Fingerprint Ridge Frequency Estimation in the Fourier Domain

Article *in* Advances in Electrical and Computer Engineering · November 2014

DOI: 10.4316/AECE.2014.04014

2 authors:

Victor-Valeriu Patriciu
Technical Military Academy of Bucharest

Stelian Spinu
Technical Military Academy of Bucharest

Fingerprint Ridge Frequency Estimation in the Fourier Domain

Victor-Valeriu PATRICIU, Stelian SPÎNU
Faculty of Military Electronic and Information Systems, Military Technical Academy,
39-49 George Cosbuc Ave., Sector 5, 050141, Bucharest, Romania
vip@mta.ro, ss@mta.ro

***Abstract*—Ridge frequency is an important parameter in fingerprint image processing and feature extraction. However, ridge frequency estimation is a difficult task in noisy fingerprint images. A simple and accurate method for the computation of fingerprint ridge frequency using the Fourier spectrum is proposed. The results of the experiments conducted on a collection of fingerprints as well as a quantitative method for performance evaluation based on a Gabor filter-bank are presented. The proposed method is robust with respect to noise and reliable frequency images are obtained.**

***Index Terms*—biometrics, feature extraction, fingerprint recognition, identification of persons, spectral analysis.**

I. Introduction

There is an increasing need for reliable person identification in modern society for safeguarding valuable information, economic assets, and critical infrastructures [1].

The use of fingerprints as a biometric identifier is both the oldest mode of automated person identification and the most widely deployed today [2-3]. Because of the distinctiveness and permanence properties, fingerprints have been successfully employed in law enforcement applications for more than a century [2]. The cost and maturity of fingerprint-based identification technology as well as the growing identity fraud/theft have led to the use of fingerprints in a wide range of government and commercial applications [3].

A fingerprint consists of a pattern of interleaved ridges and valleys [3]. The local ridge frequency f_{ij} at point (i, j) in a fingerprint image is the number of ridges per unit length along a hypothetical segment centered at (i, j) and perpendicular to the local ridge orientation [3]. By estimating the local ridge frequency at discrete positions, a fingerprint frequency image is obtained.

The frequency image estimation represents an important step in fingerprint image processing and feature extraction. Applications that require the computing of local ridge frequency include fingerprint image enhancement [4-15] and fingerprint minutiae filtering [16-18]. However, ridge frequency estimation is a difficult task in fingerprint areas of low quality.

The rest of the paper is organized as follows. In section 2, a review of previous approaches to fingerprint ridge frequency estimation is presented. Section 3 describes the method proposed for computing the local ridge frequency in fingerprint images. The results of the experiments conducted on a set of fingerprints as well as a quantitative method for performance evaluation are presented in section 4. Section 5 concludes the paper.

II. Previous Work

The approaches proposed in the literature for the estimation of local ridge frequency in fingerprint images use processing in both the spatial and frequency domains.

Hong, Wan, and Jain [6] divide the input fingerprint image I into non-overlapping blocks of size $w \times w$ pixels and estimate local ridge frequency for each block centered at point (i, j). An oriented window of size $l \times w$ pixels, centered at the point of interest, is defined in the ridge coordinate system (with the y-axis along the local ridge orientation θ_{ij}). The x-signature of the gray levels in the oriented window is determined using the following equation:

$$X(k) = \frac{1}{w}\sum_{d=0}^{w-1} I(u, v), \text{ for } k = 0, 1, \ldots, l-1, \tag{1}$$

where $u = i + \left(d - \frac{w}{2}\right)\cos\theta_{ij} + \left(k - \frac{l}{2}\right)\sin\theta_{ij}$, and $v = j + \left(d - \frac{w}{2}\right)\sin\theta_{ij} + \left(\frac{l}{2} - k\right)\cos\theta_{ij}$. The local ridge frequency f_{ij} is computed as the inverse of the average number of pixels between two consecutive peaks of the x-signature.

Maio and Maltoni [19] show that the ridge pattern in fingerprint images can be locally modeled as a two-dimensional sinusoidal signal and use the partial derivatives of first- and second-order to compute the local ridge density.

In the method proposed by Kovacs-Vajna, Rovatti, and Frazzoni [20], a two-step procedure is employed: first, the average ridge distance is computed in each significant portion of the fingerprint image and then this information is propagated onto the remaining regions to complete the estimation, according to a diffusion equation. Two methods are considered in the first step: geometric and spectral.

Based on the intrinsic characteristics of the ridge pattern in fingerprint images, Kamei [10] proposes a filter designed in the Fourier domain, having two distinct components, a frequency filter corresponding to ridge frequency and a directional filter corresponding to ridge orientation. The local ridge frequency is selected not only according to the maximum filter response, but also taking local smoothness in the fingerprint into consideration.

Yin, Tian, and Yang [21] analyze the performance of the spectral analysis method and the statistical method for ridge distance estimation in fingerprint images. Based on the performance analysis of the two methods, a hybrid approach is defined. First, ridge distances are estimated with the statistical method. For block images whose ridge distances cannot be estimated, the spectral analysis method is then applied.

The algorithm proposed by Chikkerur, Cartwright, and Govindaraju [13] is based on short time Fourier transform analysis. The fingerprint image is divided into partially overlapping, raised cosine windows. The Fourier spectrum of each window is analyzed and a probabilistic estimate of the dominant ridge frequency is obtained.

Based on local orientation, Gottschlich [15] constructs curved regions that are used for estimating the local ridge frequency in the spatial domain. Depending on an information criterion, the gray-level profile is smoothed with a Gaussian kernel. Both, minima and maxima are taken into account and the inverse median is applied for the ridge frequency estimate.

III. PROPOSED METHOD

The ridge-valley pattern in fingerprint images can be locally modeled as a sinusoidal-shaped surface. The Fourier spectrum of this surface consists of two peaks, symmetrical about the origin. The distance between these peaks indicates the local ridge frequency. Fig. 1 presents samples of fingerprint regions of different quality and the corresponding Fourier spectra.

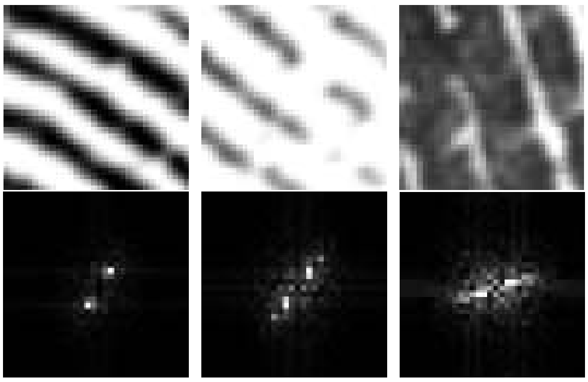


Figure 1. Samples of fingerprint regions of different quality and the corresponding Fourier spectra

Given that the two peaks of the Fourier spectrum are symmetrical about the origin, only one of the two maxima is determined. The position of the peak of the Fourier spectrum indicates the ridge frequency and its magnitude differentiates the ridge region from the fingerprint image background.

In our approach, fingerprint frequency image is estimated at a square grid spaced 16 pixels apart. The fast Fourier transform is applied on each block of size 32×32 pixels centered at each grid point. The maximum value of the centered Fourier spectrum is searched in the upper half of the frequency rectangle, only in the region of valid ridge frequencies (Fig. 2):

$$f_{\min} \le \frac{\sqrt{(u-N/2)^2+(v-N/2)^2}}{N} \le f_{\max}, \tag{2}$$

for $0 \le u \le N/2$ and $0 \le v \le N-1$, where $N=32$, $f_{\min}=1/18$, and $f_{\max}=1/3$, for 500 dpi images.

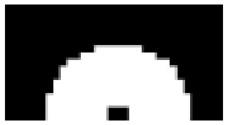


Figure 2. The upper half of frequency rectangle and the region of valid ridge frequencies

Let u_m and v_m be the coordinates of the maximum value of the Fourier spectrum, $|F(u_m,v_m)|$. Since the Fourier spectrum has a limited number of discrete components, for a more accurate determination of the position of the maximum value, these coordinates are separately adjusted for each coordinate axis by taking into account the neighbor in the Fourier spectrum with the largest value. Therefore:

$$u'_m = \begin{cases} u_m - \dfrac{|F(u_m,v_m-1)|}{|F(u_m,v_m-1)|+|F(u_m,v_m)|}, & \text{if } |F(u_m,v_m-1)|>|F(u_m,v_m+1)|, \\ u_m + \dfrac{|F(u_m,v_m+1)|}{|F(u_m,v_m+1)|+|F(u_m,v_m)|}, & \text{otherwise,} \end{cases} \tag{3}$$

and

$$v'_m = \begin{cases} v_m - \dfrac{|F(u_m-1,v_m)|}{|F(u_m-1,v_m)|+|F(u_m,v_m)|}, & \text{if } |F(u_m-1,v_m)|>|F(u_m+1,v_m)|, \\ v_m + \dfrac{|F(u_m+1,v_m)|}{|F(u_m+1,v_m)|+|F(u_m,v_m)|}, & \text{otherwise.} \end{cases} \tag{4}$$

Ridge frequency is given by the distance between the peak of the Fourier spectrum and the center of frequency rectangle. The local ridge frequency at point (i,j) is computed as:

$$f_{ij} = \frac{\sqrt{(u'_m-N/2)^2+(v'_m-N/2)^2}}{N}. \tag{5}$$

Ridge frequency is not defined in the fingerprint image background. The values obtained with equation (5) are considered only in the ridge regions, by thresholding the $|F(u_m,v_m)|$ magnitudes. We chose as a threshold a value of 0.15 of the maximum of the $|F(u_m,v_m)|$ magnitudes for all blocks in the image.

By applying the proposed method for the samples shown in Fig. 1, we obtained the following values of ridge frequencies: $1/9.9$, $1/10.2$, and $1/12.3$, respectively. Though not as fast as the processing in the spatial domain, the proposed method is more robust with respect to noise in the fingerprint images. Accurate ridge frequency estimates are obtained, even in the presence of ridge breaks and links between parallel ridges (Fig. 1).

Most of the existing algorithms for ridge frequency estimation rely on computing local ridge orientation. However, a reliable orientation image is difficult to extract in fingerprints of poor quality. The proposed method is based on finding the maxima of the Fourier spectrum in the range of valid ridge frequencies, leading to reliable ridge frequency estimates.

IV. EXPERIMENTAL RESULTS

Two representative approaches for estimating local ridge frequency in both the spatial and frequency domains, presented in [6] and [13], respectively, and the method proposed in the previous section were implemented in the MATLAB software.

In order to evaluate the performance of the three methods, experiments were conducted on set B of FVC2002 databases [22] (a total of 320 fingerprints). The set of fingerprints includes four different databases (DB1, DB2, DB3, and DB4), collected by using different sensors/technologies (see Table I).

TABLE I. FVC2002 DATABASES [22]

	Sensor type	Image size	Resolution
DB1	optical sensor "TouchView II" by Identix	388×374 (142 Kpixels)	500 dpi
DB2	optical sensor "FX2000" by Biometrika	296×560 (162 Kpixels)	569 dpi
DB3	capacitive sensor "100 SC" by Precise Biometrics	300×300 (88 Kpixels)	500 dpi
DB4	synthetic fingerprint generation SFinGe v2.51	288×384 (108 Kpixels)	about 500 dpi

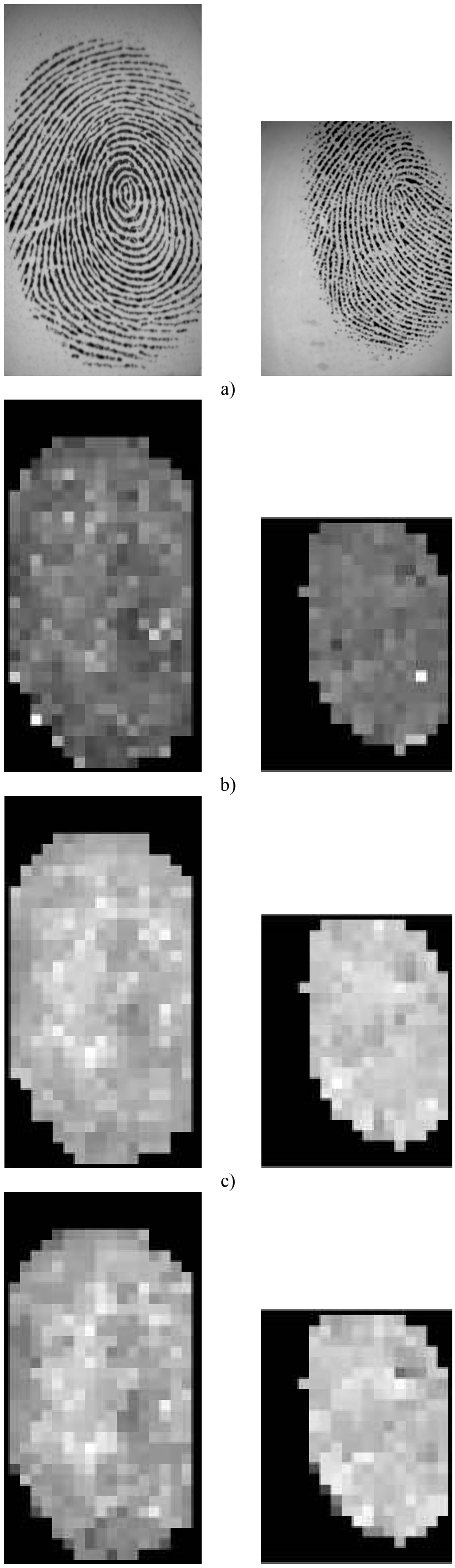
Fig. 3 shows sample images from databases DB2 and DB4 and the corresponding frequency images computed with the methods presented in [6], [13], and the proposed one. The local ridge frequency varies significantly across different regions of the same fingerprint and different fingerprint images are characterized by different average frequencies. For the sample fingerprint images shown in Fig. 3, the local ridge frequency varies within the ranges $[1/18, 1/7.3]$ and $[1/18, 1/6.7]$, respectively. The average ridge frequencies for the same fingerprint images are $1/10.5$ and $1/8.4$, respectively.

In the case of the method presented in [6], it is difficult to reliably detect consecutive peaks of gray-levels in the spatial domain in the presence of noise, high curvature regions or minutiae and it may fail to estimate a ridge frequency. On the other hand, the method presented in [13] and the proposed approach, both using processing in the frequency domain, are more robust with respect to noise and reliable frequency images are obtained.

It is difficult to objectively measure the errors of a ridge frequency estimate. Previous approaches assessed the quality of ridge frequency estimates by means of manual inspection of a limited number of fingerprint images [20] or indirectly, by evaluating the performance of the fingerprint recognition system in which the methods for estimating the local ridge frequency had been incorporated [6], [13], [19-20].

We propose a method based on a Gabor filter-bank for quantitative evaluation of the errors of a ridge frequency estimate. Gabor filters are both frequency- and orientation-selective and provide optimal joint resolution in both the spatial and frequency domains [23-24].

A reliable frequency image can be computed by using a Gabor filter-bank, providing that the number of filters is large enough. We employed a bank of 200 Gabor filters having 8 discrete orientations $\theta_i = \pi(i-1)/8$, where $i = 1, 2, \ldots, 8$, and 25 discrete frequencies equally spaced within the range $[1/18, 1/3]$. Each block in the fingerprint image is convolved with the set of Gabor filters. When the filter parameters match the local ridge features, the ridge pattern in the filtered block has a high contrast between ridges and valleys. The parameters of the Gabor filter corresponding to the filtered block with the largest standard deviation indicate the local ridge features.



d)

Figure 3. Sample images from databases DB2 and DB4 (a) and the corresponding frequency images computed with the methods presented in [6] (b), [13] (c), and the proposed one (d)

The frequency images obtained by each of the three methods were compared with the frequency image computed by using the Gabor filter-bank. However, there should be noted that the computation of local ridge frequency by using a Gabor filter-bank is time-consuming and, therefore, not suitable for real-time applications.

For each fingerprint, the mean absolute error between the ridge frequency estimate of each method and the ridge frequency obtained by using the Gabor filter-bank was computed, taking into account only the valid frequency values. The averages of the mean absolute errors for each of the four databases, along with their standard deviations, are presented in Table II.

The evaluation results show a decrease in both the average error and standard deviation of the ridge frequency estimate obtained by using the proposed method, for all of the four databases. On average, the proposed method led to reductions of 65.1% and 29.8% of the average error compared to the methods presented in [6] and [13], respectively.

TABLE II. THE FREQUENCY ESTIMATION ERRORS

		DB1	DB2	DB3	DB4
Average	Method in [6]	0.0413	0.0205	0.0448	0.0228
	Method in [13]	0.0102	0.0141	0.0259	0.0141
	Proposed method	0.0081	0.0095	0.0147	0.0129
Standard deviation	Method in [6]	0.0219	0.0065	0.0147	0.0123
	Method in [13]	0.0027	0.0041	0.0106	0.0094
	Proposed method	0.0018	0.0032	0.0046	0.0066

V. CONCLUSION

A simple and accurate method for fingerprint ridge frequency computation in the Fourier domain was proposed. Previous approaches to ridge frequency calculation assessed the quality of ridge frequency estimates by indirect means. A method based on a Gabor filter-bank was introduced for quantitative evaluation of the accuracy of ridge frequency computation. The results of the experiments conducted on a collection of fingerprints show a superior performance of the proposed method compared to previous approaches. The method proposed is more robust with respect to the quality of fingerprints and reliable frequency images are obtained.

Our future work will include the method proposed for computing the local ridge frequency in the process of fingerprint image enhancement.

REFERENCES

[1] J.R. Vacca, *Biometric Technologies and Verification Systems.* Burlington, MA: Butterworth-Heinemann, pp. 3-17, 2007.

[2] L. O'Gorman, "Fingerprint verification," in A.K. Jain, R. Bolle, and S. Pankanti (Eds.), *Biometrics: Personal Identification in Networked Society*, pp. 43-64, Boston, MA: Kluwer Academic Publishers, 1999.

[3] D. Maltoni, D. Maio, A.K. Jain, S. Prabhakar, *Handbook of Fingerprint Recognition, 2nd Edition.* London, UK: Springer-Verlag pp. 1-56, 2009.

[4] L. O'Gorman, J.V. Nickerson, "An approach to fingerprint filter design," *Pattern Recognition*, vol. 22, no. 1, pp. 29-38, Jan. 1989. [Online]. Available: http://dx.doi.org/10.1016/0031-3203(89)90035-6

[5] B.G. Sherlock, D.M. Monro, K. Millard, "Fingerprint enhancement by directional Fourier filtering," *IEE Proceedings Vision, Image and Signal Processing*, vol. 141, no. 2, pp. 87-94, Apr. 1994. [Online]. Available: http://dx.doi.org/10.1049/ip-vis:19949924

[6] L. Hong, Y. Wan, A.K. Jain, "Fingerprint image enhancement: algorithm and performance evaluation," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 20, no. 8, pp. 777-789, Aug. 1998. [Online]. Available: http://dx.doi.org/10.1109/34.709565

[7] A. Erol, U. Halici, G. Ongun, "Feature selective filtering for ridge extraction," in L.C. Jain, U. Halici, I. Hayashi, S.B. Lee, and S. Tsutsui (Eds.), *Intelligent Biometric Techniques in Fingerprint and Face Recognition*, pp. 195-215, Boca Raton, FL: CRC Press, 1999.

[8] S. Greenberg, M. Aladjem, D. Kogan, I. Dimitrov, "Fingerprint image enhancement using filtering techniques," in *Proc. of the 15th International Conference on Pattern Recognition*, Barcelona, Spain, Sep 3-7, 2000, vol. 3, pp. 322-325. [Online]. Available: http://dx.doi.org/10.1109/ICPR.2000.903550

[9] J. Yang, L. Liu, T. Jiang, Y. Fan, "A modified Gabor filter design method for fingerprint image enhancement," *Pattern Recognition Letters*, vol. 24, no. 12, pp. 1805-1817, Aug. 2003. [Online]. Available: http://dx.doi.org/10.1016/S0167-8655(03)00005-9

[10] T. Kamei, "Image filter design for fingerprint enhancement," in N. Ratha and R. Bolle (Eds.), *Automatic Fingerprint Recognition Systems*, pp. 113-126, New York, NY: Springer-Verlag, 2004.

[11] E. Zhu, J. Yin, G. Zhang, "Fingerprint enhancement using circular Gabor filter," in A. Campilho and M. Kamel (Eds.), *Image Analysis and Recognition: International Conference, ICIAR 2004, Porto, Portugal, September 29 - October 1, 2004, Proceedings, Part II*, pp. 750-758, Berlin: Springer-Verlag, 2004.

[12] C. Wu, V. Govindaraju, "Singularity preserving fingerprint image adaptive filtering," in *Proc. of the IEEE International Conference on Image Processing*, Atlanta, GA, Oct. 8-11, 2006, pp. 313-316. [Online]. Available: http://dx.doi.org/10.1109/ICIP.2006.313156

[13] S. Chikkerur, A.N. Cartwright, V. Govindaraju, "Fingerprint enhancement using STFT analysis," *Pattern Recognition*, vol. 40, no. 1, pp. 198-211, Jan. 2007. [Online]. Available: http://dx.doi.org/10.1016/j.patcog.2006.05.036

[14] W. Wang, J. Li, F. Huang, H. Feng, "Design and implementation of Log-Gabor filter in fingerprint image enhancement," *Pattern Recognition Letters*, vol. 29, no. 3, pp. 301-308, Feb. 2008. [Online]. Available: http://dx.doi.org/10.1016/j.patrec.2007.10.004

[15] C. Gottschlich, "Curved-region-based ridge frequency estimation and curved Gabor filters for fingerprint image enhancement," *IEEE Transactions on Image Processing*, vol. 21, no. 4, pp. 2220-2227, Apr. 2012. [Online]. Available: http://dx.doi.org/10.1109/TIP.2011.2170696

[16] D. Maio, D. Maltoni, "Neural network based minutiae filtering in fingerprints," in *Proc. of the 14th International Conference on Pattern Recognition*, Brisbane, Australia, Aug 16-20, 1998, vol. 2, pp. 1654-1658. [Online]. Available: http://dx.doi.org/10.1109/ICPR.1998.712036

[17] A. Farina, Z.M. Kovacs-Vajna, A. Leone, "Fingerprint minutiae extraction from skeletonized binary images," *Pattern Recognition*, vol. 32, no. 5, pp. 877-889, May 1999. [Online]. Available: http://dx.doi.org/10.1016/S0031-3203(98)00107-1

[18] D.-H. Kim, "Minutiae quality scoring and filtering using a neighboring ridge structural analysis on a thinned fingerprint image," in T. Kanade, A.K. Jain, and N.K. Ratha (Eds.), *Audio- and Video-Based Biometric Person Authentication: 5th International Conference, AVBPA 2005, Hilton Rye Town, NY, USA, July 20-22, 2005, Proceedings*, pp. 674-682, Berlin: Springer-Verlag, 2005.

[19] D. Maio, D. Maltoni, "Ridge-line density estimation in digital images," in *Proc. of the 14th International Conference on Pattern Recognition*, Brisbane, Australia, Aug 16-20, 1998, vol. 1, pp. 534-538. [Online]. Available: http://dx.doi.org/10.1109/ICPR.1998.711198

[20] Z.M. Kovacs-Vajna, R. Rovatti, M. Frazzoni, "Fingerprint ridge distance computation methodologies," *Pattern Recognition*, vol. 33, no. 1, pp. 69-80, Jan. 2000. [Online]. Available: http://dx.doi.org/10.1016/S0031-3203(99)00040-0

[21] Y. Yin, J. Tian, X. Yang, "Ridge distance estimation in fingerprint images: algorithm and performance evaluation," *EURASIP Journal on Applied Signal Processing*, vol. 2004, no. 4, pp. 495-502, 2004. [Online]. Available: http://dx.doi.org/10.1155/S1110865704310103

[22] D. Maio, D. Maltoni, R. Cappelli, J.L. Wayman, A.K. Jain, "FVC2002: Second Fingerprint Verification Competition," in *Proc. of the 16th International Conference on Pattern Recognition*, Quebec, Canada, Aug. 11-15, 2002, vol. 3, pp. 811-814. [Online]. Available: http://dx.doi.org/10.1109/ICPR.2002.1048144

[23] J.G. Daugman, "Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters," *Journal of the Optical Society of America A*, vol. 2, no. 7, pp. 1160-1169, Jul. 1985. [Online]. Available: http://dx.doi.org/10.1364/JOSAA.2.001160

[24] A.K. Jain, F. Farrokhnia, "Unsupervised texture segmentation using Gabor filters," *Pattern Recognition*, vol. 24, no. 12, pp. 1167-1186, Dec. 1991. [Online]. Available: http://dx.doi.org/10.1016/0031-3203(91)90143-S