Off-Line Signature Verification: Recent Advances and Perspectives

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Abstract
This paper is a description of recent advances in off-line signature verification research performed at our laboratory. Related works pertain to structural interpretation of signature images, directional PDF used as a global shape factor, the Extended Shadow Code (ESC) and the fuzzy ESC, a cognitive approach based on the Fuzzy ARTMAP, and shape factors related to visual perception.

Keywords: Handwritten signature verification, Shape factor definition, Visual perception, Neural networks, Fuzzy inference.

1 Introduction

A lot of work in the field of off-line signature verification has been done at our laboratory since the last twelve years. The long-term goal of this research is to design a complete Automatic Handwritten Signature Verification System (AHSVS) which is able to cope with all classes of forgeries produced with or without imitation of the genuine signature. The majority of approaches reported here have been done specifically for the problem of the elimination of random forgeries defined as genuine signatures of other writers enrolled in the verification system, a prerequisite for real applications.

First, structural interpretation of signature images has been investigated in a way to implement some *graphometric features* related to the characteristics of genuine signatures used by specialists in the field of forensic science [specially from Locard, 39]. This AHSV system was design in a way to be able to cope with all classes of forgeries [2]. The complexity of this approach, especially this one related to the segmentation of the signature line in terms of arbitrarily shaped primitives, gave us the motivation to propose the Fuzzy ESC, a shape factor based on a more flexible scheme because the segmentation problem is overcome [21]. This new scheme permits the fusion of several sources of information related to the geometric shape of the signature and to the pseudo-dynamic information related to the effects of the writing dynamics like speed variations and pressure. This approach is very promising especially for real time applications.

A lot of work has been done in the context of the elimination of random forgeries. We proposed first a global shape factor, the directional PDF [15], in a way to solve this problem with a very simple approach. In fact, the results were not satisfactory (about 5% of mean total error rate with a threshold classifier and 6 reference signatures) because global shape factors like the directional PDF [see [36] for a survey of global shape factors published by others] do not take into account the spatial position of local measurements in the representation of the signature. Moreover, we observed the same level of performance with invariant moments [2].

This observation leads to the proposal of the Extended Shadow Code (ESC) as a family of shape factors related to global and to local shape factors depending on the resolution in use [see Figure 2 in [21]]. This representation showed very good results at high resolution but the best performance was obtained with the cooperation of several classifiers tailor-made for each representation [25]. In this way, several levels of perception are considered in the analysis of a test signature image.

In order to understand more deeply the underlying process related to the local analysis of signatures, a perceptual approach based on a grid of points of attention and a sliding retina has been proposed in [36-38]. Here, the pattern spectrum and elementary segments used as structural elements permit the definition of local geometrical measurements made on the signature trace or on the background area. Experimental results obtained with this representation was closed to those one obtained with the ESC.

Another approach is to put emphasis on preprocessing and to extract *perceptual features* like loops, the body of the signature, inter-words spacing, etc [35]. Here, Binary Shape Matrices are considered as a good compromise for the encoding of signature images. This approach is in fact related to the class of mixed shape factors, eg. global shape factors where the location of measurements is embedded in the representation of the signature.

Few works have been done at the classification level. Murshed in [31] proposed a cognitive approach for the signature verification task in the context of the elimination of random forgeries. The motivation of this work is to train each classifier with genuine signatures only. In this way, a new writer can be added to the verification system without the need to retrain all other classifiers. Another interesting characteristic of this approach is the possibility to train each classifier on-line, eg. the knowledge of the system is enhanced based on a continuous utilization of the verification system. This is a good feature for the implementation of real AHSV systems. This verification system used binary segments extracted locally by the help of an identity grid as a representation of the signature. Future works will be to integrate local shape factors like the ESC [27] and this one related to visual perception [36] in a way to enhance the discriminating power of the system.

In this paper, the related shape factors and AHSV systems are reported and experimental results are compared together. This is followed by a brief description of works in progress in this field at our laboratory.

2 Structural Interpretation of Signatures Images

This study [2-14] was inspired from the work made in the field of forensic science by Locard, an expert document analyst, who proposed in [39] a survey of *graphometric techniques* used for the authentication of questioned documents. The limitations in the performance of graphometric techniques were by this time mostly attributable to the lack of accuracy of measurements taken by different expert document analysts. Locard has proposed many characteristics belonging to genuine handwritten signatures. These characteristics can be subdivided into two classes.

The first class is related to characteristics of genuine signatures imperceptible to the average forger and very difficult to imitate: the rhythmic line of the signature consisting of the positional variation of the maximum coordinate of each character composing the signature; the local variation in the width of the signature line which is closely related to the dynamics of the writing process; and the variation in aspect ratio of the whole signature followed by the local features like aspect ratio, difference in orientation, in relative position, etc., measured between pairs of characters.

The characteristics of the second class are the ones that are very easily perceived by the average forger and are consequently easier to imitate: the general design of the letter's shape; the signature's overall orientation; and the signature's position on the document.

Based on these two classes of characteristics of genuine signatures we proposed in [2-14] an image understanding system based on a signature representation defined in terms of arbitrarily shaped primitives. This approach is *text-insensitive* because no attempt is made to segment specific letters from the semantic part of the signature. Two classes of features related to those one proposed by Locard, *static* and *pseudodynamic* are taken into account for the representation of the signature. The former is related to the geometric shape and spatial relations between some primitives extracted from the signature trace. The latter is associated with the gray-level variation (contrast) and the texture inside the primitive. In considering these two classes of features simultaneously, and the separation from the local interpretation of the primitives followed by the global interpretation of the scene, a general purpose image-understanding system was designed for the interpretation of handwritten signature images. For a complete description of this system, see [2, 6].

Recently, an attempt was made to pursue this work related to the definition and the extraction of primitives for the structural interpretation signature images [1]. In this work, the writing trace of the signature is subdivided in terms of conics like straight lines, ellipses and hyperboles. This method permits a simplification of the signature tracing for the purpose of the elimination of random forgeries. Works are actually in progress in a way to use attributed string-matching techniques based on this representation for the design of a AHSV system for real time applications.

3 Directional PDF as a Global Shape Factor

In a system like this one described in [2], in order to take into account all classes of forgeries, the decision is made only at the end of the verification process. Consequently, this approach is a very costly solution in terms of computational ressources and in terms of related algorithmic complexity. Since random and simple forgeries represent almost 95% of the cases generally encountered in fraudulent cases [40], it was decided to subdivide the verification process in such a way to rapidly eliminate gross forgeries. Thus, a two-stage AHSVS seems to be a more practical solution, where the first stage would be responsible for this rapid elimination and the second stage used only in complicated cases.

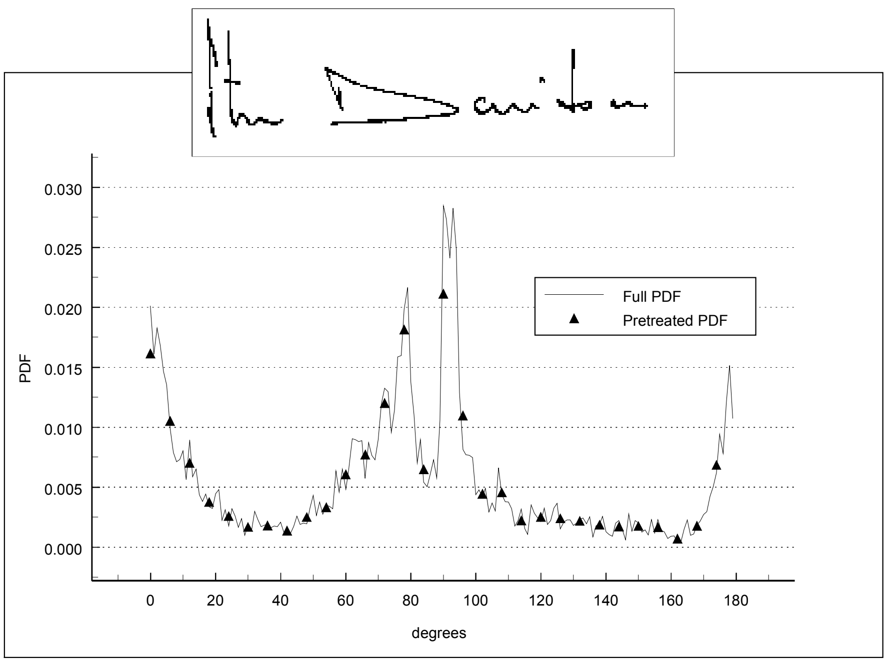


Fig. 1. A genuine signature and the related directional PDF [reprinted from 15].

The first stage of this complete AHSVS thus has two main objectives: firstly, to consider only random forgeries and, secondly, to make rapid decision. To meet the first objective, a characteristic dealing with the overall shape of the signatures has been proposed [15-20]. Accordingly, we proposed the directional Probability Density Function (PDF) as a global shape factor [Figure 1]. Its discriminating power is not optimum because, even though it is invariant in translation and in scale, it is not invariant in rotation. To meet the second objective, we have chosen to use a BackPropagation Network as a signature classifier. The networks were trained with synthetic samples derived from original reference PDFs rotated ±6° with 1° increments. See [15] for a complete description of this system.

4 Extended Shadow Code (ESC) and Fuzzy ESC

One important characteristic that a shape factor related to the signature verification problem should have is the ability to be text-insensitive. This means that measurements taken on the signature shape do not relate to specific letters. This is especially important in the case of handwritten signatures characterized by well-written to highly personalized signatures. The main problem with global features like the directional PDF is a lack of knowledge about the location of local measurements taken on the signature considered as a pattern when they are combined together for the definition of the feature vector.

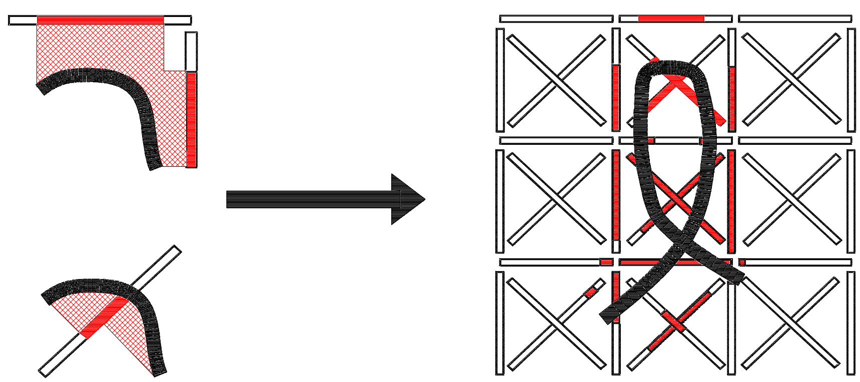
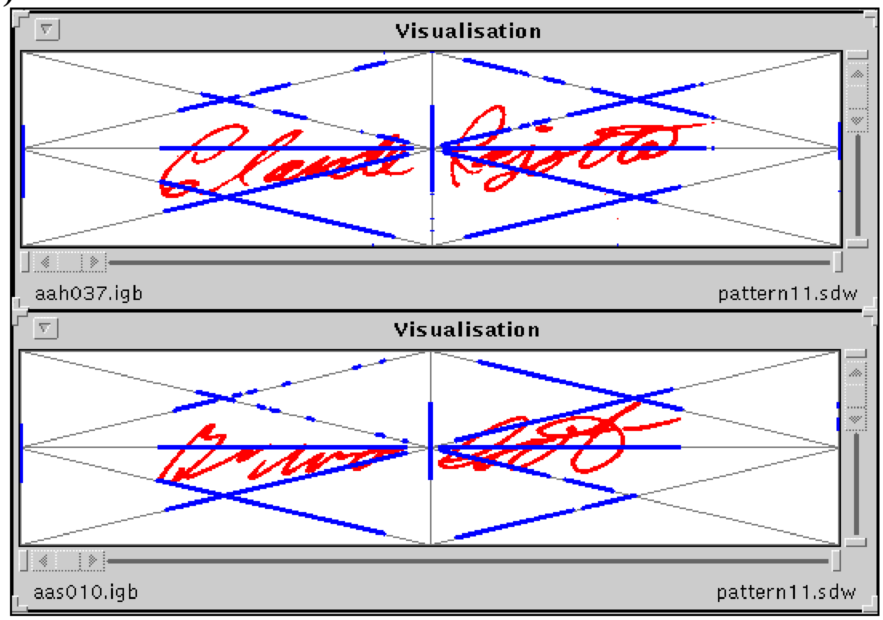


Fig. 2. Definition of the projection mechanism of the ESC [reprinted from 24].

Intrinsically, the extended shadow code is a global shape factor. The rationale behind the use of the ESC as a shape factor for the signature verification problem is that it permits the local projection of the handwriting without losing the knowledge of the location of measurements in the 2D space [Figure 2]. Thus, this shape factor seems to be a good compromise between global features related to the general aspect of the signature, and local features related to measurements taken on specific parts of the signature without requiring the low-level segmentation of the handwriting into primitives, which is a very difficult task [2]. This is acheived by the bar mask definition [21,27], where at low resolution [Figure 3a] the ESC is related to the overall proportion of the signature. In the opposite case, the values of the projections a)



b)

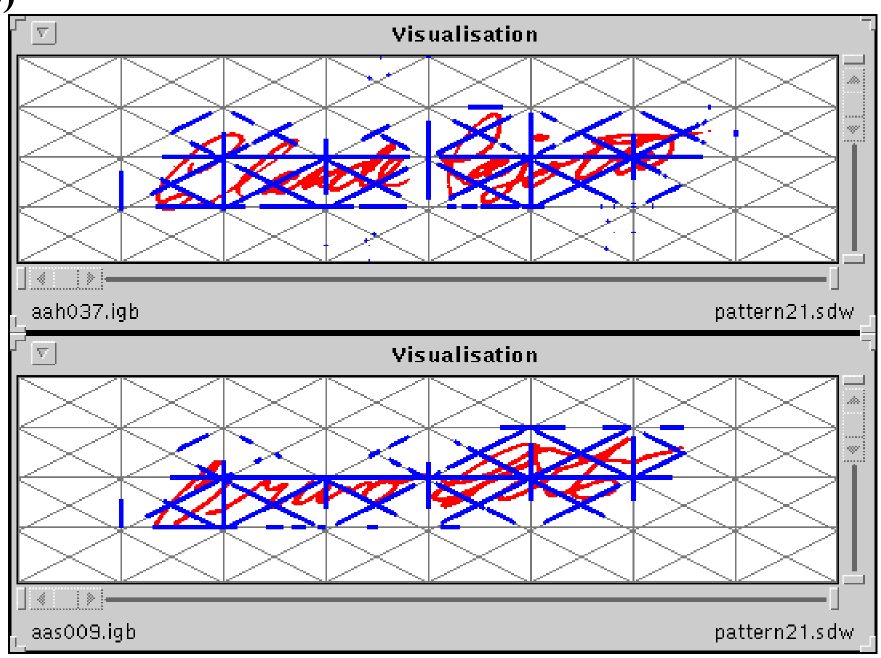


Fig. 3. Examples of the ESC representation at low resolution (a) and at high resolution (b) [reprinted from 24].

at high resolution [Figure 3b] could be related to local measurements taken on specific parts of the signature without the segmentation of specific letters or specific primitives. In this way, varying the resolution of the bar mask permits the definition of a family of shape factors ranging from purely global to almost local. The complete evaluation of this family of representation has been reported in [27], and the evaluation of integrated classifiers based on individual threshold and kNN classifiers is available in [25].

5 A cognitive Approach Based on the Fuzzy ARTMAP

In order to implement a verification system acting like an expert examiner, we proposed in [31] a cognitive approach to the signature verification problem. The expert examiner performs the verification process by comparing the questioned signature only to the reference ones and gives his decision according to the comparison results. This fact was the motivation for the one-class approach, that is, the ability to recognize a class of objects (genuine signatures) wthout the necessity of learning to recognize the shapes of other objects (random forgeries).

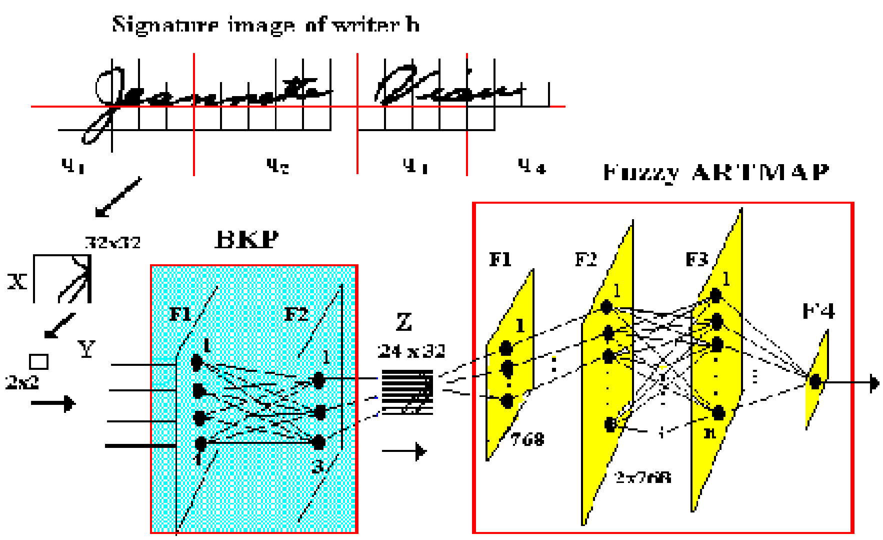


Fig. 4. Feature extraction, image compression and comparison stages of the AHSV system [reprinted from 31].

At the first stage, the signature is segmented from the background using the Otsu's algorithm, and then centralized onto the image area such that it becomes divided into *m* regions [Figure 4] through the use of the identity grid. The centralization is performed by translating the center of gravity of the binary image to the center of the image area. Thereafter, graphical segments of size 16x16 pixels with 50% overlapping in the *x* and *y* directions are extracted from each region in the binary signature and applied to a Back-propagation network which reduces the size of these segments by 1/3.

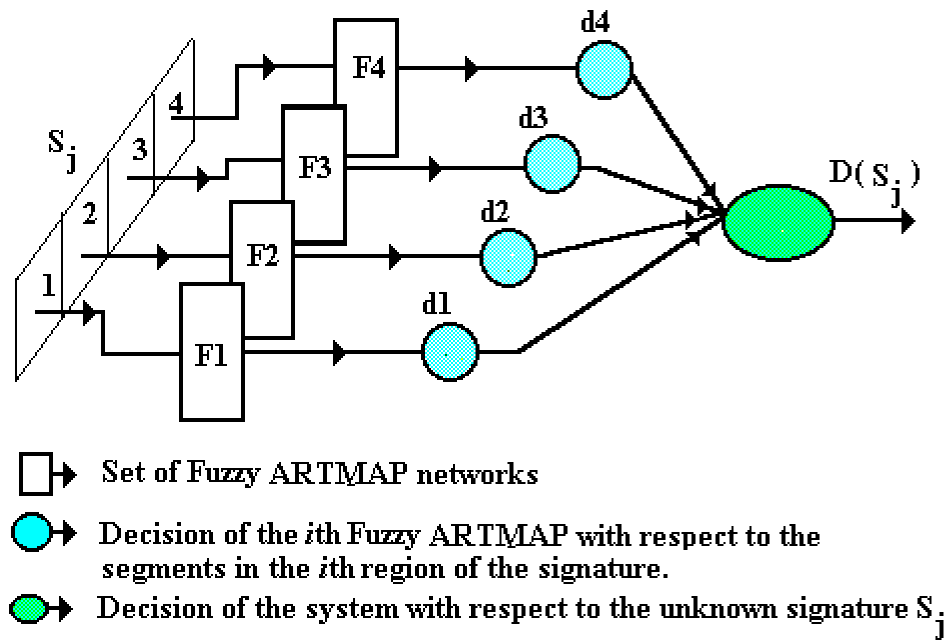


Fig. 5. Final comparison and decision stages of the AHSV system [reprinted from 31].

The reduced graphical segments are then applied to the comparison stage for learning/verification. This stage is composed of *m* Fuzzy ARTMAP networks, each of which is responsible for one region in the signature [Figure 5]. This structure can be viewed as having different experts examining different regions of the signature. Finally, the decision stage analyzes the results produced by each Fuzzy ARTMAP and gives the decision of the system with respect to authenticity of the unknon signature. The complete description of this AHSV system is available in [31].

The main drawback of this approach lies in the use of graphical segments related to a specific region without taking into account its local position in the image. Moreover, new local shape factor like the ESC is needed in a way to enhance the performance of the AHSV system. This approach based on cognitive concepts is very promising and more research in this area will be realized in a near future.

6 Visual Perception

We proposed in [36] a new formalism for the definition of a signature representation based on visual perception. As mentioned above, local approaches are better suited for defining signature representations than global ones. Based on the observations made earlier on the superposition of genuine signatures [Figure 6], the following assumptions can be made with respect to defining a shape descriptor tailored for the signature verification problem:

1) *The overall orientation and the overall proportions of genuine signatures written in a constrained 2D area are relatively stable for each writer, and*

2) *The local variability of the writing trace of the signature is an intrinsic characteristic of the identity of the writer and should be taken into account as well. This phenomenon is characterized by local displacements of strokes following the principal axis of the signature.*

From these assumptions, a certain invariance in rotation and in scale results; hence, their explicit requirement is not needed in the definition of a shape descriptor. Only a correction in translation remains necessary. Assumption 1 is in accordance with the opinion of expert examiners in the field of forensic science [39-41]. Finally, North American signatures are "cursive" in nature; this could partially explain the fact that their overall proportions are relatively stable over time.

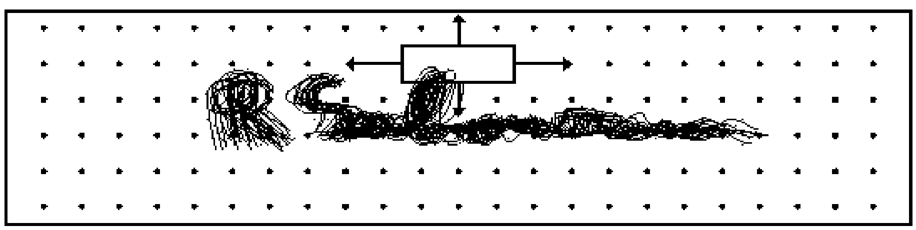


Fig. 6. A rectangular retina is shown with the field of points of attention uniformly distributed in the image space [reprinted from 36].

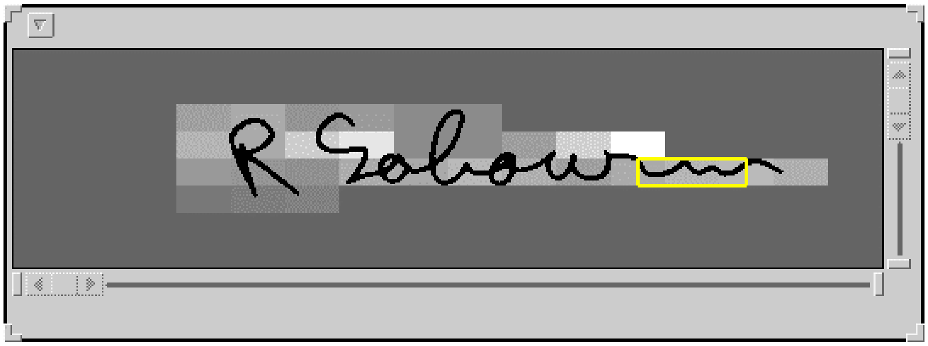
The originality of the proposed approach is that local measurements are not made on specific parts (primitives) of the signature, but on specific areas around foci of attention in the image plane. The identification and segmentation of feature points or primitives on the writing trace of the signature are performed by just assuming that the foci of attention are specified arbitrarily in the image space. This leads to a simplification of the training phase of the verification system. The method proposed for feature extraction is simple. A signature image of 512x128 pixels is centered on a grid of rectangular retinas which are excited by local portions of the image; each retina has only a local perception of the entire scene [Figure 6], and the measurement made on the subset of pixels related to a specific retina will reflect the local activity of the signal.

The definition grid (i.e. the position and the number of foci) together with the size of retinas have a great impact on the performance of this approach and a prototyping phase is necessary [see Section 5.1 in [36]]. An important aspect for signature representation is that the consistent absence of signal activity in specific areas of the image will be taken into account in an attempt to characterize the shape of the signature. This is achieved by Assumption 1 which stated that the overall proportions of genuine signatures are relatively stable. In other words, not only the signature itself but the background also are considered in the definition of the shape descriptor.

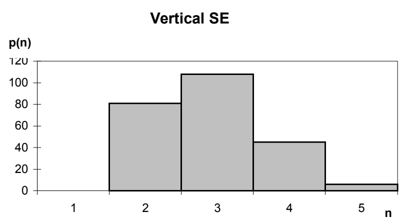
From Assumption 2, the local variability of the writing trace of the signature could be taken into account easily by adding a certain percentage of horizontal and/or vertical overlap between neighboring retinas. As the visual observations made on examples in our signature database showed that in general the displacement of strokes follows the principal axis of the signature, this fact suggests that horizontal overlap alone is enough.

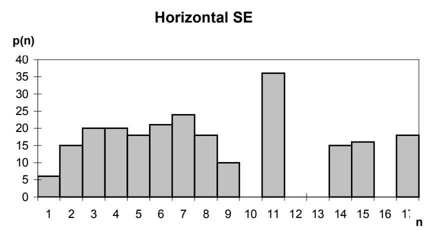
The measurement applied to the set of pixels related to a retina should be capable of detecting the presence, or absence, of any signal activity, and it should be capable in some way of quantifying it. We think that local measurement should be capable of describing the information contained in a binary image and the manner in which it is distributed between the "fine" and "coarse" details. The morphological operations of opening and closing are useful for this task. The *pattern spectrum* is an internal information non-preserving morphological shape descriptor called the *pecstrum* [36]. The pecstrum is computed by measuring the result of successive morphological openings of the image, as the size of the structuring element increases. The sequences of openings so obtained are called granulometries. Spectra obtained from the local analysis based on elementary segments as structural elements are shown in Figure 7.

Shape matrices have been used as a representation of planar shapes like industrial parts or printed characters. In [35], we investigated the use of shape matrices as a mixed shape factor for off-line signature verification. By mixed shape factor we mean any global shape factor where the position of local measurements are take into account in the definition of a similarity measure between two representations. Several preprocessing algorithms like loop filling, smearing and morphological closing have been used for emphasize some local characteristics (*perceptual features*) of the signatures. It was demonstrated that using a good similarity measure between two shape matrices, this shape factor is relatively well suited for the global interpretation of signature images. Experimental results reported in [35] are closed to those observed with local shape factors like the ESC [27] and local measurements based on the pattern spectrum [36].



a)





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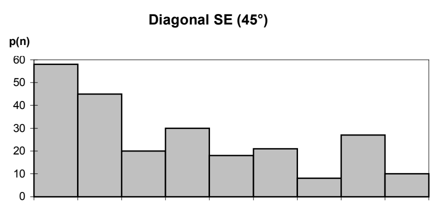

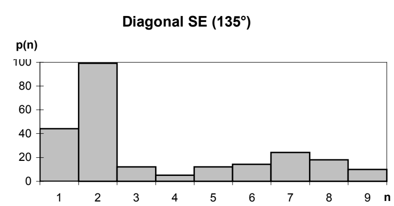

d)

e)

Fig. 7. A signature image (a) and the pecstrums based on structural elements in {|,—,/,\} are depicted in (b) to (e) [reprinted from 36].

7 Conclusion and Perspectives

Experimental evaluation of approaches reported in this paper has been made using a signature database of 800 genuine signatures from 20 individuals. Two types of classifiers, a Nearest Neighbor (NN) and a Minimum Distance (MD) classifier with threshold (Nref=6 reference signatures) was used for the implementation of all verification systems except this one based on the Fuzzy ARTMAP [Table 1].

Approaches	NN	MD with Nref=6	Nref=18
Structural Approach [2]		2.49%	
Directional PDF [15]	2.69%	5.61%	
ESC [27]	0.01%	0.88%	
ESC with Integrated classifiers [25]	0.0% (0.18%)	0.05% (2.88%)	
Cognitive Approach [31]			3.56%
Pattern Spectrum (PS) [36]	0.02%	0.85%	
PS with Integrated classifiers [36]	0.0% (0.05%)	0.27% (2.38%)	
Binary Shape Matrices [35]		0.84%	

Table 1. Experimental results, mean total error rate E_t in % (Rejection rate R_t)

We can see from Table 1 that local shape factors like the ESC and this one based on the pattern spectrum outperform global shape factors like the directional PDF and the structural approach. Moreover, cooperation of classifiers based on local shape factors shows very good results on this signature database [25, 36]. In the case of the AHSVS based on the Fuzzy ARTMAP, the experimental results are closed to those obtained with global shape factors and structural approaches. In this case, the performance of the verification system can be enhanced significantly if binary segments are replaced by local shape factors.

This survey of recent advances in off-line signature verification shows the importance of local approaches in the definition of a signature representation tailor-made for the elimination of random forgeries. Further work is needed to find a signature representation based on local measurements where several information sources can be taken into account, as is the case for the Fuzzy ESC [21]. In this way, several classes of forgeries can be considered without the need to segment the trace of the signature in terms of primitives, a prerequisite for real applications. Moreover, this research on signature representation should be integrated into the cognitive approach proposed by Murshed in [31]. If the merge of these two schemes succeed, it could be possible to implement a real AHSV system able to cope with all classes of forgeries, using only genuine signatures for training.

Works are in progress in a way to relate points of attention [36] to the dynamics of the writing process. In this way, the number, the position and the size of the retinas will be based on the model of the signature. This means that the representation of the signature will be adapted to the intrinsic characteristics of each writer. The main objective of this approach is the elimination of random, simple, simulated and freehand forgeries.

A lot of experiments showed the superiority of AHSV systems based on the cooperation of classifiers [25,36], as is actually the case in the field of character recognition. More research is needed on the design of integrated classifiers for signature verification because the number of data available for training is always small in real application. This situation restricts us to the use of integrated classifiers based on the voting principle because no training is required.

In conclusion, due to the confidentiality of this kind of data, no international signature database is available for research. This is one limitation of this research area. Experimental results can be compared only if the same experimental protocol and database are used for the evaluation of different verification schemes. We hope that an international standard database will be available soon.

8 Acknowledgments

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9 References

STRUCTURAL APPROACHES

[1] Bastos, L.C., Bortolozzi, F., Sabourin, R. et Kaestner, C. "Mathematical Modelation of Handwritten Signatures by Conics", to appears in Revista da Sociedade Paranaese de Matemática, october 1997.

[2] Sabourin, R., Plamondon, R. et Beaumier, L., "Structural Interpretation of Handwritten Signature Images", in the International Journal of Pattern Recognition and Artificial Intelligence, Series in Machine Perception & Artificial Intelligence,World Scientific publisinng co., vol. 13, 1994, pp 709-748.

[3] Sabourin, R., Plamondon, R. et Lorette, G., "Off-line Identification with Handwritten Signature Images: Survey and Perspectives", in "Structured Document Image Analysis", Baird, H.S., Bunke, H. and Yamamoto, K. editors, Springer-Verlag, pp 219-234, october 1992.

[4] Sabourin, R., "Choix d'un Facteur de Forme Basé sur l'Utilisation des Matrices d'Échantillonnage Polaire (MEP)", Conf. et Expo. sur l'Automatisation Ind., Montréal, pp 20.21-20.25, june 1992.

[5] Sabourin, R. and Plamondon, R., "Observability and Similarity in Spatial Relations in the Structural Interpretation of Handwritten Signature Images", The 7th Scandinavian Conf. on Image Analysis, Aalborg, Danemark, 12-17 august, pp 477-485, 1991.

[6] Sabourin, R., «Une Approche de Type Compréhension de Scène Appliquée au Problème de la Vérification Automatique de L'Identité par L'Image de la Signature Manuscrite», *Thèse de Ph.D.,École Polytechnique de Montréal*, December 1990.

[7] Sabourin, R. and Plamondon, R., "Steps Toward Efficient Processing of Handwritten Signature Images", Vision Interface 90, Halifax, Nova Scotia, May 1990, pp 94-104.

[8] Sabourin, R. and Plamondon, R., "Progress in the Field of Automatic Handwritten Signature Verification Systems Using Gray-level Images", Proc. of the Inter. Workshop on Frontiers in Handwriting Recognition, Montréal, april 2^{nd} and 3^{rd} ,1990, pp 1-12.

[9] Sabourin, R., Plamondon, R. and Lorette, G., "Off-line Identification with Handwritten Signature Images: Survey and Perspectives", IAPR workshop on Syntactic and Structural Pattern Recognition, AT&T Murray Hill, New Jersey, June 1990, pp 377-391.

[10] Plamondon, R., Lorette, G. and Sabourin, R., "Automatic Processing of Signatures Images: Static Techniques and Methods", in Handwriting Pattern Recognition, R. Plamondon, G. Leedham eds, World Scientific Pub., Singapore, 14 pages, july 1989.

[11] Sabourin, R. and Plamondon, R., "Segmentation of Handwritten Signature Images Using The Statistics of Directional Data", Proc. of the 9^{th} ICPR, Rome, Italy, pp 282-285, November 1988.

[12] Sabourin, R. and Plamondon, R., "On the Implementation of Some Graphometric Techniques for Interactive Signature Verification: A Feasibility Study", Proc. of The Third Int. Symp. on Handwriting and Computer Applications", Montreal, Canada, pp 160-162, 1987.
[13] Sabourin, R. and Plamondon, R., "Preprocessing of Handwritten Signatures from image Gradient Analysis", Proc. of 8th ICPR, Paris, France, pp 576-579, 1986.
[14] Sabourin, R. and Plamondon, R., "La vérification par ordinateur des Signatures Manuscrites", ACFAS-86, Université de Montréal, may 1986.

DIRECTIONAL PDF

[15] Drouhard, J.P., Sabourin, R. and Godbout, M., "A Neural Network Approach to Off-Line Signature Verification Using Directional PDF", Pattern Recognition, Vol 29, No 3, March 1996, pp 415-424.
[16] Drouhard, J.P., Sabourin, R. and Godbout, M., "A Comparative Study of the k Neareast Neighbour, Threshold and Neural Network Classifiers for Handwritten Signature Verification Using an Enhanced Directional PDF", Third IAPR Conf. on Document Analysis and Recognition, August 14-16, 1995, Montreal, Canada, pp 807-810.
[17] Drouhard, J.P., Sabourin, R. and Godbout, M., "Evaluation of a Training Method and of Various Rejection Criteria for a Neural Network Classifier Used for Off-Line Signature Verification", IEEE International Conference on Neural Networks, Orlando, Florida, june 26 - july 2, 1994, 4294-4299.
[18] Sabourin, R. and Drouhard, J.P., "Off-Line Signature Verification Using Directional PDF and Neural Networks", Proc. of the 11th ICPR, The Hague, The Netherlands, pp 321-325, August 1992.
[19] Sabourin, R., "Évaluation d'un Classificateur de Type LVQ de Kohonen pour la Vérification Automatique de l'Identité", Actes du Colloque National sur l'Écrit et le Document, Nancy, France, 6-7 july, pp 160-167, 1992.
[20] Sabourin,R., Drouhard, J.P., Gagné, L. and Paquet N., "Automatic Handwritten Signature Verification Using Directional PDF and Neural Networks: A Feasibility Study", Conférence et Exposition sur l'Automatisation Industrielle, Montréal, 1-3 June, pp 20.17-20.20, 1992.

EXTENDED SHADOW-CODE (ESC) and FUZZY-ESC

[21] Simon, C., Levrat, E., Sabourin, R. and Bremont, J. "A Fuzzy Perception for Off-line Handwritten Signature Verification", Proc of the BSDIA'97, Curitiba, Brazil, november 1997.
[22] Simon, C., Levrat, E., Brémont, J. and Sabourin, R., "Codage d'images de signatures manuscrites pour la vérification hors-ligne", LFA'96, Nancy, 4-5 december, pp 23-30, 1996.
[23] Simon, C., Querelle, R., Levrat, E., Brémont, J. and Sabourin, R., "Codage d'images de signatures manuscrites pour la vérification hors-ligne", 4ième Colloque National sur l'écrit et le document, Nantes, 3-5 july, pp 171-177, 1996.
[24] Sabourin, R. and Genest, G., "Définition et Évaluation d'une Famille de représentations pour la vérification hors-ligne des signatures", Traitement du Signal, Vol.12, No. 6, 1995, pp 585-596.
[25] Sabourin, R. and Genest, G., "An Extended-Shadow-Code Based Approach for Off-Line Signature Verification: Part -II- Evaluation of Several Multi-Classifier Combination Strategies", Third IAPR Conf. on Document Analysis and Recognition, August 14-16, 1995, Montreal, Canada, pp 197-201.
[26] Sabourin, R. and Genest, G., "Coopération de Classificateurs pour la Vérification Automatique des Signatures", Colloque National sur l'écrit et le Document, Rouen, France, july 6-8, 1994.
[27] Sabourin, R. and Genest, G., "An Extended-Shadow-Code Based Approach for Off-Line Signature Verification: Part -I- Evaluation of The Bar Mask Definition", 12th ICPR, Jerusalem, Israel, October 9-13, 1994, pp 450-453.

[28] Sabourin, R., Cheriet, M. and Genest, G., "An Extended-Shadow-Code Based Approach for Off-Line Signature Verification", Second IAPR Conf. on Document Analysis and Recognition, Tsukuba, Japan, october 20-22, pp 1-5, 1993.
[29] Simon, C., Levrat, E., Sabourin, R. and Bombardier, V., "Vérification Automatique des Signatures Manuscrites par Classification Floue", Troisièmes Journées Nationales : Les Applications des Ensembles Flous, Nîmes, october 26-27 1993.

FUZZY ARTMAP, LOCAL TEMPLATE MATCHING
[30] Murshed, N.A., Bortolozzi, F. and Sabourin, R., "Binary Image Compression Using Back-propagation Neural Network", SPIE Congress on Electronic Imaging (EI'97), San Jose, California, Feb 1997.
[31] Murshed, N.A., Bortolozzi, F. and Sabourin, R., "A Cognitive Approach to Signature Verification", in the International Journal of Pattern Recognition and Artificial Intelligence, Special Issue on Bank Cheques Processing, to appear in 1997.
[32] Murshed, N.A., Bortolozzi, F. and Sabourin, R., "Off-Line Signature Verification Using Fuzzy ARTMAP Neural Networks", IEEE Inter. Conf. on Neural Networks, Perth, Western Australia, november 27 - december 1st 1995, pp. 2179-2184.
[33] Murshed, N.A., Bortolozzi, F. and Sabourin, R., "Off-line Signature Verification Without Requiring Random Forgeries for Training", 3rd Inter. Computer Science Conference., Hong Kong, december 11-13 1995, pp 107-115.
[34] Murshed, N.A., Bortolozzi, F. and Sabourin, R., "Off-line Signature Verification, Without a Priori Knowledge of class w_2. A New Approach", Third IAPR Conf. on Document Analysis and Recognition, August 14-16, 1995, Montreal, Canada, pp 191-196.

VISUAL PERCEPTION
[35] Sabourin, R., Drouhard, J.-P. and Sum Wah, E., "Shape Matrices as a Mixed Shape Factor for Off-line Signature Verification", Proc. of the ICDAR'97, Ulm, Germany, August 18-20, 1997.
[36] Sabourin, R., Genest, G. and Prêteux, F., "Off-Line Signature Verification by Local Granulometric Size Distributions", to appear in IEEE TPAMI (accepted for publication in june 1997).
[37] Sabourin, R., "Une approche perceptuelle pour la définition d'une représention adaptée au problème de la vérification hors-ligne des signatures manuscrites", ACFAS-96, Colloque sur l'intelligence artificielle dans les technologies de l'information : les enjeux et les techniques, may 15-16 1996, Univ. McGill, Montréal.
[38] Sabourin, R., Genest, G. and Prêteux, F., "Pattern Spectrum as a Local Shape Factor for Off-Line Signature Verification", 13th ICPR, Viena, Austria, August 1996, pp C43-C48.

RELATED REFERENCES IN THE FIELD OF FORENSIC SCIENCES
[39] Locard, E., "Traité de Criminalistique", Lyon, Payoy, 1936.
[40] Harrison, W.R., "Suspect Documents, Their Scientific Examination", Nelson-Hall Publishers, Chicago, 1981, 583 pages.
[41] Mathyer, J., "The Expert Examination of Signatures", Journal of Criminal Law, Criminology and Police Science, Vol. 5, No. 3, May-June, pp. 122-133, 1961.