A COMPARATIVE STUDY ON THE ADAPTIVE LATTICE FILTER STRUCTURES IN THE CONTEXT OF TEXTURE DEFECT DETECTION*

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Abstract - *In this paper, the three-, the six-, and the eight-parameter two-dimensional gradient based adaptive lattice filters are compared in the context of defect detection in textures corresponding to textile fabrics. A novel histogram modification technique is also applied for preprocessing the gray level texture image. Moreover, with the proposed scheme, it is possible to detect defects in an unsupervised manner.*

1. INTRODUCTION

Quality is a topical issue in manufacturing, designed to ensure that defective products are not allowed to reach the customer. Machine vision is an important technology resulting in accurate and inexpensive quality control equipment. Since in many areas, the quality of a surface is best characterized by its texture, texture analysis plays an important role in automatic visual inspection of surfaces. There has been a number of applications of texture processing to inspection problems [1-3].

In this paper we used the 2-D filter structures, proposed by Moro et.al. [4], the eight-parameter 2-D lattice filter structure [5-6], and the three-parameter lattice filter [7], for performing forward prediction on the texture image. In order to increase the effectiveness of this approach, a novel histogram modification technique has also been used before the forward prediction error filtering.

The organization of this paper is as follows. First, a general description will be given about the 2-D lattice filter structures and the three-, the six- and the eight-parameter filters will be explained in detail.

Second, the adaptation algorithm will be described and the modification of the adaptation algorithm will be explained for each lattice structure. Then motivations about the scope of quality control in textile industry will be given, the type of defects in the textures will be briefly listed and the defect detection scheme will be elaborated. The role of the lattice filter as a prediction error-filter will be presented. Finally a detailed comparison among the algorithms will be given and conclusions will be drawn.

2. 2-D LATTICE FILTER STRUCTURES

2-D lattice filter structures consist of concatenated multi-input/multi-output stages that are defined in terms of the reflection coefficients. The inputs and the outputs are forward and backward prediction error fields that are generated simultaneously.

In 2-D lattice filters, one forward and a number of backward prediction error fields are combined into a single 2-D structure. Compactly, the input/output relation of a 2-D lattice filter is given as a linear combination of input prediction error fields as follows:

$$\mathbf{e}^{(n)} = \mathbf{K}^{(n)}\mathbf{e}^{(n-1)*} \qquad (1)$$

where $\mathbf{e}^{(n)}$ and $\mathbf{e}^{(n-1)*}$ are, respectively, the output and the delayed input vectors consisting of forward and backward prediction error fields associated with stage (n). The first element of these vectors is the forward prediction error field and the remaining elements are the backward prediction error fields. The number of backward prediction error fields depends on the 2-D lattice structure used. $\mathbf{K}^{(n)}$ is the matrix of reflection coefficients associated with stage (n) and its size, as well, depends on the structure. The mean squared error, $Q^{(n)}$, for the (n)-th order lattice model is defined as:

$$Q^{(n)} = \mathrm{E}[\mathbf{e}^{(n)}(\mathrm{i},\mathrm{j})^{\mathrm{T}}\mathbf{e}^{(n)}(\mathrm{i},\mathrm{j})] \qquad (2)$$

where E[ ] is the expectation operator and T denotes vector transposition.

If Eq.(1) is substituted into Eq.(2), an expression is obtained that can be minimized with respect to the reflection coefficients. This minimization results in the normal equation as:

$$\mathbf{R}^{(n-1)}\mathbf{k}^{(n)} = \mathbf{r}^{(n-1)} \qquad (3)$$

Here, $\mathbf{k}^{(n)}$ is the vector of reflection coefficients. The elements $\Phi^{(n)}_{ab.xy}$ of the symmetric matrix $\mathbf{R}^{(n)}$ and the vector $\mathbf{r}^{(n)}$ are the cross-correlations between the prediction error fields given as:

$$\mathrm{F}_{ab.xy}{}^{(n)} = \mathrm{E}\,[\mathrm{e}_{kl}{}^{(n)}(\mathrm{i}-\mathrm{a},\mathrm{j}-\mathrm{b})\,\mathrm{e}_{pq}{}^{(n)}(\mathrm{i}-\mathrm{x},\mathrm{j}-\mathrm{y})]$$
$$(\mathrm{a},\mathrm{b},\mathrm{x},\mathrm{y},\mathrm{k},\mathrm{l},\mathrm{p},\mathrm{q} = 0,1,2) \qquad (4)$$

depending on the lattice structure. The prediction error field elements, e_{kl}'s, will be defined subsequently for each structure.

2.1. The Three-Parameter Lattice Filter

This filter structure is developed by Parker and Kayran [7] and is derived by assuming that data has four quadrant symmetry. Under the four quadrant symmetry assumption, three backward prediction error fields are generated at each stage. For three-parameter lattice filter Eq.(1) can be explicitly written as:

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$$\begin{bmatrix} e_{00}^{(n)}(i,j) \\ e_{10}^{(n)}(i,j) \\ e_{11}^{(n)}(i,j) \\ e_{01}^{(n)}(i,j) \end{bmatrix} = \mathbf{K}^{(n)} \begin{bmatrix} e_{00}^{(n-1)}(i,j) \\ e_{10}^{(n-1)}(i-1,j) \\ e_{11}^{(n-1)}(i-1,j-1) \\ e_{01}^{(n-1)}(i,j-1) \end{bmatrix} \qquad (5)$$

where $\mathbf{K}^{(n)}$ is a 4x4 circulant and symmetric matrix [7].

The first row of $\mathbf{K}^{(n)}$ is $\left[1\ \mathbf{k}^{(n)^T}\right]$.

For this filter, the $\mathbf{k}^{(n)}$ vector in Eq.(3) is defined as follows:

$$\mathbf{k}^{(n)} = \left[k_1^{(n)} \quad k_2^{(n)} \quad k_3^{(n)}\right]^T \qquad (6)$$

2.2. The Six-Parameter Lattice Filter

Normally, four quadrant symmetry assumption does not hold and this should not be imposed. Moro et.al [4] derived a lattice structure which is equivalent to using two quadrant filters by ignoring this assertion. In this case, we have to use two sets of parameters. Eq.(5) is still valid, but the $\mathbf{K}^{(n)}$ matrix has to be modified [4].

As a consequence of this, we have to solve two sets of normal equations.

$$\mathbf{R}_m^{(n-1)}\mathbf{k}_m^{(n)} = \mathbf{r}_m^{(n-1)} \quad (m = 1,2) \qquad (7)$$

where

$$\mathbf{k}_1^{(n)} = [k_1^{(n)}\ k_2^{(n)}\ k_3^{(n)}]^T \qquad (8)$$

$$\mathbf{k}_2^{(n)} = [k_4^{(n)}\ k_5^{(n)}\ k_6^{(n)}]^T \qquad (9)$$

Naturally, this will lead to modifications of $\mathbf{R}^{(n)}$ and $\mathbf{r}^{(n)}$, as well.

2.3. The Eight-Parameter Lattice Filter

The three-parameter lattice filter is not adequate to represent all classes of 2-D quarter plane AR processes since it lacks sufficient number of parameters resulting in information loss. The loss of information can be reduced by introducing new backward prediction error fields. Thus, the number of reflection coefficients is increased.

The eight-parameter lattice filter [5-6] introduces five new backward prediction error fields at coordinates (2,0), (2,1), (2,2), (1,2), (0,2). This new model differs from the three- and the six-parameter lattice filters as one stage of this model is equivalent to two stages of the three- and the six-parameter structures. The related reflection coefficients are k_4, k_5, k_6, k_7 and k_8, respectively.

The input-output relation of a typical stage of the eight-parameter lattice filter is in the same form as Eq.(1) with the following definitions.

$$\mathbf{e}^{(n)}(i,j) = [e_{00}^{(n)}(i,j)\ e_{10}^{(n)}(i,j)\ e_{11}^{(n)}(i,j)\ e_{01}^{(n)}(i,j)\ e_{20}^{(n)}(i,j)\ e_{21}^{(n)}(i,j)\ e_{22}^{(n)}(i,j)\ e_{12}^{(n)}(i,j)\ e_{02}^{(n)}(i,j)]^T \qquad (10)$$

$$\mathbf{e}^{(n)*}(i,j) = [e_{00}^{(n)}(i,j)\ e_{10}^{(n)}(i-1,j)\ e_{11}^{(n)}(i-1,j-1)\ e_{01}^{(n)}(i,j-1)\ e_{20}^{(n)}(i-2,j)\ e_{21}^{(n)}(i-2,j-1)\ e_{22}^{(n)}(i-2,j-2)\ e_{12}^{(n)}(i-1,j-2)\ e_{02}^{(n)}(i,j-2)]^T \qquad (11)$$

$\mathbf{K}^{(n)}$ is a 9-by-9 circulant and symmetric matrix [5-6], and its first row is $\left[1\ \mathbf{k}^{(n)^T}\right]$ where the reflection coefficient vector $\mathbf{k}^{(n)}$ is given by:

$$\mathbf{k}^{(n)} = \left[k_1^{(n)}\ k_2^{(n)}\ k_3^{(n)}\ k_4^{(n)}\ k_5^{(n)}\ k_6^{(n)}\ k_7^{(n)}\ k_8^{(n)}\right]^T \qquad (12)$$

3. THE ADAPTIVE ALGORITHM

The adaptive algorithm derived in [4] will be used to update the coefficients of the three-, the six-, and the eight-parameter lattice filters. It briefly states that:

(i) The normal equation at space position (i,j-1) after the minimization of the mean squared error is given as:

$$\mathbf{R}^{(n)}(i,j-1)\mathbf{k}^{(n+1)}(i,j-1) = \mathbf{r}^{(n)}(i,j-1) \qquad (13.a)$$

(ii) The adaptive algorithm introduces the correction term for **R**(i,j), namely $\Delta\,\mathbf{R}(i,j)$

$$\mathbf{R}^{(n)}(i,j) = \mathbf{R}^{(n)}(i,j-1) + \Delta\mathbf{R}^{(n)}(i,j) \qquad (13.b)$$

(iii) It also introduces the correction term for **r**(i,j), namely $\Delta\,\mathbf{r}(i,j)$

$$\mathbf{r}^{(n)}(i,j) = \mathbf{r}^{(n)}(i,j-1) + \Delta\mathbf{r}^{(n)}(i,j) \qquad (13.c)$$

(iv) The normal equation at space position (i,j) can also be utilized as:

$$\mathbf{R}^{(n)}(i,j)\mathbf{k}^{(n+1)}(i,j) = \mathbf{r}^{(n)}(i,j) \qquad (13.d)$$

The equations (i)-(iv) result in the following adaptive algorithm:

$$\mathbf{k}^{(n+1)}(i,j) = \mathbf{k}^{(n+1)}(i,j-1) - [\mathbf{R}^{(n)}(i,j)]^{-1} [\Delta\mathbf{R}^{(n)}(i,j)\mathbf{k}^{(n+1)}(i,j-1) - \Delta\mathbf{r}^{(n)}(i,j)] \qquad (14)$$

The matrix inversion lemma is used in order to update the inverse of the matrix $\mathbf{R}^{(n)}(i,j)$ in a recursive fashion:

$$[\mathbf{R}^{(n)}(i,j)]^{-1} = [\mathbf{R}^{(n)}(i,j-1)]^{-1} - a\{[\mathbf{R}^{(n)}(i,j-1)]^{-1} \Delta\mathbf{p}^{(n)}(i,j)[\Delta\mathbf{p}^{(n)}(i,j)]^T[\mathbf{R}^{(n)}(i,j-1)]^{-1}\} \qquad (15.a)$$

where a is given as follows:

$$a = 1/([D\mathbf{p}^{(n)}(i,j)]^T[\mathbf{R}^{(n)}(i,j-1)]^{-1}D\mathbf{p}^{(n)}(i,j)^{-1}) \qquad (15.b)$$

The recursion starts with j=0 with **K**(0,0)=**0** and recursively computes K(i,j) (i=0,1,...,I and j=0,1,...,J) according to either row and column scanning [4]. The initial condition for $\mathbf{R}^{(0)}$ is the identity matrix **I**.

3.1. The Three-Parameter Adaptive Lattice Filter

For the adaptive algorithm given by Eq.(14), the vector $\mathbf{k}^{(n+1)}$ is given by Eq.(6). The correction terms $\Delta\,\mathbf{R}^{(n)}$ and $\Delta\,\mathbf{r}^{(n)}$ are given by the following:

$$\Delta\mathbf{R}^{(n)}(i,j) = \Delta\mathbf{p}^{(n)}(i,j)\,\Delta\mathbf{p}^{(n)}(i,j)^T \qquad (16.a)$$

$$\Delta\mathbf{p}^{(n)}(i,j) = \left[e_{10}^{(n)}(i-1,j)\ \ e_{11}^{(n)}(i-1,j-1)\ \ e_{01}^{(n)}(i,j-1)\right]^T \qquad (16.b)$$

$$\Delta\mathbf{r}^{(n)}(i,j) = e_{00}^{(n)}(i,j)\,\Delta\mathbf{p}^{(n)}(i,j) \qquad (16.c)$$

3.2. The Six-Parameter Adaptive Algorithm

For the six-parameter lattice filter, the algorithm given by Eq.(14) will be utilized twice for each vector $\mathbf{k}_1^{(n)}$ and

$\mathbf{k}_2^{(n)}$ so that the normal equation will be solved recursively. In this case Eq.(15) will be utilized twice to calculate the inverse of $\mathbf{R}_1^{(n)}(i, j)$ and $\mathbf{R}_2^{(n)}(i, j)$. Here $\Delta\mathbf{p}_1^{(n)}$ is given by Eq.(16.b) and $\Delta\mathbf{p}_2^{(n)}$ is defined as:

$$\Delta\mathbf{p}_2^{(n)}(i,j) = \left[e_{00}^{(n)}(i,j) \quad e_{11}^{(n)}(i-1,j-1) \quad e_{01}^{(n)}(i,j-1)\right]^T \quad (17)$$

3.3. The Eight-Parameter Adaptive Algorithm

We can easily determine the correction terms $\Delta\mathbf{R}^{(n)}(i,j)$ and $\Delta\mathbf{r}^{(n)}(i,j)$ using the relations given by Eqs.(16.a) and (16.c) respectively, with the new definition for $\Delta\mathbf{p}^{(n)}(i,j)$;

$$\begin{aligned}\Delta\mathbf{p}^{(n)}(i,j) = [&e_{10}^{(n)}(i-1,j)\, e_{11}^{(n)}(i-1,j-1) e_{01}^{(n)}(i,j-1)\\ &e_{20}^{(n)}(i-2,j)\, e_{21}^{(n)}(i-2,j-1)\, e_{22}^{(n)}(i-2,j-2)\\ &e_{12}^{(n)}(i-1,j-2)\, e_{02}^{(n)}(i,j-2)]^T \end{aligned} \quad (18)$$

4. SCOPE OF QUALITY CONTROL IN TEXTILE FABRICS

The general approach in textile quality control is to find the defects on the fabrics before any colorful pattern is put on it. Fabrics have various types, depending on the material and the color. We have worked on gray level images obtained from white wool and black wool fabrics. The major defects were, missing threads (causing dark lines on the image), gathered knots and oil stains (causing small dark regions on the image), gathered threads (causing dark curves on the image), and tiny holes on the fabrics. It is clear that there is an inherent texture and there is the defect of a slightly darker tone on the image. Quality control should be able to locate the defect on the image.

5. DEFECT DETECTION

Prediction error filtering removes any predictable part of the image and only the unpredictable part of the image remains after filtering. The unpredictable part in an image is potentially a defect.

The block diagram of the system we have used to detect and locate defects is given in Figure 1. This system is used to locate defects in fabric images taken by a black and white camera in a real textile environment. The function of each block will now briefly be explained:

i. Histogram Modification: This operation is done for increasing the range of the dark pixels (comparable to histogram stretching) that are potentially the defects and translating the light pixels towards white. The ultimate goal is an image where the defective pixels are highlighted.

ii. Pre-Median Filtering: Histogram Modification causes the background color to be lighter, and increases the range of dark pixels towards black. Therefore isolated pixels appear after this modification. These pixels are not defects so they must be eliminated. Simple 3x3 median filter has been used in all applications.

iii. Prediction Error Filtering and Thresholding: The pre-median filtered image is modified so that it becomes a zero mean and unit variance image. This is essential for determining a unique threshold for the prediction error filtered image.

In this way the same threshold can be applied for all of the lattice structures in order to compare their performances on the same scale. The operation of prediction error filtering is performed by using the adaptive 2-D lattice filter. After increasing and scaling the difference between the defect and the background, the next step is to find the forward prediction error field of the 2-D lattice filter and to threshold it in order to have a binary image where only the defect will remain and no texture will appear.

iv. Post-Median Filtering and Noise Removal: This operation removes the isolated pixels that may still remain after the thresholding.

6.RESULTS AND CONCLUSIONS

The comparison of the algorithms can be made in several aspects. The first aspect is the number of arithmetic operations which is directly proportional to the total number of reflection coefficients.

Before any comparison is made, a preliminary assumption has to be made about the order of the system, which will effectively determine the number of lattice stages to be used. The order is, experimentally, found out to be 4, which is equivalent to four stages of the three- and the six-parameter filters, and to two stages of the eight-parameter filters.

Thus the total number of reflection coefficients has to be 12 for the three-parameter filter, 24 for the six-parameter filter and 16 for the eight-parameter filter. Therefore the number of arithmetic operations is the least for the three-parameter filter and the greatest for the six-parameter filter. On the other hand, whichever filter is used, the pre- and the post-median filters and the histogram modification have to be applied to the image, and the number of arithmetic operations are independent from the type of lattice filter used. For the median filters, 3x3 windows have been employed.

Another aspect for comparison will be the false alarm rate. The lattice filters are compared on the basis of their false alarm rates on the corresponding output images. According to this criteria, the best performance is given by the six-parameter filter, then comes the eight-parameter filter, and the three-parameter filter is the last one.

The difference between the performances of the lattice filters result from the kind of symmetry assumptions that the structure is based on. If the image possesses these symmetry conditions then the filter is expected to perform in a superior manner. However if it does not have the symmetry, the false alarm rate will blow up. Therefore, the more general the filter structure, the better is the performance with the trade off on the number of arithmetic operations. This is because, the more general filter structure becomes the more reflection coefficients it has.

The adaptive algorithm uses the gradient itself rather than the estimate of it, which is the case in the LMS type adaptation algorithm. Compared to LMS, the adaptation is more noisy [6].
Using an adaptive algorithm in order to solve equation (3) is absolutely essential because for the three-parameter filter one 3x3 matrix inversion, for the six- parameter filter two 3x3, and for the eight-parameter filter one 9x9 matrix inversions will be thus eliminated.

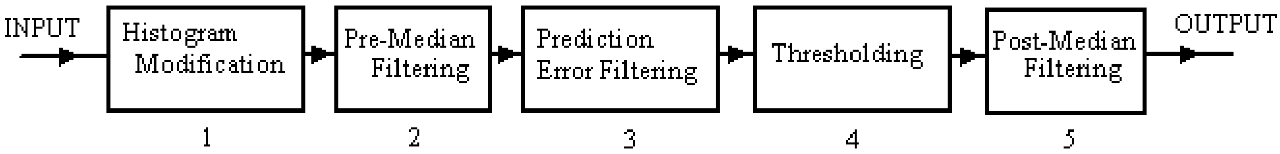

Figure 1 Defect detection scheme as a block diagram

Figure 2 Original defective image

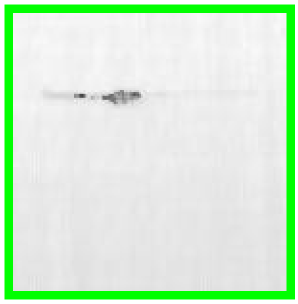

Figure 3 Image after histogram modification and noise removal

Figure 4 Output of the Parameter Filter

Figure 5 Output of the 6-Parameter Filter

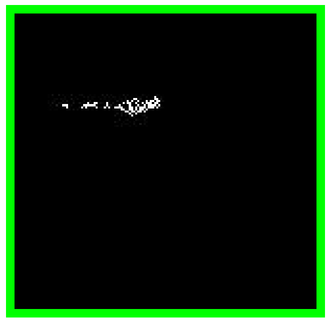

Figure 6 Output of the 8-Parameter Filter

The idea of using a 2-D lattice filter structure can also be employed in a different sense. The defective image can be subdivided into blocks and the reflection coefficients can be calculated separately for each block. These coefficients will then be used as a feature set for the identification of each block as defective or not.
The main advantage of this approach is that it works in an unsupervised manner. Moreover this scheme can be designed as a very large scale integrated circuit (VLSI). All the defects in the sample set used were detected successfully, however, different false alarm rates were obtained by the application of different lattice filters.

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