Image quality and position variability assessment in minutiae-based fingerprint verification

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Abstract: The assessment of a complete minutiae-based fingerprint automatic verification system, when degrading variability factors are included, is presented. A new large public fingerprint database, the so-called MCYT Fingerprint Database, is used to evaluate the performance of the system in verification tasks. The design of this database, in terms of controlled variability in fingerprint positioning, has made it possible to determine the system performance when the test or the stored images are subject to changes in fingerprint core placing. Some procedures are proposed to cope with this problem, including a multiple-reference strategy. Human supervision and labelling of the image quality of the acquired fingerprint images has also been accomplished, permitting a precise assessment of the proposed minutiae extraction and pattern matching processes. Results, including enhanced procedures for both position variability control and image quality consideration, are presented in terms of DET plots, leading to highly competitive verification scores in terms of EER.

1 Introduction

One of the critical problems regarding the evaluation of biometric recognition systems is the scarcity of public databases involving large populations. In the specific case of fingerprint recognition systems, the number of existing public databases is quite limited. Nonetheless, some outstanding public databases can be quoted, such as the DB 4 NIST Fingerprint Image Groups [1] or the FVC2000 Fingerprint Database [2]. In any case, the enormous acquisition effort for thorough design of the database contents, makes this process in many cases incomplete, costly and unrealistic. Furthermore, biometric features under realistic applications exhibit empirical variability, so acquisition under controlled conditions makes worthless, in many cases, the available data in order to develop, train and test real commercial applications.

Taking this into account, some of the key factors emerging in the database design process are the statistical relevance of the acquired data (dimension of the enrolled population, number of biometric modalities per individual, number of samples for each modality, etc.) and the variability included in the acquisition (both intrinsic variability, due to changes in the feature itself, and extrinsic variability, due to changes in the acquisition scenario, i.e. changes in background, channel or sensor).

Concerning performance of biometric systems on different databases (including modalities like fingerprint, face, voice or signature), diverse evaluation and assessment methodologies are considered in the literature [2–7]. The MCYT Fingerprint Database, described in Section 2, which includes relevant characteristics, due to the large volume of enrolled individuals or the number of variability factors considered, permits evaluation of the verification performance of our minutiae-based fingerprint automatic recognition system, previously proposed in [8]. In Section 3, the architecture and the implemented processing algorithms for this system are described. In Section 4, results achieved in the different evaluation experiments are presented [9, 10]. Finally, Section 5 presents conclusions that tend to improve system performance through the control of the variability conditions in the acquisition stage.

2 MCYT Fingerprint Database

Regarding fingerprints, very few standard public massive databases are available to the scientific community. In this context, a large biometric database acquisition process was launched in 2001 within the MCYT project. The expected number of individuals in the database is roughly 400. About 300 of them are currently being acquired following a single-session procedure, although by the time this contribution was realised less than 100 were fully available. About 100 more individuals are planned to be acquired by mid 2004, in a multisession procedure. This multisession procedure will mainly focus on analysing the effect of making use of several acquisition devices, and to obtain fully automated unsupervised samples [11].

A single-session fingerprint database acquisition process has been designed to include different types of sensors and different acquisition conditions. Two types of acquisition devices, producing both 8-bit grey-scale images, are used: (i) a CMOS-based capacitive capture device, model 100SC from Precise Biometrics [12], with resolution of 500 dpi, producing a 300×300 pixel image (about 90 kB file size), and (ii) an optical scanning device, model UareU from Digital Persona [13], also with resolution of 500 dpi, producing in this other case a 256×400 pixel image (about 102 kB file size).

With the aim of including variability in fingerprint positioning on the sensor, the MCYT Fingerprint subcorpus

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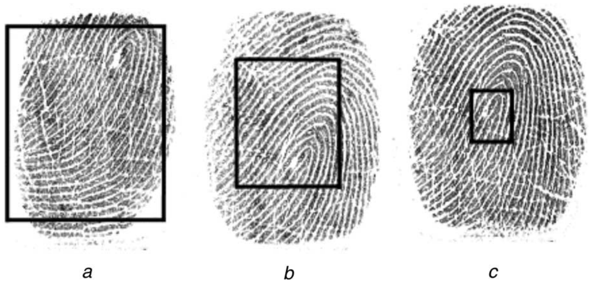

Fig. 1 *Examples of the same MCYT fingerprint samples acquired at different levels of control*

a Low
b Medium
c High

includes 12 different samples of each fingerprint, all of them acquired under human supervision and considering three different levels of control. These levels of control just consider positioning variability, as the fingerprint core must be located inside a size-varying rectangle (displayed in the acquisition software interface viewer), as shown in Fig. 1; in Figs. 1*a*–*c*, three samples of the same fingerprint are shown, so that variability in fingerprint positioning can be clearly observed in this case. In all cases, human supervision ensures that the fingerprint core is inside the proposed rectangle. Fingerprints are acquired by asking the person to remove the finger from the device and then to put it on again in order to avoid exact copies between consecutive samples.

Depending on the size of the rectangle, the different levels of control will be referred to as 'high', 'medium' and 'low', namely: (i) low level of control: in this case (see Fig. 1*a*), three fingerprint samples are acquired, preventing the individual from watching the viewer (without visual feedback on fingerprint placing); (ii) medium level of control: In this other case (see Fig. 1*b*), the individual must produce three more samples, while watching his/her own finger location (with visual feedback on fingerprint placing); (iii) high level of control: Finally, six more samples, acquired with the same procedure as described in (ii), but this time the rectangle has an even smaller size, so a more severe position restriction is applied, as shown in Fig. 1*c*. The proportion of the restricted area of control versus the total available area of the captured image is respectively 70%, 30%, and 5%, for low, medium and high levels of control. For both sensors, every individual provides a total number of 120 fingerprint images (10 fingers × 12 images/finger) to the database. Regarding multi-session acquisition, it is now being designed to include in the future a fully-automated fingerprint acquisition (in which the acquisition process will take control by itself on fingerprint positioning), and also to include other input devices.

3 Fingerprint recognition system

The implemented architecture of the automatic fingerprint recognition system, as shown in Fig. 2, can be divided in four phases: (i) fingerprint image acquisition from the sensor device; (ii) the image enhancement process, in order to reconstruct the ridge structure of the fingerprint; (iii) feature extraction from the enhanced image; and (iv) the pattern matching process, in which a biometric fingerprint sample is compared with the database registered patterns. Since fingerprint acquisition for the MCYT Database has been previously described in Section 2, we will briefly focus on phases (ii), (iii) and (iv).

3.1 Image enhancement

The aim of the image enhancement stage is to provide a high-quality image, so that the feature extractor can obtain a precise biometric pattern. In terms of accuracy, it is common to make use of the minutiae pattern [3, 4, 8–10, 14–17]. A point in the fingerprint image is considered as a minutia if it is derived from an ending, beginning or bifurcation of a ridge. Image imperfections may induce misdetermination of the spatial co-ordinates and relative orientation of each minutia. If so, the recognition system reliability will decrease significantly, making this image enhancement procedure necessary.

Regarding our system, the complete sequence of stages that performs the enhanced minutiae pattern extraction is: (i) normalisation; (ii) calculation of the orientation field; (iii) region of interest extraction; (iv) ridge extraction; and (v) ridge profiling. Details from each stage are explained in [4, 8].

3.2 Feature extraction

In order to generate a reliable biometric pattern, a complete feature extraction process must be accomplished. Therefore, the sequence of processes involved in such extraction is [4, 8, 15]: (i) thinning of the reconstructed binary ridge structure achieved after image enhancement; (ii) removal of all structure imperfections from the thinned image, and (iii) minutiae extraction. The thinning process is performed without modifying the original ridge structure of the image. For each detected minutia the following parameters are stored: (i) the x and y co-ordinates of the minutia; (ii) the orientation angle θ of the ridge containing the minutia; (iii) in the case of an ending ridge, the x and y co-ordinates of the sampled ridge segment containing the minutia; (iv) in the case of a ridge bifurcation, the x and y co-ordinates of the

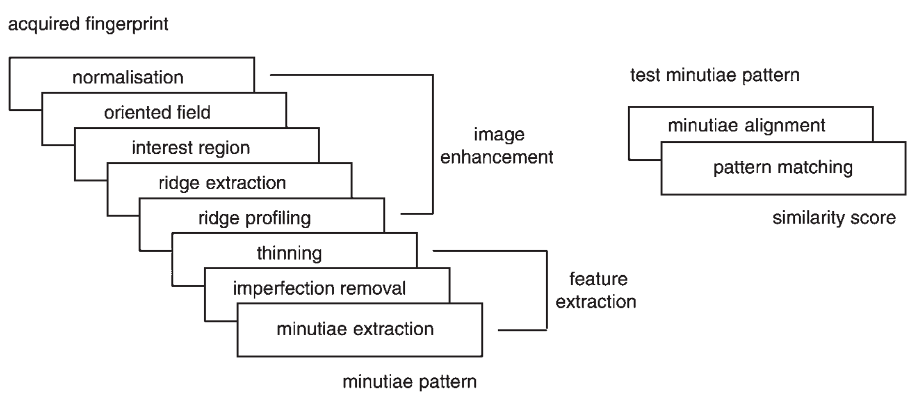

Fig. 2 *Block diagram architecture of the automatic fingerprint recognition system*

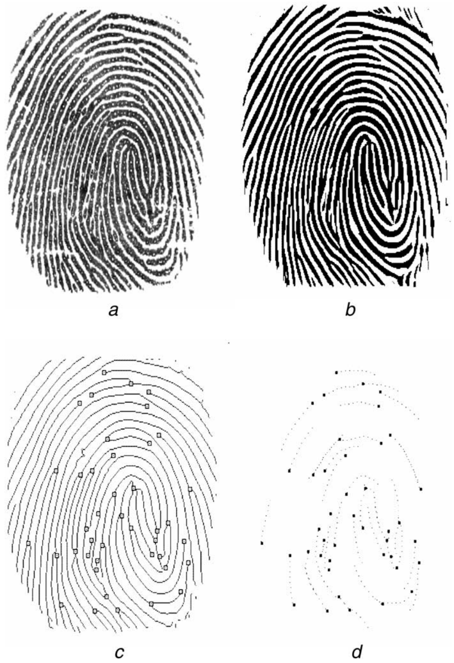

Fig. 3 *Processing of fingerprint from MCYT*

a '*dp_0080_0_5*' fingerprint from MCYT
b Resulting binary image after image enhancement
c Reconstructed thinned ridge structure showing the extracted minutiae (superimposed)
d Minutiae pattern and sampled ridge segments

sampled ridge segment of one of the bifurcation branches. The sampling interval is the mean distance between ridges in the image, and the maximum number of stored sampled points for each minutia is ten. The original acquired fingerprint '*dp_0080_0_5*' from the MCYT Database, the resulting binary fingerprint (after image enhancement), the minutiae pattern superimposed on the thinned image and its corresponding sampled ridge segments are shown, respectively, in Figs. 3*a*–*d*.

3.3 Pattern recognition

Given two biometric patterns, namely test and stored patterns, the verification process is aimed to determine whether those fingerprint patterns have been produced by the same finger or not. Due to elastic deformations of the skin, imperfections in the image and different interest regions of the acquired fingerprints, the two patterns must be aligned before fingerprint matching. Pattern alignment is achieved considering the relative position of the minutiae in the image, and then the matching process is accomplished seeking correspondence between the two aligned structures. In this matching process, a score is defined to measure the similarity (edit distance) between the compared patterns. An elastic technique for minutiae comparison is used, permitting a certain spatial tolerance margin. To compensate for the nonlinear elastic deformations of the skin, the technique is also adaptive. For this purpose, a size-adaptive tolerance box adjustable to the spatial co-ordinate values of the explored minutiae is defined [4, 14, 15].

4 Evaluation of the verification performance

The evaluation procedure of the fingerprint recognition system is aimed: (i) to assess the performance and reliability of the image processing algorithms, in the phases of image enhancement, feature extraction and pattern recognition, with large unsupervised databases, analysing the influence of the position variability in the verification performance (Section 4.1); (ii) to explore a multiple-reference strategy to improve the similarity scores (Section 4.2); and finally, (iii) to analyse the experiments proposed in (i) and (ii) when a supervised database (in terms of fingerprint image quality) is available (Section 4.3).

In order to perform the evaluation in cases (i) and (ii), we have selected a database subcorpus consisting of the first 75 individuals acquired with the optical device; with such a device, a total number of 120 samples per individual are available and, consequently, the total number of involved fingerprints is 9000. To accomplish evaluation in case (iii), the number of individuals in the database subcorpus is reduced depending on a certain image quality degree that will be defined in Section 4.3.

In order to evaluate the FAR (false acceptance rate), the set of impostors for each individual contains one high level of control fingerprint from the remaining population, which, in cases (i) and (ii), means that there are 740 impostor images per individual (74 impostors $\times$ 10 samples), and a total number of impostor attempts of 55 500 (740 samples $\times$ 75 individuals). The number of impostors per individual to evaluate the FAR in case (iii), and number of client attempts, in each case, to evaluate the FRR (false rejection rate), will be further specified.

Results will be expressed, not in the traditional form of ROC (receiver operating characteristic) curves, but rather in the more convenient and equivalent form of DET (detection error trade-off) plots, since these make use of a normal deviate scale that moves the curves away from the lower left of the plot when performance is high, making comparisons between competitive systems easier.

4.1 Variability assessment in fingerprint positioning

The following experiments consider the variability in fingerprint positioning by taking into account the above described levels of control contained in the MCYT Fingerprint Database. Regarding the different experiments, we have selected the following sets: (i) enrolled patterns: for each test fingerprint, three images of different level of control will be used as patterns; and (ii) test images: the remaining nine images per fingerprint will always be used as test images. The EER (equal error rate) values in all experiments have been calculated according to the referred method in [2].

4.1.1 Experiments considering position variability:

In this set of tests we intend to evaluate the verification performance when matching between test and enrolled patterns is accomplished considering different variability levels in positioning. Regarding position variability, three different experiments (in which the enrolled pattern corresponds to a fingerprint of low, medium or high level of control), have been performed. Curves (i)–(iii) in Fig. 4, show, respectively, the results obtained for each of the above mentioned levels of control. The number of comparisons for FRR evaluation, in each case, is 6750 ($9 \times 10 \times 75$). When the pattern has a low level of control, we obtain an EER of 7.77% (this experiment will be denoted as the *baseline* experiment); when the pattern has a medium level of control, the EER is 5.77%; and when pattern has a high level of control, we get 5.31%. These experiments demonstrate that controlling the position of the pattern set produces improved results (note the improvement for medium and high levels of control compared to the low level of control.

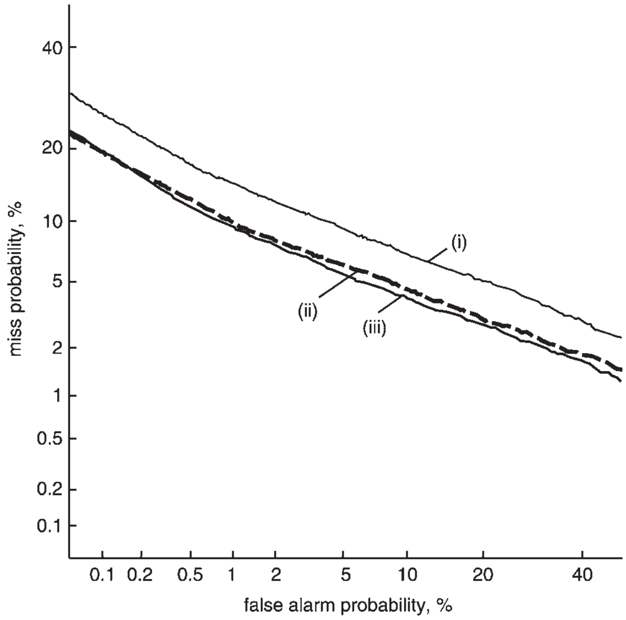

Fig. 4 *DET curves when no control in positioning is applied*

Curves (i), (ii) and (iii) correspond to cases in which enrolment corresponds to fingerprints of low, medium and high level of control, respectively

4.1.2 Experiments controlling position variability: Another set of three experiments has been accomplished to show the verification performance when comparisons are performed between fingerprints of the same level of control (no position variability is hence considered). In each experiment, the enrolled pattern corresponds to a fingerprint of low, medium or high level of control. Curves (i)–(iii) in Fig. 5, show the results obtained when comparisons are accomplished between fingerprints of low, medium and high levels of control, respectively. The number of tests for FRR, in curves (i) and (ii), is 1500 $(2 \times 10 \times 75)$; and in curve (iii), is 3750 $(5 \times 10 \times 75)$. For curves (i)–(iii) we obtain, respectively, 7.64%, 4.09% and 3.52% EERs. These results demonstrate that controlling the position of both pattern and test induces an improvement, which is highly significant for medium and high levels of control.

4.2 Multiple-reference strategy for similarity enhancement

In order to avoid an excessive level of control in fingerprint positioning during the acquisition process, in this Section we propose that each test fingerprint is compared with all three enrolled patterns. The highest attained score from this matching procedure is therefore considered as the similarity value (MAX-rule). Attempts for FRR and FAR evaluation are those from section 4.1.1, and results are represented by curve (vii) in Fig. 6. A remarkable decrease of EER down to 2.54% EER is achieved, which permits us to conclude that system performance is improved if the set of enrolled reference patterns contains variability due to the finger position during the acquisition process.

4.3 Fingerprint image quality assessment

The above results are attained over an unsupervised database, in which position but no image quality control has been accomplished. In this Section we analyse the influence of several fingerprint image quality characteristics on the performance of the verification system. In order to obtain results depending on the quality of the stored fingerprint images, a quality supervision and labelling process is accomplished. This means that on the initial subcorpus of 75 individuals, human supervision of each file has led to image quality labelling, so that a sample belongs to a group if a predefined quality degree is exceeded. In order to make possible this image quality labelling, the following 11 different fingerprint image characteristics have been defined:

(*a*) Incomplete fingerprint: a significant part of the interest region is out of the capturing area of the sensor.
(*b*) Incomplete fingerprint: weak pressure is made on the sensor.
(*c*) Smudged ridges in different zones of the image or nonuniform contrast of the ridges: due to finger movement

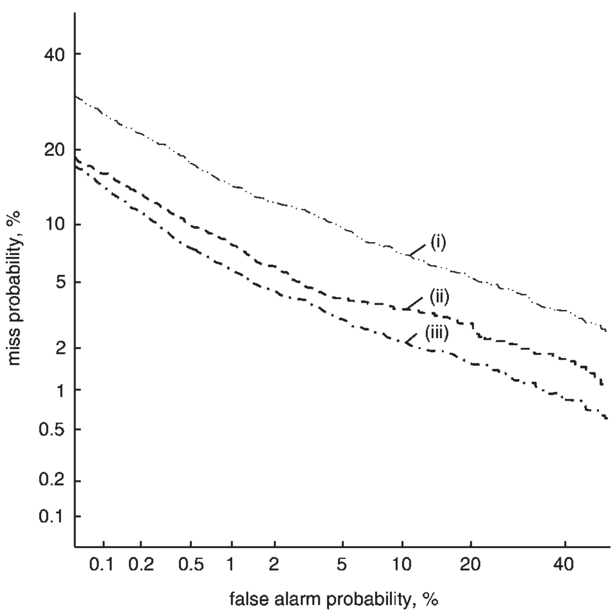

Fig. 5 *DET curves when control in fingerprint positioning is considered*

Curves (i), (ii) and (iii) correspond to low, medium and high level of control, respectively

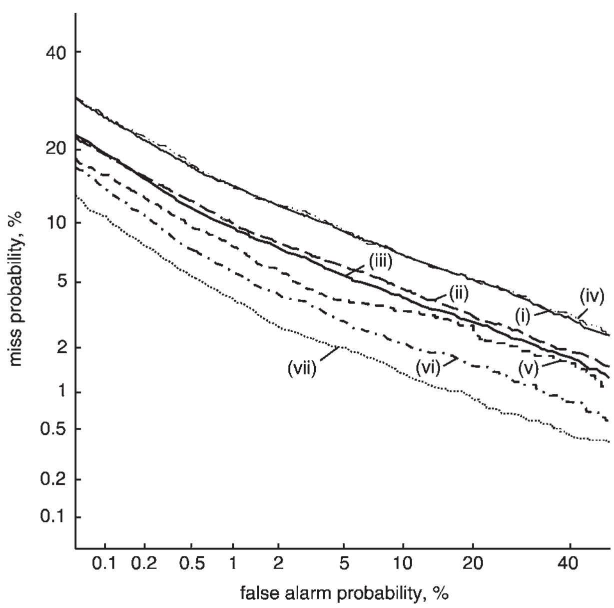

Fig. 6 *DET curves*

(i)–(iii) Cases with control in finger positioning
(iv)–(vi) Cases without control in finger positioning
(vii) Multiple-reference case

during acquisition, finger dirtiness, pressure excess over the sensor or wetness excess of the skin.
(*d*) Background noise in the image or latent fingerprints from previous acquisitions: due to wetness excess of the skin or sensor dirtiness.
(*e*) Weak impression of the ridge structure except in some well defined zones of the image: due to finger/sensor dirtiness or skin dryness.
(*f*) Ridge segments in some areas of the image without defining any ridge structure: due to finger dirtiness, burned skin, skin dryness or deficient pressure over the sensor.
(*g*) Lacks of impression as hollows or discontinuous ridges: due to finger dirtiness, skin dryness, skin defects or deficient pressure over the sensor.
(*h*) Significant breaks in the ridge structure
(*i*) Artifacts between ridges
(*j*) Presence of skin pores
(*k*) Disproportion among the occupied area of the image and the total capturing area of the sensor.

For each fingerprint image in the subcorpus, these characteristics are quantified by visual inspection of an expert, and each of them were in the range 0–9. Also, a global image quality factor is derived from the analysis of these 11 achieved rates, for each image. Again for each individual in the database, a set of three images (each of different level of control) will be considered as the enrolled pattern set, and the remaining nine images per fingerprint as the test image set. Individuals are then classified as belonging to different image quality-based groups by considering the following criteria: (i) an individual is assigned to a group if the three enrolled patterns exceed the minimum quality required, and (ii) At least one of the nine test samples of the individual must exceed the same quality degree. Test samples which do not exceed the threshold of quality do not compute in the verification rates. Therefore, the following groups are assembled:

- Group I: This is the initial group of 75 individuals, which has no restrictions in terms of image quality.
- Group II: In this group, only individuals from Group I with average quality rates 1–9 are included, so individuals with average image quality rate equal to zero are excluded.
- Group III and group IV: These groups include only those individuals from Group II whose fingerprints have average quality rates in the intervals (3, 9) and (6, 9), respectively.

Examples of fingerprints according to this classification are showed in Fig. 7. After visual inspection, the average image quality rates achieved for images Figs. 7*a*–*h* are, respectively, 0, 0, 1, 2, 3, 5, 8 and 9. All images, Figs. 7*a*–*h*, belong to group I. Figs. 7*a* and *b*, 7*a*–*d*, and 7*a*–*f* are images excluded from groups II, III and IV, respectively. The percentage of fingerprints assigned to each group is 95.3%, 81.1% and 34.2%, for groups II, III and IV, respectively.

4.3.1 Experiments considering image quality and possible position variability:

In these experiments the system verification performance is evaluated (for both training and testing) within three different sets of individuals, defined by groups II, III and IV, considering three separate image quality categories. In all cases, and in order to cope with possible variability conditions due to fingerprint positioning, the multiple-reference strategy is employed. Curves (ii)–(iv) in Fig. 8 show the achieved results with groups II, III and IV, respectively, in which EERs of 1.80%, 1.32% and 0.41% are obtained. Attempts for FAR and FRR evaluations are 37 646 and 6106, respectively, for group II, 25 206 and 4864, respectively, for group III and 4081 and 1759, respectively, for group IV. Curve (i) is included in Fig. 8 as a reference in order to permit a direct comparison of these results with those obtained in Section 4.2. These results confirm that image quality is directly related with the improvement of the verification performance.

4.3.2 Experiments considering just image quality:

In this case, each set of individuals is randomly matched with one of the three enrolled patterns. The random

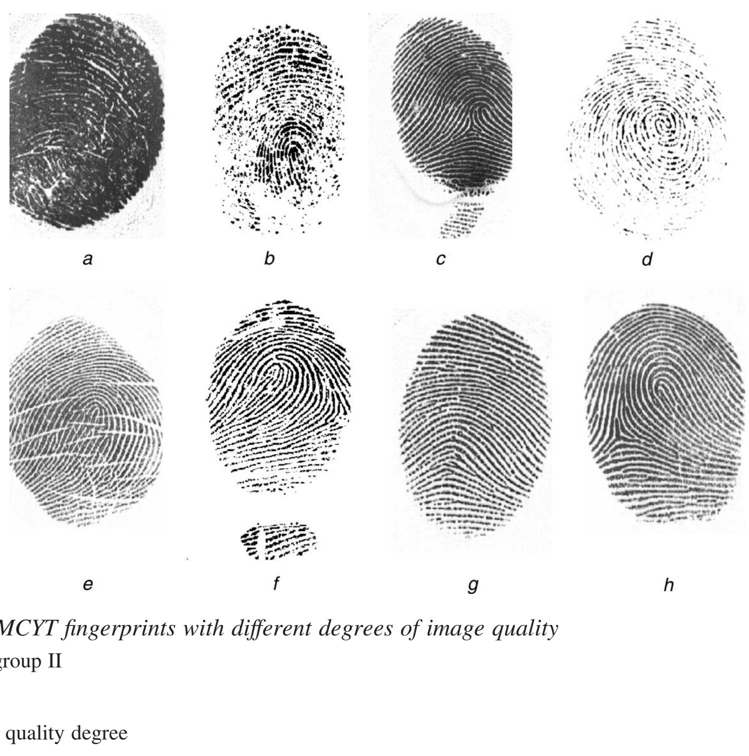

Fig. 7 *Several examples of MCYT fingerprints with different degrees of image quality*
a, *b* Fingerprints excluded from group II
a–*d* Excluded from group III
a–*f* Excluded from group IV
g, *h* Fingerprints with the highest quality degree

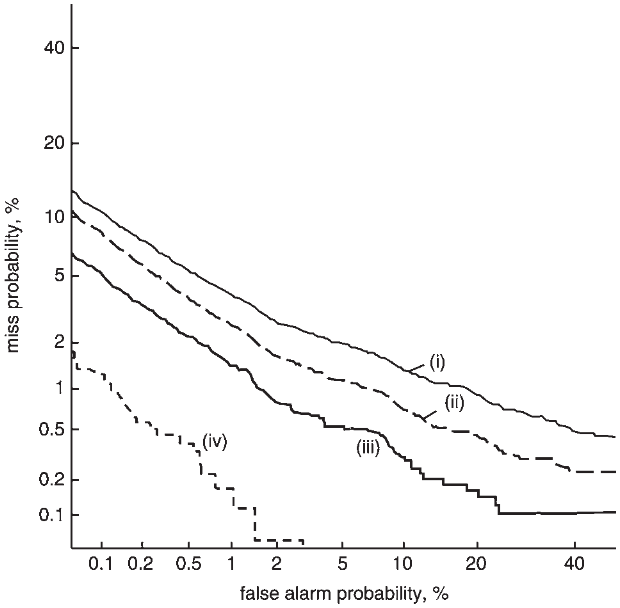

Fig. 8 *DET curves when image quality and position control are considered*

Curve (i) corresponds to the case of multiple-reference depicted in curve (vii) Fig. 6

Curves (ii)–(iv) correspond to evaluation with image quality groups II, III and IV, respectively

probability that a test image is matched with a pattern of low, medium or high control is 1/3, so no procedure to control the fingerprint position variability is applied. Figure 9 shows the achieved results, in which the baseline of Fig. 4 curve (i) is again depicted to facilitate comparisons. From curves (ii)–(v), ERRs can be derived as 5.59%, 5.22%, 4.22% and 2.12%, corresponding to groups I–IV, respectively. Attempts for FAR and FRR evaluations for group I are the same of those in Section 4.1.1, and for groups II–IV, the same as those expressed in Section 4.3.1. This set of results shows that, regardless of

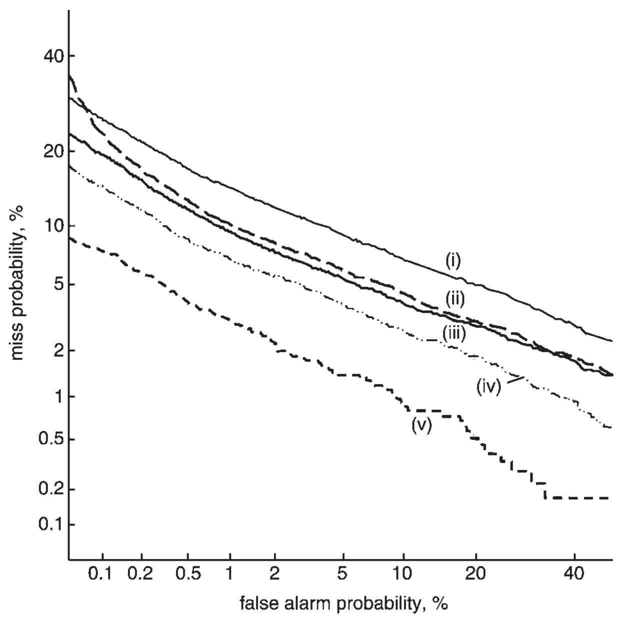

Fig. 9 *DET curves when just image quality but not position variability is considered*

Curve (i) is the baseline, depicted in curve (i) Fig. 4

Curves (ii)–(v) correspond to evaluation with image quality groups I, II, III and IV, respectively

the variability in fingerprint positioning, performance can be highly increased by just improving image quality. Note that the EER in curve (v) is similar to the value achieved in Section 4.2, where position variability and the multiple-reference strategy was applied to group I (curve (vii) in Fig. 6). Comparing now the plot in curve (ii) of Fig. 9, for group I, with curves (v) and (vi) in Fig. 5 where medium and high control levels were considered, and comparing curves (ii)–(v) in Fig. 9 with curves (i)–(iv) in Fig. 8, it can also be confirmed that controlling position variability leads to a significant improvement in system performance.

5 Conclusions

In this paper, the performance evaluation of the proposed minutiae-based fingerprint automatic verification system has been accomplished. The set of experiments, conducted over a large population from the MCYT Fingerprint Database, include several variability factors that may occur in the acquisition process. The influence of controlling the position of the fingerprint over the optical sensor during acquisition has been analysed, and several conclusions have been reached. The system performance will be significantly enhanced if we increase: (i) the level of control over both the reference pattern and the test patterns, as an initial baseline EER of 7.77% has been decreased to just 3.52% when a high level of control is applied to both test and reference samples: (ii) the number of reference patterns, if variability in fingerprint positioning is considered, as an EER of 2.54% has been attained with a multiple-reference strategy.

These results are achieved over an unsupervised database, in which position variability, but no image quality control, during acquisition has been initially taken into account. We have then analysed the combined influence of both quality and position variability over a supervised database, in which an average image quality rate has been assigned to each fingerprint. A great improvement in terms of system performance can therefore be achieved if both factors, position and quality, are controlled. In such a case, the already mentioned EER of 2.54% (applying the multiple-reference strategy, but without any control on the image quality) is significantly decreased to an EER of 0.41%, when quality is supervised and only images from group IV are considered. Finally, experiments considering only image quality rates, without control on position variability, confirm that this control is a basic requirement to achieve a reasonable system performance, as the best EER of 0.41%, obtained, when both quality and position are controlled, is decreased to 2.12% EER when position is not controlled.

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