABLE PYRAMID FOR CONTRAST ENHANCEMENT AND DIRECTIONAL STRUCTURES DETECTION

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ABSTRACT

The object of this work is the application of steerable filters for the diagnosis of breast cancer. Because of the very specific geometry of malignant densities, we intend to apply a multiscale and orientation shiftable method for the detection of breast cancer in mammograms. Stellate masses have an irregular appearance and are frequently surrounded by a radiating pattern of linear spicules. Multiscale approaches using oriented filters have proved to be efficient to detect such stellate patterns. We first use the fact that tumors are always brighter than the surrounding tissues to locate suspicious regions. The detection is then based on steerable filters, which can be steered to any orientation fixed by the user, and are synthesized using a limited number of basis filters. These filters are used in a recursive multi-scale transform: the steerable pyramid. Using the steerable pyramid, oriented contrast enhancement is performed. The resulting enhanced image is then analyzed to estimate whether a stellate mass is present or not.

1 INTRODUCTION

Breast cancer is currently among the leading causes of death for middle-aged women world-wide. For example, every year, 26000 new cases are detected in France and 9000 women die from cancer. The early diagnosis and detection of breast cancer is the key to its successful management. X-ray mammography is the recommended method for early detection and identification of subtle, minute microcalcifications and other signs of abnormalities on X-ray mammograms can assist in the early diagnosis of non-palpable breast carcinoma. However, radiologists cannot detect all incipient stages of cancer that are visible in follow-up examinations of mammographic images. It has been estimated that 30% or more of potentially detectable lesions are missed. In addition, only 10 to 35% of detected lesions that are sent for biopsy are found to be cancerous. Once in the digital domain (scanned mammograms), the processing power of the computer can be applied to assist in the diagnostic process. The form (nodular or stellate masses), the volume, the lesion homogeneity, the presence or absence of microcalcifications are informations that can be extracted from these images, in order to increase the diagnostic accuracy of mammography screening programs. Mass abnormalities can be classified into three main categories: stellate (or spiculated), ill-defined and well-defined masses. The different properties of these tumors, as well as the complex background in the mammogram, make it difficult for one algorithm to work efficiently. Furthermore, normal breast tissue often looks like tumors. Many studies have focused on this issue: "how to distinguish pathologic tissues from normal ones ?" and several different approaches have been proposed. Most of them include an enhancement pre-processing, a detection scheme and a classification algorithm. More details can be found in [3, 4] In this study, we will focus on the detection of stellate masses which present a geometric form and also privileged directionality. We develop an image analysis method based on a multiresolution approach using steerable filters. Their usage ranges from:
- analyzing local orientations;
- angular adaptive filtering;
- contour detection.

The first two points are of particular interest in this study. These filters are applied with arbitrary orientation and phase, and the output examined. They allow a directional analysis of the image content (oriented energy) and can be interesting and efficient for suspicious area detection like stellate masses.

2 THE STEERABLE PYRAMID

The steerable pyramid is a multiscale decomposition based on steerable filters. It has been designed by Freeman and Simoncelli in 1995 [5]. The steerable filters are directional derivative operators, which can vary in size and orientation, in a way to provide multiscale and multiresolution analysis.

2.1 Steerable filters: definition

Let $f(x,y)$ be a two-dimensional function. We call $f^{\theta}(x,y)$ the rotated version of f by a θ angle. Freeman and Adelson define the property of steerability as

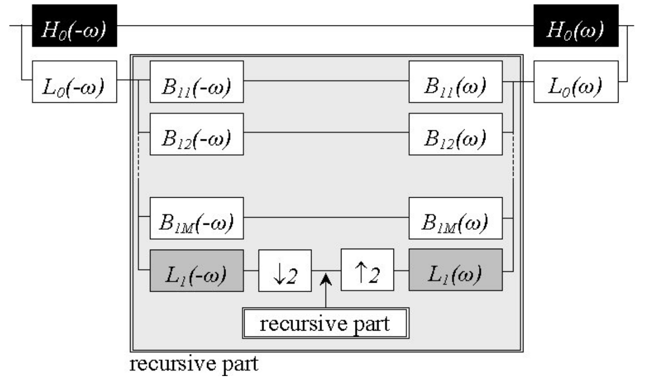

Figure 1: *Decomposition scheme in the frequency domain.*

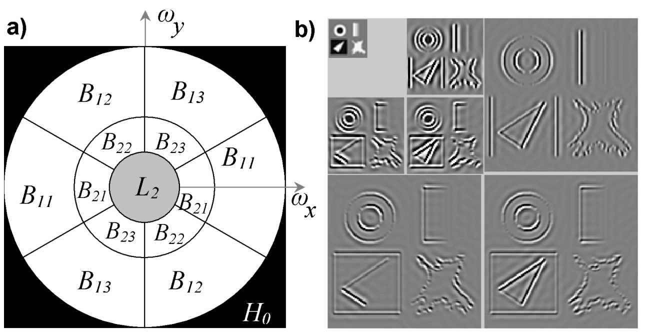

Figure 2: *Filter cascade scheme for the steerable pyramid with $M = 3$ and a two levels decomposition.*

follows: "f is called steerable if it can be written as a linear sum of rotated versions of itself" [1]. The steering constraint is then:

$$f^{\theta}(x,y) = \sum_{i=1}^{M} k_i(\theta) \cdot f^{\theta_i}(x,y) \qquad (1)$$

where $k_i(\theta)$ are the interpolation functions and M the number of basis images. The authors have also detailed the conditions under which f is steerable, the minimum number M of terms required and what $k_i(\theta)$ are.

2.2 The steerable pyramid: definition

The steerable pyramid uses steerable filters in a multi-scale recursive structure. This structure, proposed by Freeman and Simoncelli, is shown in Fig. 1. Initially, the image is separated into low and high-pass subbands. The former is then divided into M oriented bandpass subbands and a lower-pass subband. This last one is then subsampled by a factor of 2, both in the x and y directions. The recursivity is achieved by inserting another level of decomposition in the lower branch.

Fig. 1 shows that the reconstructed image in the frequency domain is:

$$\hat{F}(\omega) = \{|H_0(\omega)|^2 + |L_0(\omega)|^2 \cdot (|L_1(\omega)|^2 + \sum_{i=1}^{M} |B_{1,i}(\omega)|^2)\} \cdot F(\omega) + a.t. \qquad (2)$$

where a.t. are aliasing terms. For recursion, when a level $l+1$ is considered, the filters $B_{l+1,i}$ and L_{l+1} are defined by:

$$\begin{aligned} B_{l+1,i}(\omega) &= B_{l,i}(\tfrac{\omega}{2}) \quad \text{where} \quad i = 1..M \\ L_{l+1}(\omega) &= L_l(\tfrac{\omega}{2}) \end{aligned} \qquad (3)$$

This particular way of combining steerable filters brings new constraints, which are described by Karasaridis and Simoncelli [2] : first, the low-pass response at level l must remain the same when the $(l+1)^{th}$ level is added. Second, to perform a perfect reconstruction, we must on one hand insure the elimination of the aliasing terms (Shannon theorem) and on the other hand avoid amplitude distortion. Finally, the filters must be steerable 6. Those constraints imply three conditions on the radial part:

$$\begin{aligned} &L_1(\omega) = 0 \quad \text{if} \quad \omega > \tfrac{\omega_{max}}{2} \\ &|L_1(\omega)^2 + \textstyle\sum_{i=1}^{M} |B_{1,i}(\omega)|^2 = 1 \\ &|H_0(\omega)|^2 + |L_0(\omega)|^2 = 1 \end{aligned} \qquad (4)$$

The form of the radial part of the $B_{l,i}$ filters must also be:

$$[-j \cdot \cos(\theta - \theta_i)]^{M-1} \qquad (5)$$

where $\theta = \arg(\omega)$, $\theta_i = \frac{\pi i}{M}$ and $j^2 = -1$.

An example of decomposition in the frequency domain is shown in Fig. 2a. There, we can see two scales and three orientations subbands, with the gray region being the low-pass band and the black region being the high-pass band. Fig. 2b shows the result images of a two-scale steerable pyramid transform with three orientations.

2.3 Steerable pyramid versus wavelets

Like wavelets, the scheme is recursive and the transformation matrix is self-inverting: inverting the process consists in applying the inverse matrix of the transform. This is usually called a "tight frame". The main advantage of the steerable pyramid is translation invariance and rotation invariance, which is not always the case with wavelets. Yet, unlike wavelets, the decomposition is over-complete: it takes more memory space than the original image. The rate between the two is $1 + 4M/3$. Therefore, the steerable pyramid is more adapted to image analysis than to image compression.

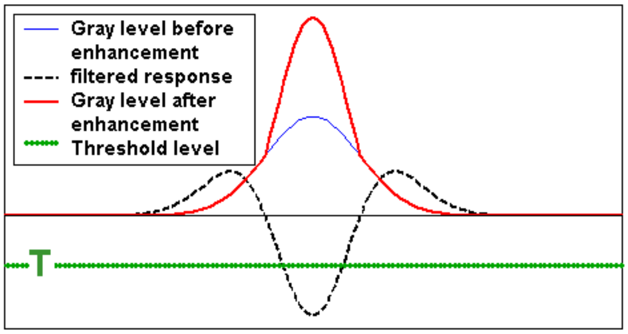

Figure 3: *One dimensional illustration of the enhancement method.*

3 IMAGE ENHANCEMENT USING THE STEERABLE PYRAMID

3.1 Enhancement method at each scale

The image enhancement method we improve in this section has been initially proposed by Wu, Schulze and Castleman [6]. This algorithm is applied during the reconstruction process. It enables a selective enhancement, at a chosen scale l, in a chosen direction θ. In this study, considering M orientated bands for pyramidal decomposition, we achieve enhancement in the same M directions.

Let us call θ_i the direction in which we intend to enhance the image at level l (scale). $f_{L_{l-1}}$ denotes the reconstructed image at level l and $f_{B_{l,i}}$ the image filtered in the direction θ_i with $B_{l,i}$ (Fig. 2). Since we wish to enhance the "black-white-black" transitions in the image, we keep only the negative part $f^-_{B_{l,i}}$ of $f_{B_{l,i}}$, which we subtract from the $f_{L_{l-1}}$ image, to obtain the enhanced image $f^{e_i}_{L_{l-1}}$:

$$f^{e_i}_{L_{l-1}} = f_{L_{l-1}} - \eta_l \cdot f^-_{B_{l,i}} \tag{6}$$

η_l is chosen by the user, and controls the strength of the enhancement. Fig. 3 shows a one-dimensional example with both the reconstructed signal, the filtered signal and the enhanced signal. Enhancement is performed for each direction θ_i and the resulting enhanced image $f^{e_i}_{L_{l-1}}$ is obtained from :

$$\forall(x,y), \quad f^{e}_{L_{l-1}}(x,y) = max_i\{f^{e_i}_{L_{l-1}}(x,y)\} \tag{7}$$

After enhancement at level l, the reconstructions is pursued with lower levels, till level 1 is reached.

3.2 Threshold for selective enhancement

One drawback of the method proposed in [6] is to enhance all convex features (black-white-black transitions)(Fig. 4b), so it introduces directional noise. We propose to introduce a threshold level T to control and adapt the enhancement to the content of the image at each scale and each orientation . If the absolute value of the negative part is higher than this level, the response is used to enhance the image, if not, it is discarded. This level has been set proportional to the highest negative peak (Fig. 4c-d).

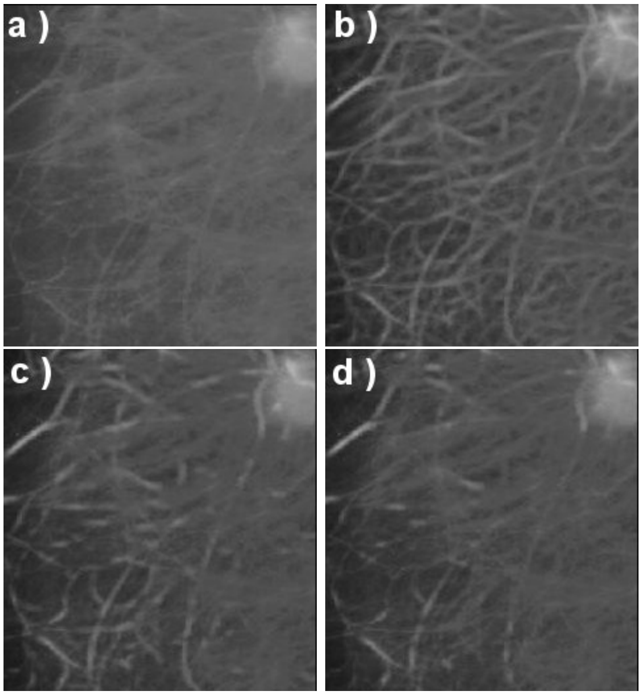

Figure 4: *Example of selective enhancement: a)original image - b)the threshold is set to 0 [6] - c)the threshold is set to 1/3 of the maximum negative value - d)the threshold is set to 1/2 of the maximum negative value.*

4 STELLATE MASS DETECTION

The proposed method, when applied for stellate mass detection uses the two preceding techniques (steerable filters and pyramidal decomposition) both for image enhancement and region of interest (ROI) selection, these two tasks being closely tied in the algorithm. Indeed, the above enhancement technique, which considers the maximal value for each image pixel, does not reveal stellate patterns with many characteristic directions. Then, the directional information has to be pointed out for the decision step, so that enhancement and detection must be jointly operated. The technique is associated with a subimage processing scheme, and the enhancement process only applies on regions where a malignant mass is suspected. The selection of suspicious regions is based on the following considerations:

- stellate opacities are slightly bright structures compared to the surrounding breast tissues (Fig. 5);
- they have stellate morphology with fibrous branches in several directions. So, the selection process will act in two steps, first detecting the bright zones and then deciding if these bright zones contain suspicious structures or only normal ones.

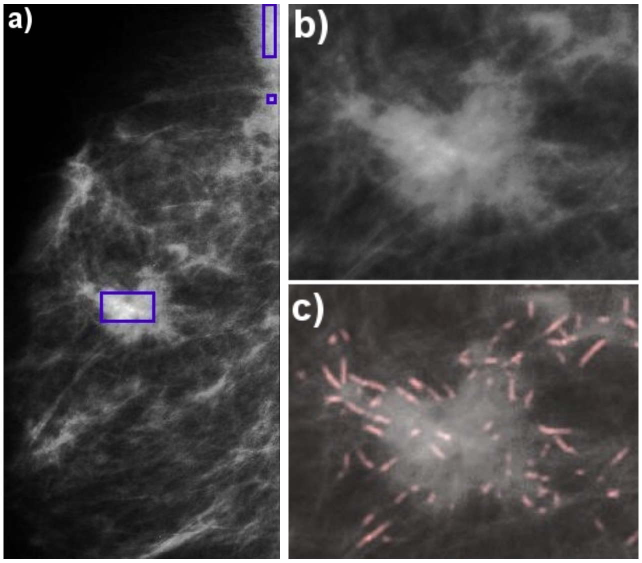

Figure 5: *a) Whole image with the selected ROI - b) Selected ROI c) Selected ROI and corresponding enhanced structures at level 3 for 7 directions.*

4.1 Bright zone detection

In this part of the process, the image is split in small non-overlapping $K \times K$ blocks. Among them, the brighter blocks are selected as candidate blocks with a thresholding procedure.

4.2 Decision step

Next, we consider the $K \times K$ bright candidate blocks, and for each of them the following procedure is applied:

- When many connected $K \times K$ blocks are selected by the threshold operator, a unique region is studied, whose center coincides with the center of mass of all the connected $K \times K$ candidate blocks (Fig. 5a). A larger subimage, centered on each initial region is considered. This serves, on one hand, to prevent border effects. On the other hand, it helps to integrate the small blocks into a larger region that contains the entire tumor.
- Then a pyramidal decomposition of the ROI with M directions and L levels is performed.
- At each level, the enhancement procedure is applied for each of the M directions, giving M directional images.
- M difference images are computed from the difference between the M directional images and the original ROI, showing only the orientated structures which have been affected by enhancement.
- M difference images are merged taking the maximum value for each pixel, resulting in a unique image with directional patterns. In Fig. 5c, these patterns are superimposed on the original ROI (Fig. 5b).

5 CONCLUSION

A method combining the image enhancement and the directional structure detection processes has been proposed. This method is based on the steerable pyramid decomposition and reconstruction scheme. During the reconstruction, the pixels of one directional image at a given scale are enhanced if the local activity of the image exceeds a given threshold. Using the M difference images between the original image and those enhanced for M different directions, only the enhanced directional structures are considered and quantized. The method is applied to stellate mass detection in mammograms. Our radiologists, expert for mammograms, visually analyzed the preliminary results obtained for some images and thought that this tool can really help the early diagnosis and detection of stellate masses. The evaluation of results by experts on a large image database is under investigation. Furthermore, this method can be applied to other imaging modalities and other domains i.e. nondestructive control in order to detect industrial defects.

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