BULGARIAN ACADEMY OF SCIENCES

CYBERNETICS AND INFORMATION TECHNOLOGIES • Volume **6**, No 1

Sofia • 2006

Signature Verification via “Hand-Pen” Motion Investigation*

Mladen Savov, Georgi Gluhchev

Institute of Information Technologies, 1113 Sofia

Abstract: *In this paper a new method for human identification with web-camera video capture while making a signature is proposed. It permits measure of hand position and dynamics of the system “hand-pen”. A set of features for separate hand and pen description as well as for estimation of their mutual disposition at the time of signing is suggested. Verification rules assuming the writer-specific variation in the values of the measured parameters are presented. Preliminary experimental results confirm the applicability of this method.*

Keywords: *biometrics,verification, signature, motion.*

1. Introduction

The signature has been and is still used as a principal mean for document authentication. It is due to the comparative stability of the graph and of the movement dynamics which results from the stereotype built in the years. Along with the steadiness of the main signature elements and their mutual disposition, however, deviations, provoked by natural variance, may be observed in a concrete realization which could make the direct graphic comparison more complicated. Serious deflections may appear in case of various diseases or under the influence of different opiates [13, 14].

In criminology the signature identification is usually executed by a qualified expert. In many cases, for example in banking or at border check-points, hundreds or thousands of identifications are needed daily which makes impossible the man’s involving. This imposes the necessity to elaborate automated identification methods. The first efforts in this direction were made in the 60-ies of the past century [16, 17]. In a large measure, these efforts, as well as most of the publications in the last years [2, 3, 5, 7, 9, 11, 12, 15, 24, 25], use the degree of similarity in the graphs of the compared signatures.

---

* This work is supported by the Ministry of Education and Sciences, contract No И-1302/2003.

Unfortunately, the graph can be imitated skillfully within the range of the admissible variations of the individual. This makes the identification methods using *off-line* analysis of the signature not quite reliable.

To accelerate the identification process when it is impossible to wait for prolonged treatment (e.g. border checks and access-permit systems), an *on-line* analysis is used, where the signature is entered on a graphic tablet and the graph and the dynamics are simultaneously analyzed [4, 8, 10, 18]. The non-standard way of signing, however, may cause deviations in the signature parameters and decision-making errors.

To reduce to the minimum the possible identification errors, serious attention is paid to the elaboration of combined methods including different modalities. The importance of this problem will be increasing in relation with the augmenting human mobility from one side, and the growing terrorist menace from the other; this imposes strengthening of the access control for important objects and information. The up-to-now used technical means as passwords, identification numbers, smart-cards etc., are not reliable enough, because they can be easily cracked. A good solution for this situation is the use of biometric parameters, related to face, voice, hands, fingerprints, signature, iris etc. These can complement one another or be used together, thus ensuring high reliability of the identification.

This paper is one of the efforts in this direction, intended to represent a complex study of the process of signing including the use of color, geometric and dynamic parameters of the hand as well as the pen movement and the mutual disposition of the hand and the writing tool in time of signing. To the best of our knowledge, such investigation, measuring a set of interconnected parameters, but of different character, reflecting the individual features of the signing subject, has not been carried out. An interesting approach based on the pen tip tracking is described in [19].

The paper is organized in the following way: in Section 2 some preprocessing and segmentation steps are presented; Section 3 describes feature extraction; Section 4 includes the decision rules; Section 5 contains experimental results; finally, in Section 6 some problems are discussed and the possibilities for further investigation are outlined.

2. Preprocessing and segmentation

The proposed method is based on image sequence processing. Images reflecting the process of signing are recorded using a web-camera placed above the table. The signature is placed on a white sheet of paper using a blue pen, so a good contrast between the three components: background, hand and pen, is obtained. To reduce the light variation effect, two artificial light sources, fixed on the two sides of the table, are used (Fig. 1).

Fig. 1. Experimental setting

The videos are recorded in AVI file format with rate 20 frames per second. Depending on the signature length, the series of images can contain between 100 and 200 frames. For further processing, videos are divided into frames in BMP format.

The image processing consists of several steps: elimination of the useless frames, separation of the hand and the pen from the background and from each other, contour formation, extraction of features, related to hand parameters and to "hand-pen" system dynamics.

2.1. Elimination of useless frames

Useless frames are those outside the signature itself – the first frames when the hand enters the field of view of the camera and the last frames showing the outdrawing of the hand, as well as the repetitions of same frames in the series of images (all of the several tested web-cameras performed double or triple frame repetitions at different moments of the captured videos at frame rate bigger than 15).

The repetitive frames elimination is not a problem because it is reduced to the comparison of successive frames and deletion of repeated ones. A lot more complicated is the elimination of the initial and final frames. Essentially, it requires finding the start and the end of the signing. Since it is described in detail in [23], we will mention here only the principal steps.

Two cases may be present when capturing the signing process. In the first case the hand with the writing tool is in the field of view of the camera, then the capture begins and the hand starts moving. After the signature is completed the hand remains motionless and the camera stops. The starting and ending moments of signing are obtained by differentiating the consecutive frames and comparing the result with a threshold.

In the other case the signing hand enters the field of view of the camera while the camera is already working, accomplishes writing and then goes out. The differentiation of consecutive frames cannot provide the moments of signature's beginning and end because the entering and the outdrawing of the hand are included in the video. The problem could be solved using the absolute differences between the frames and a reference frame, which does not include the hand. When the hand enters the view field of the camera these differences would rise sharply, then oscillate about some constant value during the signing and would diminish with the hand's outdrawing, so a graph with steep beginning and end will be produced. Calculating the values of the gradient of the graph provides an easy determination of the "plateau" and so of the beginning and the end of the signature. Fig. 2 and Fig. 3 show the graphs of the absolute differences and the slope in the consecutive points for a real signature.

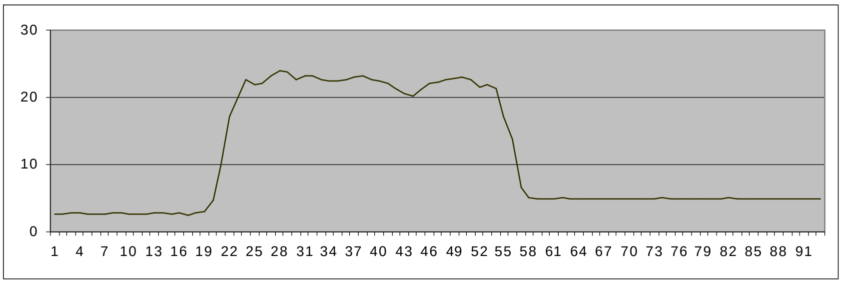


Fig. 2. Graph of the absolute differences when the hand enters and leaves out the field of view of the camera

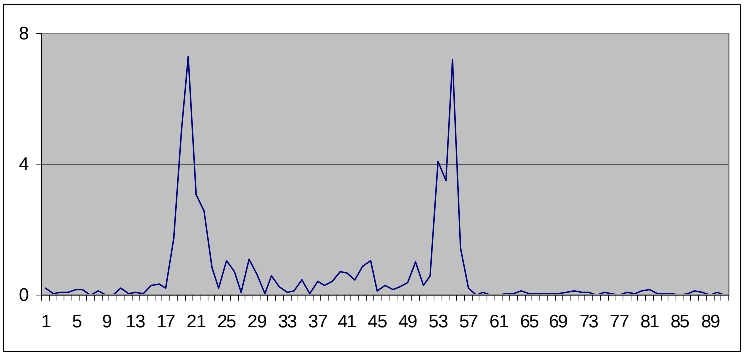


Fig. 3. Graph of the slope of the curve from Fig. 2

At this initial step, one of the possible features characterizing the subject can be obtained – the signature duration in number of frames.

The experiments carried out [23] show satisfying precision in the signature start and end points detection. Variations of 1-2 frames are observed.

2.2. Extraction of the system “hand-pen” from the background

Regardless of the fact that the videos were captured in laboratory conditions, no special care for constant illumination was taken. This was leading to some brightness and contrast changes in the recorded images depending on the external sunlight and might hamper the background elimination.

The problem of objects extraction is fundamental in image processing [21]. To resolve this in our case several frames are recorded in the absence of object. For every two consecutive frames (*k*, *k+1*) the maximal absolute difference $E^{k,k+1}$ of the values of the three color components is to be evaluated:

$$E^{k,k+1} = \max | E^{k+1}(i,j) - E^{k}(i,j) |, \tag{1}$$

where $E^{k}(i,j)$ is the color components vector at pixel (i, j) in the k-th image ($k = 1, 2, \ldots, K-1$) and K is the number of the frames in the series.

The maximal difference

$$E = \max_{k} E^{k,k+1} \tag{2}$$

in the empty image sequence is further used as a threshold for the object detection in the image sequence.

The subtraction of a reference background image from a current signature frame gives a good separation of the “hand-pen” complex as can be seen in Fig. 4.

a) b)

Fig. 4. Original image (a); background subtraction (b)

Fig. 4a contains the initial image while Fig. 4b shows the result from the background subtraction where the values of the pixels from the current frame, which absolute differences with the corresponding values in the reference frame do not surpass *E*, are replaced by white color. After this operation, “salt and pepper” noise can still remain in the image, but this does not harm further processing.

The so obtained series of images permits the extraction of quantitative description of the “hand-pen” complex.

2.3. Separating the hand and the pen

For the analysis of the hand and pen movements when signing, a separation of the two elements is necessary. This provides a possibility to estimate their mutual position in each frame and its variation during the sequence. To facilitate the differentiating, the pen is selected blue which makes good contrast with the predominating skin color (red with blue and green tinges) and the sheet of paper. The use of “red/blue” relation in the pixels outside the background leads to a good separation of the hand from the pen. The pixels, where this relation is bigger than a preliminary determined threshold, are set to red while others are colored in blue (Fig. 5). By reason of possible presence of separate pixels mislabeled red instead of blue and vice versa, a morphological erosion operation with “cross” structuring element of dimensions 3×3 is applied. The eliminated pixels are changed to white. This gives also a better visual pen separation as the border pixels between hand and pen are also deleted.

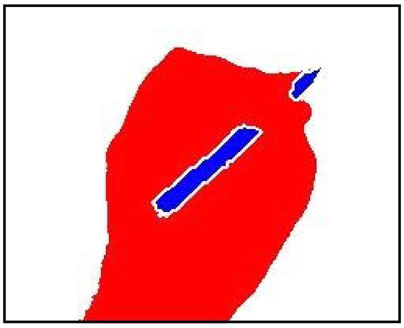


Fig. 5. Separation of the pen
from the hand and the background

3. “Hand-pen” system features extraction

The essential features for signing subject verification can be related to hand characteristics and movement, pen position and mutual hand-pen disposition. After the separation of the hand and the pen these features can be measured individually.

Hand features come from its color and contours. As a general color feature, the average values of the pixels of the hand region can be used. This rough feature may help for the person’s race belonging determination. It is also possible to use color properties in different parts of the hand directly for verification purposes. The features representing the hand geometry are extracted from the contour line as described further.

Additional features which would facilitate the verification can be extracted from the pen position in each frame of the sequence. The most important between them are the angle of orientation of the pen and the pen inclination towards the plane of the sheet of paper.

3.1. Contour formation

The use of the whole contour, obtained by consecutive clockwise movement starting with the upper left point, is not preferable, because first, in different frames, contours with different length will be obtained, and second, spur noise may appear due to insufficient background removal. This could make difficult the contour variation estimation in consecutive frames as well as the measure of its local properties. These troubles can be mostly avoided using an "upper" contour in each frame. In addition, due to the disposition of the artificial light sources, noise is absent in the upper part of the images.

The upper contour K of the hand can be obtained if all the columns x in the image ($x = 0,...,M$, where M is the image width) are scanned in up-down direction. When the first pixel with the hand color is found, its coordinates (x, y) are saved as point from the contour. To avoid accidental noise, a check if the following several pixels below are also from the hand has to be made. If it is not so, the pixel is deleted and the scan continues. In the columns where no hand pixels are found, a zero value is registered as contour coordinate ($y = 0$).

After the contour is formed, it is filtered by replacing the coordinates of the pixels with their average value in an environment of ±5 pixels.

3.2. Contour approximation

For each person, the hand shape will be different, because it depends on the size of the hand, on the way it holds the pen and on the character of its movements while making a signature. The inclination angle of the line, which approximates the upper hand contour the best way in the sense of minimal mean-square deviation, could be used as a general characteristic of the hand contour. For that the following formula is used:

$$S = \sum_{x=0}^{M-1} [y - (ax + b)]^2 = \min \tag{3}$$

for $(x, y) \in K$.

The partial derivatives $\frac{\partial S}{\partial a}$ and $\frac{\partial S}{\partial b}$ are set to zero and a system of equations is obtained. The solution gives the inclination angle of the mean-square line

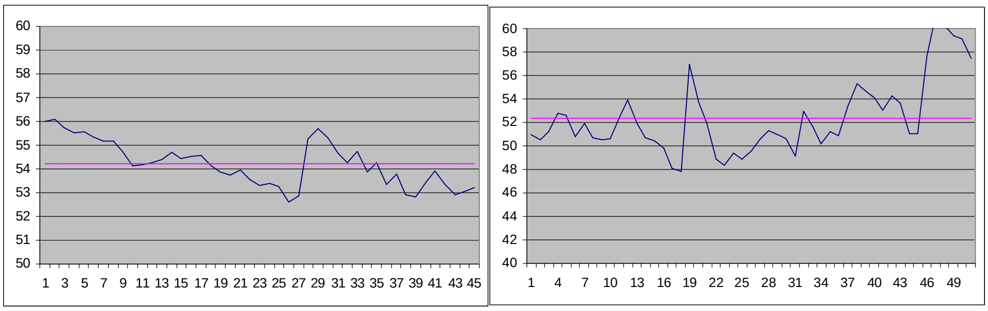
$$\alpha = \mathrm{arctg}(a), \tag{4}$$

where

$$a = \frac{n \sum yx + \sum y \sum x}{n \sum x^2 + \left(\sum x\right)^2} \quad . \tag{5}$$

The sums in (5) are for the points (x, y) from the contour K and n is their number.

For each frame of the signature, the orientation angle of the contour K is calculated. Fig. 6 shows the graphs of the values of the angle α for the frames of two experimental signatures.



A B

Fig. 6. Graphs of the orientation angle of the upper hand contour for participants A and B

3.3. Extraction of geometric features

The geometric feature extraction is based on the detection of characteristic points on the hand's contour. End points and points of curvature larger than a predefined could be assumed as "characteristic". End points are easily detected because they coincide with the beginning and the end of the contour. For the other points detection, an evaluation of the curvature is required. The well-known formula

$$c = \frac{\sqrt{\dot{y}^2\,\ddot{y}^2 - (\dot{y}\,\ddot{y})^2}}{\dot{y}^3}, \tag{6}$$

where (x, y) are coordinates of the current point P, $y = y(x)$ is the contour's line equation, $\dot{y}$ and $\ddot{y}$ stand for the first and second derivatives respectively, may cause difficulties due to the discrete presentation of the contour, presence of noise and possible division by zero. To avoid this and to simplify the calculations, simpler formulae may be used based either on the magnitude of the angle at the current point or the ratio of the sides of a triangle related to it. The arms of the triangle are defined by two contour points $P_{-q} = (x_{-q}, y_{-q})$ and $P_{+q} = (x_{+q}, y_{+q})$ remote q points far from P in both directions. The angle at the vertex P is evaluated using the formula

$$\zeta = \cos^{-1}\left(\frac{\left(\overline{PP_{-q}}, \overline{PP_{+q}}\right)}{\left|\overline{PP_{-q}}\right|\left|\overline{PP_{+q}}\right|}\right), \tag{7}$$

where the inner product of the vectors $\overline{PP_{-q}}$ and $\overline{PP_{+q}}$ is in the nominator and denominator contains the product of their norms. Since $\zeta \in [-\pi/2, \pi/2]$, to obtain a value that could be used straightforwardly as curvature's figure of merit, the angle has to be in the interval $[-\pi, \pi]$. For this the angle ζ' obtained from formula (8) may be used instead of ζ,

(8) $$\zeta' = \zeta + \pi(1 - \mathrm{sign}(\cos(\zeta))/2 \ .$$

In this case the ratio $1/\zeta'$ may be used as curvature estimation.

Another simple estimation of c could be obtained via the following formula

(9) $$c = \frac{\left|\overline{PP_{-q}}\right|\left|\overline{PP_{+q}}\right|}{\left|\overline{P_{-q}P_{+q}}\right|} \ .$$

The figures from formulae (8) and (9) are equivalent in the sense that both values will behave in a similar way, i.e. the local maximums in their graphs will correspond to the points of maximal local curvature.

The points of significant curvature are determined from the histogram of *c*. Since the small values are predominant, the histogram will have a maximum in the beginning. The first minimum following that maximum is used as a curvature threshold. The local maximums position determines the points of significant curvature. Fig. 7 shows the detected points in the upper hand contour. Due to the preceding smooth of the contour some of the points may be displaced by 1-2 pixels from their actual position.

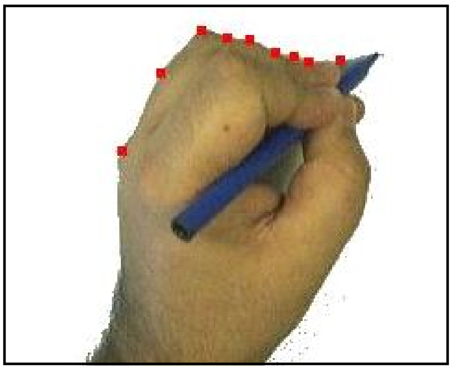


Fig. 7. Characteristic points of the upper hand contour

Thus determined characteristic points may be thought as vertices of a polygon and different geometric parameters may be evaluated.

The number of these points may be different in different frames depending on the position of the hand but the shape of the polygon and its size will not change significantly. This gives the possibility to use its perimeter, area or distances from its center to some points as verification features.

3.4. Pen slope evaluation

The pen position after separation from the hand and the background could be described by the angle γ of its tilt towards the plane and the angle β of its projection in the plane. Since the pen length l is fixed, the first angle may be easily determined by the ratio of the projection length l' to l.

To determine β and l' we have to determine the major axis of the pen. For this its center (C_x, C_y) is evaluated first according to the following formulae

(10) $$C_x = \frac{1}{n}\sum_{i=0}^{n-1} x_i \ , \quad C_y = \frac{1}{n}\sum_{i=0}^{n-1} y_i \ ,$$

where n is the number of pixels from the pen and (x_i, y_i) are coordinates of the i-th pixel ($i = 0,\ldots,n-1$). After that the characteristic equation

$$|\Sigma - \lambda I| = \begin{vmatrix} \sigma_{11}^2 - \lambda & \sigma_{12}^2 \\ \sigma_{21}^2 & \sigma_{22}^2 - \lambda \end{vmatrix} = 0, \tag{11}$$

where

$$\sigma_{11}^2 = \frac{1}{n}\sum_{i=0}^{n-1}(x_i - C_x)^2, \tag{12}$$

$$\sigma_{22}^2 = \frac{1}{n}\sum_{i=0}^{n-1}(y_i - C_y)^2, \tag{13}$$

$$\sigma_{12}^2 = \sigma_{21}^2 = \frac{1}{n}\sum_{i=0}^{n-1}(x_i - C_x)(y_i - C_y) \tag{14}$$

and its own values are determined. The larger value λ is used in the equation

$$(\Sigma - \lambda I)v = \begin{bmatrix} \sigma_{11}^2 - \lambda & \sigma_{12}^2 \\ \sigma_{12}^2 & \sigma_{22}^2 - \lambda \end{bmatrix}\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = 0 \tag{15}$$

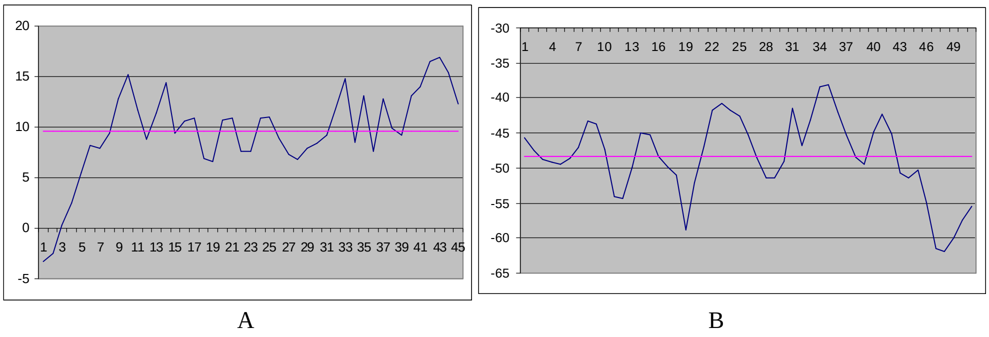
and the angle β is obtained from the relations

$$\mathrm{tg}\beta = \frac{v_2}{v_1} = -\frac{\sigma_{11}^2 - \lambda_1}{\sigma_{12}^2} \tag{16}$$

or

$$\beta = \mathrm{arctg}\left(-\frac{\sigma_{11}^2 - \lambda_1}{\sigma_{12}^2}\right). \tag{17}$$

Fig. 8 shows plots of β for the individuals A and B that have participated in the experiments.



A B

Fig. 8. Plots of the angle β for the individuals A and B

The following way is used for determining of the angle γ. A straight line of angle β is plotted through the center (C_x, C_y) and the distance l' between the utmost pixels from the pen coinciding with the straight line is evaluated. γ is obtained from the equation

$$\gamma = \arccos(l'/l). \tag{18}$$

3.5. Hand-pen relative position

The mutual position of the hand and pen may be evaluated from their geometric parameters in the frames. The following approaches seem to be intuitively acceptable:

a) the difference $\delta = \alpha - \beta$ between the angles of the straight lines described in 3.2 and 3.4;

b) the distances between the pen center and hand contour. For this a straight line perpendicular to the pen's longitudinal axis and passing through the center (C_x, C_y) may be used. The distances $r_1(C, H_1)$ and $r_2(C, H_2)$ between the two utmost cross-points H_1 and H_2 between that line and the contour could be evaluated (Fig. 9).

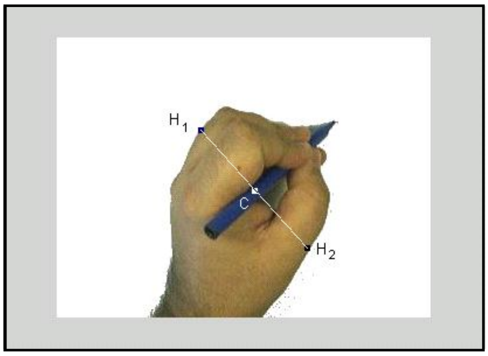


Fig. 9. Distances between the pen and hand contour

4. Authentication

The described in Section 3 set of features will be measured for each individual whose signing has to be verified. Some of the features like skin color are single-valued and could be used straightforwardly for the verification. The others depend on the movement and will have values varying within the frames. For them mean values together with the variation interval could be evaluated. Thus, the interval Δ_i^X of the admissible values of feature F_i for a particular individual X will be defined. This suggests the following simple decision-making rule:

Let (i=1,…, L) be the measured values of an individual Y. If the conjunction

$$D = \bigcap_{i=1}^{L} (F_i \subset \Delta_i^X) \tag{19}$$

is TRUE, then Y is authenticate as X.

In some practical cases however it may not be possible to acquire a sufficiently large number of signatures from the individuals in interest. As a result, the feature intervals may not cover the admissible variations, i.e., the rule (19) will be too restrictive and false-negative answers will often occur. In such cases it is recommendable to increase the intervals and use instead of (19) the following formula:

$$D = \bigcap_{i=1}^{L} (F_i \subset (1 \pm \varepsilon)\Delta_i^X), \tag{20}$$

where $0 \le \varepsilon \le 1$.

5. Experimental results

To test the described approach, 10 volunteers have taken parts in the experiments. Six of them were right-hand writers, the other four used to use their left hand. Ten signature clips have been acquired from each of them in different days and at different time of the day. Six randomly selected signatures of each volunteer were used for feature interval evaluation; the other four were used for testing. The following seven features have been measured and put into formulae (19) and (20): 1) hand slope α; 2) pen slope β; 3) pen slope γ; 4) difference $\delta = \alpha - \beta$; 5) ratio r_1/r_2 of the distances between the pen center and the hand contour; 6) perimeter p of the polygon defined by the characteristic points of the upper hand contour; 7) signature length d as a number of frames. The feature "skin color" was not used because all the volunteers were from one race.

When the more restrictive rule (19) was applied, an average number of 15% false-negative decisions was obtained. In that case there were no false-positive results. The application of (20) at $\varepsilon = 0.5$ decreased the false-negative results by more than 10 %, preserving a zero rate of the false-positive decisions.

6. Conclusion

Preliminary results from work in progress concerning the problem of on-line signature verification are presented. A new approach that takes into account the dynamics of the complex "hand-pen" is suggested. It allows evaluating specific parameters of the hand on the one side, and the interconnection of the hand and pen, on the other side. Thus, some biologically determined parameters are combined with parameters resulting from the writing practice.

The approach pays attention to all aspects of the verification process, starting with image capturing, pre-processing, segmentation, feature extraction and decision-making. While the acquired source information allows for the extraction of many features of different nature, in this investigation only a small number of global features are used and a simple classification rule. Depending on the verification accuracy more sophisticated local descriptors could be involved and more complicated rules could be suggested. The answer of the question "What features and what rule?" is application dependent.

The future work will be aimed at the investigation of some of the parameters dynamics and acquisition of more experimental data. Also, new decision-making rules will be checked.

An interesting extension of the approach will include a tablet instead of a sheet of paper. Thus, more accurate dynamic information may be obtained, including pressure change alongside the signature.

Another possibility is to capture the signature and apply the *off-line* methods for its investigation.

References

1. Cedras, C., M. Shah. Motion-Based Recognition, a Survey. – Image and Vision Computing, **13(2)**, 1995, 129-154.
2. Fang, B., C. H. Leung, Y. Y. Tang, K.W. Tse, P.C. K.Kwok, Y. K.Wong. Off-Line Signature Verification by the Tracking of Feature and Stroke Positions. – Pattern Recognition, **36**, 2003, 91-101.
3. Fang, B., C.H.Leung, Y.Y. Tang, P. C. K. Kwok, K. W.Tse, Y. K.Wong. Off-Line Signature Verification with Generated Training Samples. – In: IEE Proc. Vis. Image Signal Process, Vol. **149**, 2002, No 2, 85-90.
4. Fink, G., M. Wienecke, G. Sagerer. Video-Based On-Line Handwriting Recognition. – In: Proc. International Conf. on Document Analysis and Recognition, IEEE, 2001, 226-230.
5. Gluhchev, G., N. Nikolov. Pressure Evaluation in Handwriting Analysis. – In: Proc. International Conf. on Automatics and Informatics, Sofia, 2001, I-17 – I-20.
6. Gluhchev, G., V. Shapiro, S. Ogorelkov. Automatic Investigation of Handwritten Characters. – Forensic Science and Criminology, **5**, Sofia, 1989, 135-142.
7. Hairong, L., W. Wenyuan, W. Chong, Quing Zhuo. Off-Line Chinese Signature Verification Based on Support Vector Machines. – Pattern Recognition Letters, **26**, 2005, 2390-2399.
8. Hangai, S., S. Yamanaka, T. Hamamoto. On-Line Signature Verification Based on Altitude and Direction of Pen Movement. – In: Proc. of the IEEE International Conf. on Multimedia and Expo (ICME), Vol. **1**, 2000, 489-492.
9. Ismail, M. A., S. Gad. Off-Line Arabic Signature Recognition and Verification. – Pattern Recognition, **33**, 2000, 1727-1740.
10. Jain, A. K., F. D. Griess, S. D. Connell. On-Line Signature Verification. – Pattern Recognition, Vol. **35**, December 2002, No 12, 2963-2972.
11. Kai, H., H. Yan. Off-Line Signature Verification Based on Geometric Feature Extraction and Neural Network Classification. – Pattern Recognition, Vol. **30**, 1996, No 1, 9-17.
12. Kai, H., H. Yan. Off-Line Signature Verification Using Structural Feature Correspondence. – Pattern Recognition, **35**, 2002, 2467-2477.
13. Kalcheva, E., G. Gluhchev. Evaluation of Handwriting Changes in Case of Neurological Diseases. – In: Proc. of CompSysTech'2000, Sofia, Bulgaria, V.16.1-16.5.
14. Kalcheva, E., G. Gluhchev. Investigation of Handwriting General Features in Case of Neurological Diseases. – In: Proc. ICEST 2003, Sofia, Bulgaria, 262-265.
15. Klement, V. An Application System for the Computer-Assisted Identification of Handwritings. – In: International Carnahan Conf. on Security Technology, Zurich,1982, 75-79.
16. Kuckuk, W., B. Rieger, K. Steinke. Automatic Writer Recognition. – In: Proc. of Carnahan Conf. on Crime Countermeasures, Kentuky, 1979, 57-64.
17. Lantzman, R. Cybernetics and Forensic Handwriting Investigation. Moscow, Nauka, 1968.
18. Martens, R., L. Claesen. On-Line Signature Verification by Dynamic Time Warping, – In: Proc. of the 13th IEEE International Conf. on Pattern Recognition (ICPR), Vienna, Austria, Vol. **1**, 38-42, 1996, ISBN 0-8186-7282-X.
19. Munich, M.E., P. Perona. Camera-Based ID Verification by Signature Tracking. – Proc. of 5th European Conf. on Computer Vision EECV'98, Freiburg, Germany, 1998, 782-796.
20. Pacut, A., A. Czajke. Recognition of Human Signatures. – In: Proc. of the IEEE Joint Intl. Conf. on Neural Networks, IJCNN 2001, Vol. **2**, 2001, 1560-1564.
21. Pratt, W. K. Digital Image Processing. New York, Wiley, 1991.
22. Reed, T. Digital Image Sequence Processing, Compression and Analysis. CRC Press LLC, 2005.
23. Savov, M., G. Gluhchev. Automated Signature Detection from Hand Movement. – In: Proc. of CompSysTech'2004, Rousse, III.A.3-1–III.A.3-6.
24. Shapiro, V. Computerized Handwritten Text Investigation. PhD Thesis, Technical University, Sofia, 1990.
25. Shapiro, V., G. Gluhchev, V. Sgurev. Automatic Document Authentication: Approach and Methods. – In: 1st International Conf. on Document Analysis and Recognition, France, V. **2**, 1991, 894-902.
26. Xuhong, X., G. Leedham. Signature Verification Using a Modified Bayesian Network. – Pattern Recognition, **35**, 2002, 983-995.
27. Yoshiki, M., M. Yoshimura, H. Miike, I. Yoshimura. An Off-Line Signature Verification System Using an Extracted Displacement Function. – Pattern Recognition Letters, **23**, 2002, 1569-1577.