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MATCHED FILTER DESIGN FOR FINGERPRINT IMAGE ENHANCEMENT

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ABSTRACT

A procedure for filter design is described for enhancing fingerprint images. Four steps of this procedure are described here: user-specification of appropriate image features, determination of local ridge orientations throughout the image, smoothing of this orientation image, and pixel-by-pixel image enhancement by application of oriented, matched filter masks. The contribution of this work is to quantify and justify the functional relationships between image features and filter parameters so that the design process can be easily modified for different conditions of noise and scale. Application of the filter shows good ridge separation and continuity, and background noise reduction.

1. INTRODUCTION

The problem of enhancing fingerprint images to facilitate matching is one that has been much examined[1] [2] [3] [4]. Though many of the enhancement methods are similar, specific parameter values and rationale in the filter design process are usually not given. Reasons for this are perhaps that the specifics of the design process are proprietary, or that the design methods are *ad hoc*. In this paper parameter calculations as well as design rationale are detailed.

One goal in this work is to facilitate filter design for different conditions of noise and image scale. For instance, many fingerprint filters described in the literature are designed for a particular image size and scale. Digitization at a different resolution requires redesign of filter mask sizes and coefficient values. In the procedure described here, quantitative relationships between filter parameters and image features are established. The user specifies values of appropriate image features, and the filter parameters such as filter mask sizes and coefficient values are calculated from these.

The fingerprint image contains narrow ridges separated by narrow background valleys. This pattern may be corrupted by various kinds of noise causing breaks in the ridges, bridges between ridges, and overall gray-scale intensity variation. Despite this noise, humans can often analyze the images easily using such visual clues as local ridge orientation, ridge continuity, and small ridge curvature. A goal of this work is to take advantage of some of these assumptions about the underlying fingerprint pattern to design filters for effective enhancement.

A general approach to fingerprint filter design — one that is followed at least in part in other fingerprint work — is also followed here. First, local ridge orientations are determined at each point in the image to produce an orientation image. This orientation image is smoothed. Then matched, oriented filters are applied throughout the image. For this filtering step, the orientation of the filter mask at each point is the same as that on the orientation image for the same location, and the filter is matched to the image features as specified by the user. Finally, post-processing is performed on the image to reduce background noise. Quantitative and algorithmic details of the approach are given in the next section.

2. FINGERPRINT FILTER DESIGN

The major stages of the filter method are described in this section.

2.1 Fingerprint Image Features and Mask Design

Fingerprint patterns can be described by the following features: minimum and maximum ridge widths, $w_{\min}$, $w_{\max}$, minimum and maximum valley widths, $\bar{w}_{\min}$, $\bar{w}_{\max}$, and the minimum radius of curvature of the ridges, $r_{\min}$. The parameters which need to be specified by the user to make the filter task-specific are any three of the widths (we fix the fourth from the other three: $w_{\min}+\bar{w}_{\max} = w_{\max}+\bar{w}_{\min}$), and the minimum radius of curvature. Since these features can be easily seen, a non-expert in filter design can supply the required parameters.

The optimal filter for signal detection is the matched filter, and one can be designed to perform fingerprint image enhancement effectively. This filter will accentuate ridges

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and valleys whose widths are described by $w_{\min}$, $w_{\max}$, $\bar{w}_{\min}$, and $\bar{w}_{\max}$. It will have different mask orientations which will be dependent on the local ridge orientation. The dc component (or average) of the filter will be zero, so there is no dependence on average intensities of regions. The filter will have a minimum size of one period of the signal, and be symmetric both about the orientation axis and perpendicular to the orientation axis.

The spatial domain filter mask is described in the remainder of this section. We describe the filter mask which is oriented horizontally to match horizontally oriented ridges. Rows in the mask are horizontal, parallel to the ridges; columns are vertical, perpendicular to the ridges. Location in a row is denoted by the subscript i. The value of i is 0 in the center, negative left of center, and positive to the right. Location in a column is denoted by the subscript j. The value of j is 0 in the center, negative above the center, and positive below. Other mask orientations are found by rotating this horizontal mask.

The filter mask is chosen to be square with sidelengths equal to the period of the signal, or the period plus 1, whichever is odd. For the filter mask in the horizontal orientation, the middle rows — or middle strip — consists of coefficients to amplify ridges. The columns on both sides of the middle strip — the side strips — are chosen to negatively amplify the valleys. The width of the middle strip is odd. To reduce interference, the middle and side strips have widths equal to or less than the minimum ridge and valley widths respectively. Depending on the widths of the middle and side strips, there may be a transition strip between them. The transition strip contains zero valued coefficients. Mathematically stated, the horizontally oriented filter mask consists of:

$$\begin{array}{ll} \text{middle strip:} & -h_m \le j \le h_m \\ \text{transition strips:} & -h_t < j < -h_m \ ;\ h_m < j < h_t \\ \text{side strips:} & -h_f \le j \le -h_t \ ;\ h_t \le j \le h_f \end{array} \tag{1}$$

where j is the column index, and h_m, h_t, and h_f are the half widths from the middle row to the end of the middle, transition, and side (end of filter) strips respectively. Hence,

$$h_m = \left[\frac{w_{\min}-1}{2}\right]_- \tag{2}$$

$$h_t = \left[\frac{w_{\max}+1}{2}\right]_+ \tag{3}$$

$$h_f = h_t - 1 + \left[\frac{\bar{w}_{\min}+1}{2}\right]_+ , \tag{4}$$

where $[\cdot]_-$ means, truncate a non-integer to an integer, and $[\cdot]_+$ means, round a non-integer up to the next higher integer value. For the $k \times k$ sized filter mask, $k = 2h_f+1$. Therefore,

$$k = \begin{cases} w_{\max}+\bar{w}_{\min}+1 , & \bar{w}_{\min} \text{ even, } w_{\max} \text{ even} \\ w_{\max}+\bar{w}_{\min}+1 , & \bar{w}_{\min} \text{ odd, } w_{\max} \text{ odd} \\ w_{\max}+\bar{w}_{\min} , & \bar{w}_{\min} \text{ even, } w_{\max} \text{ odd} \\ w_{\max}+\bar{w}_{\min}+2 , & \bar{w}_{\min} \text{ odd, } w_{\max} \text{ even} \end{cases} \tag{5}$$

To calculate the filter coefficients $f(i,j)$, the middle column $f(0,j)$, is first examined. The center coefficient value $f(0,0)$ is set to a_o. To reduce holes in the ridges of the resulting filtered image, the cross section of the middle strip is cosine tapered from a_o at $j = 0$ to half power $a_o/\sqrt{2}$, at $j = \pm h_m$. The coefficient values in the transition strip are zero. The peak value of the side strip $f(0,h_f)$ is set to b_o. The side strip is cosine tapered from b_o at $j = h_f$ to half power $b_o/\sqrt{2}$, at $j = h_t$. The $f(0,j)$ coefficients are calculated as follows:

$$f(0,j) = f(0,-j) = \begin{cases} a_o \cos\dfrac{j\pi}{4h_m} , & 0 < j \le h_m \\ 0 , & h_m < j < h_t \\ b_o \cos\dfrac{\pi(h_f-j)}{4(h_f-h_t)} , & h_t \le j \le h_f . \end{cases} \tag{6}$$

The value of b_o is determined by setting the sum of the coefficients within the column equal to zero,

$$a_o + 2\sum_{j=1}^{h_m} f(0,j) + 2\sum_{j=h_t}^{h_f} f(0,j) = 0. \tag{7}$$

Substituting for $f(0,j)$ from equation (7),

$$b_o = \frac{-a_o\left[1+2\sum\limits_{j=1}^{h_m}\cos\dfrac{j\pi}{4h_m}\right]}{2\sum\limits_{j=h_t}^{h_f}\cos\left[\dfrac{\pi(h_f-j)}{4(h_f-h_t)}\right]} . \tag{8}$$

The coefficients in the middle column are determined from equations (6) and (8). The other coefficients are found from the middle column coefficients. The coefficients in each row are cosine tapered with respect to the middle column value in the same row. We put greater emphasis in the filter mask to the coefficient weights perpendicular to its axis of orientation rather than along it to reduce the effect of high ridge curvature. We choose to attenuate from the middle column to 1/4 power in the side columns. From the middle column coefficients, the other coefficients are found,

$$f(i,j) = f(-i,j) = f(i,-j) = f(-i,-j) = f(0,j)\cos\frac{i\pi}{3h_f} , \tag{9}$$

for $0 < |i| \le h_f$.

Other filter orientations are found by rotating this horizontally oriented filter mask. The coefficient at location (i',j') on the rotated mask is found by rotating by angle θ back to the location (i,j) on the original mask:

$$\begin{bmatrix} i \\ j \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i' \\ j' \end{bmatrix}. \tag{10}$$

The (i,j) location will usually not fall exactly on a sampling location. When this is the case, the coefficient of the rotated mask at (i',j') is calculated as a function of the four coefficients of the original mask nearest (i,j) by Lagrangian interpolation. If these four coefficient coordinates are denoted (i_L,j_L), (i_L,j_U), (i_U,j_L), (i_U,j_U), where subscripts L and U denote lower and upper sampling locations nearest to (i,j), then,

$$\begin{aligned} f(i',j') = {} & (j_U-j')(i_U-i')f(i_L,j_L) + (i'-i_L)(j_U-j')f(i_U,j_L) \\ & + (j'-j_L)(i_U-i')f(i_L,j_U) + (j'-j_L)(i'-i_L)f(i_U,j_U). \end{aligned} \tag{11}$$

For a $k \times k$ sized filter mask of orientation θ and coefficient indices (i,j), we use the notation $f(k,\theta,(i,j))$. For simplicity when k and θ are implicit, we use the notation $f(i,j)$.

2.2 Orientation Image

To apply the oriented filter masks, local ridge orientation must first be determined at each location. To do this, the high spatial frequency content is estimated perpendicular to three orientations, $\theta \; \varepsilon \; \{0, \pi/3, 2\pi/3\}$, and the average of these is found. This value is said to be the dominant orientation.

For the horizontal orientation ($\theta = 0$), we calculate an estimate of the oriented high-pass frequency content, called the orientation weight $\rho(\theta)$, as,

$$\rho(\theta = 0) = \sum_{x = x_A}^{x_B} \left[\sum_{y = y_A+1}^{y_B} | s(x,y) - s(x,y-1) | \right]. \tag{12}$$

For the $\pi/3$ and $2\pi/3$ orientations, the sum of absolute values of differences is taken along $\pi/3$ and $2\pi/3$ rotated lines respectively for $\rho(\pi/3)$ and $\rho(2\pi/3)$.

To find the orientation of maximum high spatial frequency content, a "circular average" is computed from the three orientation weights. For the three orientation axes, the circular average is calculated,

$$\theta_{AVG} = \begin{cases} \theta_{\max} + \dfrac{1}{2} \dfrac{\rho(\theta_{mid}) - \rho(\theta_{\min})}{\rho(\theta_{\max}) - \rho(\theta_{\min})}, & (\theta_{\max}+1)_\pi = \theta_{mid} \\ \theta_{\max} - \dfrac{1}{2} \dfrac{\rho(\theta_{mid}) - \rho(\theta_{\min})}{\rho(\theta_{\max}) - \rho(\theta_{\min})}, & (\theta_{\max}-1)_\pi = \theta_{mid}, \end{cases} \tag{13}$$

where $\rho(\theta_{\max}) \geq \rho(\theta_{mid}) \geq \rho(\theta_{\min})$. The $(\cdot)_\pi$ notation denotes that the quantity in parentheses is modulo π.

2.3 Orientation Image Smoothing

Each image point in the orientation image contains a value between 0 and π representing the local orientation, or a flag indicating that no significant orientation was determined at that location. This orientation image may be noisy, therefore smoothing is performed to reduce the noise. Smoothing is performed on the basis of *consistent* orientation, where consistency is a measure of the confidence of a dominant orientation within a window.

Because there are large areas of constant orientation as well as high curvature regions where orientation is constant only for smaller areas, the smoothing is performed from low to high resolutions in the same manner as multi-resolution or scale-space approaches[5]. Local orientation consistency is measured within square $W \times W$ sized windows from $W = W_{\max}/2$ to $W = 3$. The window sidelengths are halved at each level from low to high resolution. The $W_{\max}$ parameter is the maximum expected sidelength of a consistent square region, as chosen by observation. This choice of $W_{\max}$ is not critical. A larger valued choice has little effect on the smoothing results, but increases computation. Too small a choice for $W_{\max}$ will result in less smoothing. At each resolution level, the window is applied in row-wise and column-wise steps of $W/2$. That is, each window is overlapped by 50% upon each neighboring window. Consistency is measured within the $W \times W$ area. If the area is consistent, the central $W/2 \times W/2$ area within the square on the orientation image is set to the consistent orientation value. If the area is not consistent, it is split into four subsquares of sizes $3W/4 \times 3W/4$ (i.e. each is overlapped by 50%) and consistency is checked as before.

To determine consistency within a window, a histogram of the number of pixels at each orientation is first low-pass filtered and subsampled to the desired final number of orientations. The final number of orientations is equal to the number of different orientations of enhancement masks chosen, and this depends on the desired fineness of the orientation resolution. (There are 10 final orientations chosen for the fingerprint application.) For low-pass filtering before subsampling, a Gaussian shaped window is circularly convolved with the original orientation histogram to reduce aliasing from subsampling. For a subsampling rate of p, a Gaussian window limited to a finite width of $3p$ samples and with a standard deviation of $\sigma = 2.4p$ is chosen to do this. If the peak of the subsampled histogram is greater than a confidence threshold, the orientation is considered to be significant and the central area of the window is set to the orientation corresponding to the peak. If the peak is below the confidence threshold, the area is not orientationally consistent at that level, and the next smaller window is checked. If the procedure progresses to the smallest window $W = 3$, then the middle pixel is set to the peak orientation value independently of the confidence test. The confidence threshold calculation is given in reference[6].

2.4 Enhancement Filtering and Binarization

The enhanced fingerprint image $s'(x,y)$ is determined by applying to each pixel location the filter mask with orientation the same as that on the orientation image for that location:

$$s'(x,y) = \sum_{j=-\frac{k-1}{2}}^{\frac{k-1}{2}} \sum_{i=-\frac{k-1}{2}}^{\frac{k-1}{2}} s(x+i,y+j)\, f(k,\theta,(i,j)). \qquad (14)$$

If the flag is set on the orientation image indicating that no consistent orientation value was found, then $s'(x,y)$ is set to the background value at this location.

Since the enhancement filter has a zero dc component, binarization can be performed on the enhanced image using a threshold of 0. That is, if the result of application of the filter mask at a point is above zero, the pixel value is set high, otherwise it is set to zero.

3. RESULTS AND DISCUSSION

The filter has been used for fingerprint enhancement with good results. In Figure 1, results of filtering are shown for an image digitized at 333 lines/inch. The filter parameters used were $w_{\min} = 3$, $w_{\max} = 5$, $\bar{w}_{\min} = 1$, $\bar{w}_{\max} = 3$, $r_{\min} = 8$, and $W_{\max} = 36$. Other examples on images of different sampling resolution and image quality are shown and discussed in reference[6].

Figure 1. Original gray-scale fingerprint image on left and result of filtering and binarization on right.

Although the pixel-by-pixel calculation of orientation by equation (12) gives a good estimate of local orientation, this stage in the filter method is time-consuming. This stage (before orientation smoothing) takes about 84% of the run time. The other stages take about 4% for orientation image smoothing and 12% for enhancement filtering and binarization. For parameters $w_{\min} = 3$, $w_{\max} = 5$, $\bar{w}_{\min} = 1$, and $\bar{w}_{\max} = 3$, resulting in a filter mask size of 7×7, filtering on a 500×500 size image takes about 5 minutes of run time on a VAX 8650. Processing of this duration and expense is clearly impractical for general use, therefore a VLSI chip has been designed to perform the filtering task. This application-specific integrated circuit (ASIC) is for the specific parameter values of $w_{\min} = 3$, $w_{\max} = 5$, $\bar{w}_{\min} = 1$, and $\bar{w}_{\max} = 3$, that we found worked well over the range of male and female adults in our database. This chip performs the processing steps described here in about 11 seconds per 500×500 size image. The chip architecture is described in detail in[7].

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