# PERFORMANCE TESTING EVALUATION

# REPORT OF RESULTS

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## REVISION HISTORY

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**TABLE OF CONTENTS**

CONTENTS

CONTENTS

# 1. INTRODUCTION

## 1.1. INTRODUCTION

This report presents the results of performance testing of three fingerprint sensors: one active thermal (NB-3010-U Fingerprint sensor) and two active capacitive sensors (FPC1011F3 and UPEK Eikon Touch 510).

Performance testing has been conducted following the ISO/IEC 19795 Biometric testing and reporting standard requirements [1]. In particular, different technology evaluations have been carried out with different purposes.

First, the performance of the different sensors has been measured based on comparisons of the images captured by them. In addition, these images have been cropped for modelling three possible reduce sizes of the active area of the sensors: 12x12mm$^2$, 10x10mm$^2$ and 8x8mm$^2$. Considering these cropped images, performance testing has been conducted targeting two kind of comparisons: full size vs. cropped size images and cropped size vs. cropped size images, being the first the enrolment image and the second the verification samples.

For these evaluations, a database has been specifically collected composed by total of 589 users who have provided more than 100,000 fingerprints. Moreover, all the aforementioned evaluations have been executed using two different algorithms, the public algorithm provided by NIST [2] (called NBIS throughout this document) and the commercial algorithm developed by Neurotechnology [3] (called NEU throughout this document).

This report describes, in detail, the characteristics of the sensors analysed, the collection of the database for the evaluations and the results achieved per each sensor and algorithm. In particular the results attached are:

- Performance results when processing the full size database:
  - Quality analysis using NFIQ quality score [4]
  - Error rates
  - Throughput rates
- Performance results when processing the cropped databases considering two kind of comparisons:
  - Quality analysis using NFIQ quality score [4]
  - Full sizes vs. Cropped size images
    - Error rates
    - Throughput rates
  - Cropped size vs. Cropped size images
    - Error rates
    - Throughput rates

The document provides an analysis and discussion on the results obtained, comparing each of the technologies at each of the evaluations carried out.

## 1.2. ORGANIZATION OF THE DOCUMENT

Considering the objectives aforementioned, this document is organized in the following set of sections:

1. This section, stating an introduction to the report, which will be finished with an introduction to the laboratory that has conducted the test.
2. The following section will describe the sensors used during the evaluation
3. The description of the database collection, its procedures and specifications
4. A detailed view on the composition of the database, including the demographics of the users taking part as test crew
5. The analysis on the quality of the samples acquired
6. The results obtained by carrying out a performance testing on the database collected, including error rates and throughput rates
7. The method to crop the collected images as to obtain a set of databases with images of 8x8, 10x10 and 12x12.
8. The quality analysis of the cropped subsets obtained.
9. The performance achieved when cropped images are compared to the biometric references created with the full size images
10. The performance achieved when comparing cropped images of the same size
11. The overall discussion on the results obtained, driving conclusions and lessons learned

## 1.3. IDTESTINGLAB

IDTestingLab is an evaluation laboratory belonging to Carlos III University of Madrid (UC3M). UC3M (http://www.uc3m.es) is one of most prestigious technical Universities in Spain. Due to its public, non-profit nature, the exploitation and dissemination strategies of UC3M largely coincide on its main objective, which is to use research results to advance and progress scientific knowledge. Exploitation of research achievements is carried out along two activities: educational in which existing and well established knowledge and methods are diffused among the attendants of the University lectures and activities, and research into advancements and extensions of the understanding of scientific disciplines. To this end, UC3M relies on a pool of expert human resources and its reputation, which is based on past achievements, helping to attract the top choice of prospective students and research associates.

Research at Carlos III University of Madrid has always been one of the basic pillars of the University's activities, both to improve teaching and to generate new knowledge and new lines of research.

Within UC3M, the Electronics Technology Dpt. has 5 Research Groups. Among them, the University Group for Identification Technologies (GUTI –

http://www.guti.uc3m.es) has a great experience in Biometrics, Smart Cards and Security in Identification Systems. In detail, GUTI's expertise in its R&D lines is:

- Smart Cards, from R&D to final applications (active since 1989).
- Biometrics, having large experience in different biometric modalities such as hand geometry, iris recognition, fingerprint, vascular system and handwritten signature (active since 1994).
- Match-on-Card Technology, achieving the first ever Match-on-Card solution in 1999.
- Security Infrastructures, developing their own PKI using smart cards in 1997.
- Their work in all these lines has leaded to hold the Secretariat in the Spanish Mirror Subcommittee in Biometrics (AEN/CTN71/SC37) and the Chair in the Spanish Mirror Subcommittee in Identification Cards (AEN/CTN71/SC17). They are also experts in SC27.

As a result of this work, UC3M opened IDTestingLab (http://idtestinglab.uc3m.es) as an Evaluation Laboratory for Identification Technologies. IDTestingLab is equipped with all relevant instruments to perform technology and scenario evaluations, and its personnel are trained to carry out operational evaluation as soon as a customer requests that kind of work.

This laboratory has carried out several tests, both by Industry request and by R&D project requirements. For those test, a variety of tools have been developed, as well as building scenarios for end-to-end evaluations (scenario evaluations). Several innovative methodologies have already been designed and developed, amongst which are a methodology to measure the environmental condition influence on biometric systems (which has led to the development of ISO/IEC 29197), and a methodology for measuring the influence of usability in the performance of biometrics.

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# 2. FINGERPRINT SENSORS

This section describes the characteristics of the fingerprint sensors under evaluation.

## 2.1. NB-3010-U Fingerprint sensor (NXT)

This sensor uses thermal technology to obtain the images of the fingerprint. When a finger is in contact with the sensor area, the heat of the finger is transferred to the sensitive surface. The characteristic of this sensor are given in Table 1. Also, an image of this sensor can be seen in Figure 1. For the readability of this report, this sensor will be mentioned by the acronym NXT.

**Table 1. NXT sensor characteristics**

| | |
|---|---|
| Sensor resolution | 385 dpi |
| Image Capture Area | 11.9 x 16.9 mm |
| Fingerprint image size | 180 x 256 pixels |

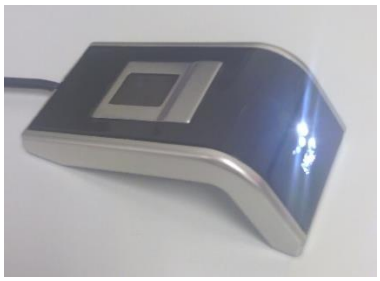


**Figure 1. NXT fingerprint sensor**

## 2.2. FPC1011F3 fingerprint sensor (FPC)

This sensor uses active capacitive technology to obtain the images of the fingerprint. When a finger is in contact with the sensor area, a weak electrical charges is sent via the finger. Using these charges the sensor measures the capacitance pattern across the surface. The characteristics of this sensor are provided in Table 2. Moreover, an image of this sensor is shown in Figure 2. For the readability of this report, this sensor will be mentioned by the acronym FPC.

**Table 2. FPC sensor characteristics**

| | |
|---|---|
| Sensor resolution | 363 dpi |
| Image Capture Area | 10.6 x 14 mm |
| Fingerprint image size | 152 x 200 pixels |

**Figure 2. FPC fingerprint sensor**

## 2.3. UPEK EikonTouch 510 fingerprint sensor (UPK)

This sensor uses the capacitive technology, similar to the previous device. The characteristics of this sensor are given in Table 3. Also, Figure 3 shows an image of this sensor. For the readability of this report, this sensor will be mentioned by the acronym UPK.

**Table 3. UPK sensor characteristics**

| | |
|---|---|
| Sensor resolution | 508 dpi |
| Image Capture Area | 12.8 x 18.0 mm |
| Fingerprint image size | 192 x 270 pixels |

**Figure 3. UPK fingerprint sensor**

# 3. DATABASE COLLECTION PROCEDURES

The objectives of the data collection is to obtain a large dataset of fingerprint images using the three sensors under test. This process shall be done in similar conditions for all the sensors to be able to compare results. The following sections detail how this process was conducted and the requirements defined.

## 3.1. ENVIRONMENT

### 3.1.1. Environmental conditions

The database collection has been conducted indoors in a laboratory. The temperature of this place is around 26ºC and the relative humidity is around 35%. In addition, the illumination of this laboratory is fluorescent light, installed at the ceiling.

### 3.1.2. Database collection configuration

For the purpose of the database collection, two stations have been dedicated. Each station includes the following elements:

- a PC which has connected the three fingerprint sensors.
- two chairs, one for the test subject and the other for the operator that control the overall process.

A photograph of one station can be seen in Figure 4.

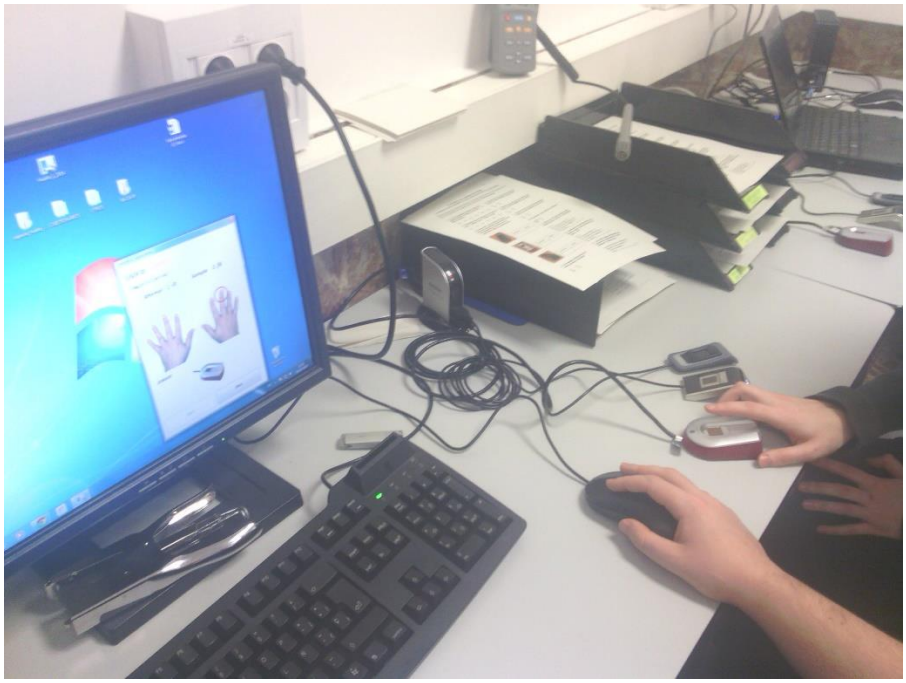


**Figure 4. Database collection station**

In addition, a general view of the database collection can be seen in Figure 5. In the middle of the two stations there are office supplies to sign and classify data protection forms and the delivery receipts of the incentives.

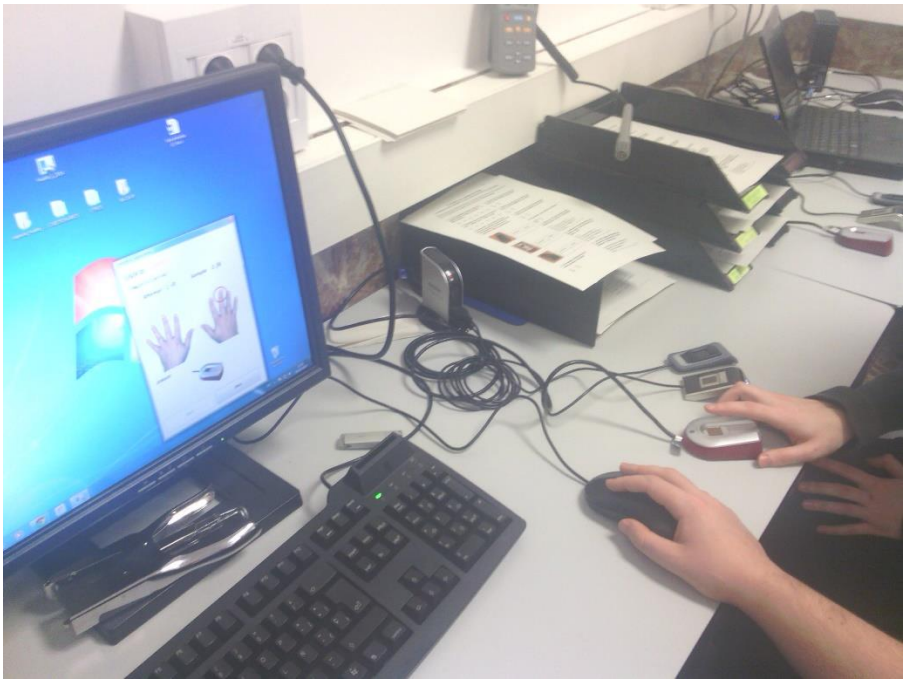


**Figure 5. Layout of the database collection**

## 3.2. DATABASE COLLECTION PROCEDURES

The database collection is carried out in two different days with a separation of 15 days at least.

During the first day, test subjects must come to the laboratory and conduct the following procedures:

1. Listen to the general instructions about the whole process
2. Provide personal data for enrolment
3. Sign the acceptance form in accordance to data protection laws
4. Listen to instructions about how to present a finger to the sensor correctly and which sensor to use at each time
5. Carry out the enrolment process. This process is detailed in section 3.2.1.
6. Carry out the 1st acquisition process (1st visit). This process is detailed in section 3.2.2.

During the second visit (at least 15 days after the first one), test subjects must come to the laboratory and conduct the following procedures:

1. Listen to a short reminder about how to present a finger to the sensor correctly
2. Carry out the 2nd acquisition process. This process will be detailed in section 3.2.2.
3. Receive the incentive gained by cooperating in the experience.

For conducting all these steps, an application has been developed to indicate the next steps to be developed in order to correctly collect all the fingers. This application is used by an operator who guides the test subjects during all the process. The next paragraphs describe how this application works for enrolment and acquisitions processes.

### 3.2.1. Enrolment

Enrolment is the process in which six fingers of one test subject are collected (i.e. thumb, index and middle fingers of both hands). In order to consider that one finger has been successfully enrolled, one image of this finger shall be correctly acquired and then a second image of the same finger that is also correctly acquired shall be compared to the first image and this comparison shall be successful (i.e. above a certain threshold).

For achieving this goal, for each finger test subjects have two transactions composed by three attempts. If after this number of attempts, the test subject does not successfully accomplish the aforementioned process, a Failure To Enrol (FTE) is raised for the corresponding finger in this sensor.

An image is correctly acquired is the quality score of the image is equal or less than 3 and the operator considers that the fingerprint image contains an

appropriate fingerprint image. The quality assessment algorithm used has been the NFIQ algorithm provided by NIST.

A screenshot of this application for the enrolment process is shown in Figure 6.

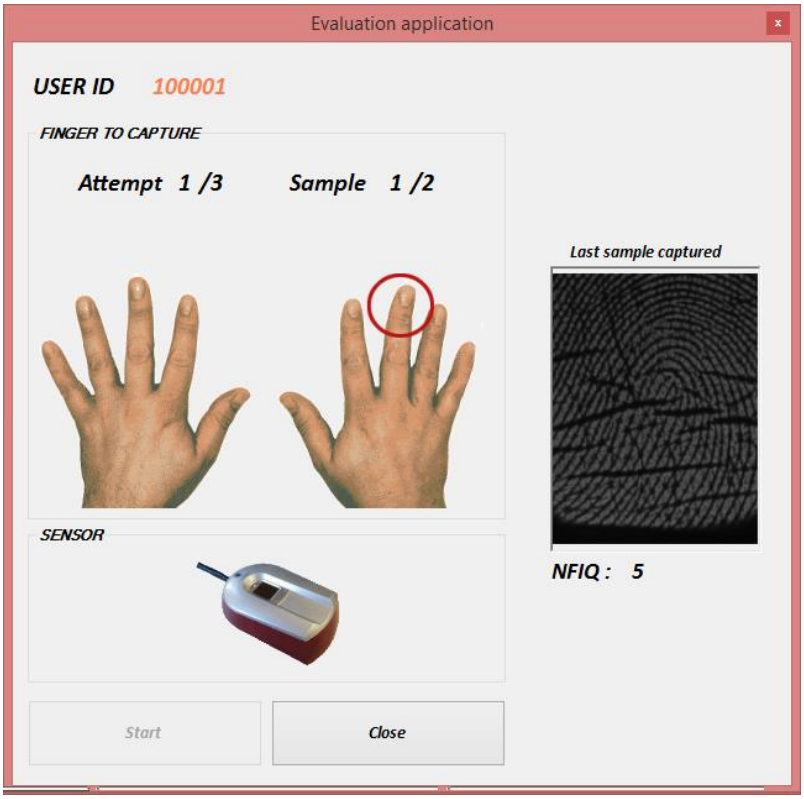



**Figure 6. Screenshot of the database collection application for enrolment**

For enrolment, this application works as follows:

Firstly, the application shows the operator how fingerprint sensors shall be ordered (See Figure 7). This order is selected randomly. Each time that this process is executed, sensors are placed in different order to avoid the influence of habituation on the results.

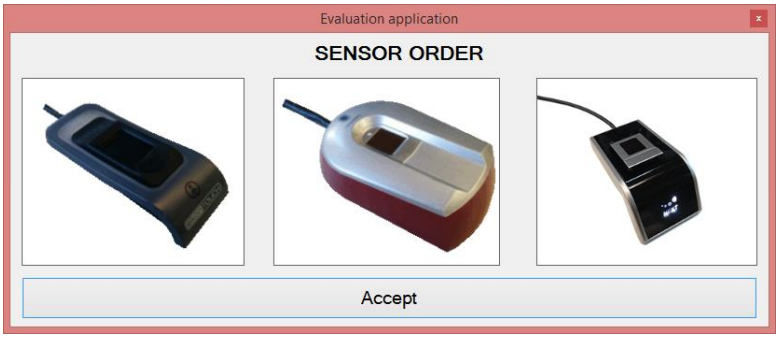



**Figure 7. Screenshot of the sensor order for the process**

Then, when the operator placed the sensors in the right order, the enrolment process stars. The finger to present and the sensor are shown to the operator and test subjects. The test subject has a total of 30 seconds to provide an image. If not, a timeout error happens and a new attempt is required. When the image is captured, this image is displayed together with its NFIQ score.

If the NFIQ is higher than 3, the image is discarded automatically by the application and a new attempt is required. If not the operator has the possibility to discard it. It everything is correct, a second image is required. For this second image the operator does not has the possibility to discard it. If the NFIQ is equal or less than 3, the image is directly compared to the previous image. If the result of the comparison is successful, this finger has been enrolled and a new enrolment of other finger or in other sensor is required. If the comparison fails, a new window appears (See Figure 8) and the operator has the opportunity to check what happened. Also, he can decide if the second image is discarded and ask for a new attempt or if the enrolment is discarded completely, starting it again. The process of enrolment can be repeated if the number of transactions and attempts have not overcome the above mentioned limits. Operators have been trained to act in a consistent manner for discarding samples and deciding repeating the enrolment.

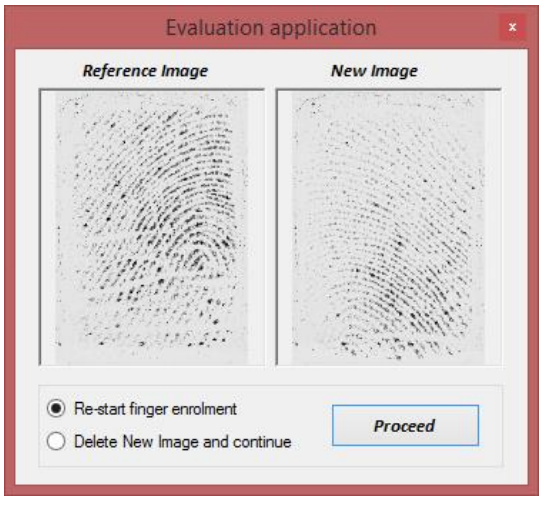



**Figure 8. Screenshot that shows the operator after a wrong comparison**

The sequence of enrolment begin by one finger of one hand. This is selected randomly. This finger is enrolled in all the sensors following the order decided at the beginning and the procedures above mentioned. When that finger is enrolled in all the sensors, then a new finger of this hand is required. When all the fingers (i.e. thumb, index and middle fingers) of this hand have been enrolled, the fingers of the other hand are requested to be presented.

Considering this process, fingerprint images are classified as follows:

- 'DESOP' that means that the image has been discarded by the operator.
- 'FTP' that means that the image has a NFIQ higher than 3, or any other kind of processing error has occurred.
- 'CI' that means that the image has been compared to the previous image but the comparison fails or there is no reference to compare this sample.
- Successful enrolled images for which any code is used.

When all six fingers of that user has been attempted to enrol in the system by all three sensors, the enrolment phase is considered finished, and the 1st acquisition process is started.

### 3.2.2. Acquisition

Acquisition is the process in which six images of each of the different fingers (i.e. thumb, index and middle fingers of both hands) are collected. In order to consider that the image of one finger has been successfully collected, the image of this finger shall be correctly acquired and then, successfully compared to the image captured at the enrolment process for this finger (see section 3.3).

For doing it, test subjects have one transaction composed of three attempts. If after this number of attempts, the test subject does not successfully accomplish the aforementioned process, a Failure To Acquire (FTA) error is claimed for the corresponding finger in this sensor.

In this case, an image is correctly acquired if the quality score of the image is equal or less than 4. The operator does not have the chance to discard any image.

A screenshot of the database collection application for the acquisition process is shown in Figure 9.

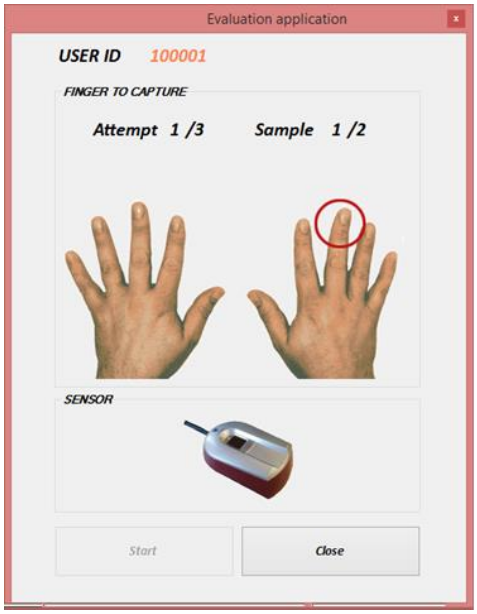



**Figure 9. Screenshot of the database collection application for acquisition**

For acquisition, this application works as follows:

Firstly, the application shows the operator how fingerprint sensors shall be ordered (See Figure 7) in a similar way to the enrolment process (this order is again randomly calculated to avoid habituation effects).

Then, when the operator placed the sensors in the right order, the enrolment process stars. The finger to present and the sensor are shown to the operator and the test subject. The test subject has a total of 30 seconds to provide an image. If not, a timeout error happens and a new attempt is required.

If the NFIQ is higher than 4, the image is discarded automatically by the application and a new attempt is required. If not, the captured image is directly compared to the previous image. If the result of the comparison is successful, this finger has been acquired and the process continues (either a new acquisition of the same finger, changing the sensor, or changing the finger). If the comparison fails, a new attempt is required. The process of acquisition can be repeated per one finger in one sensor till the number of attempts is not run out for it. Then, the sensor is changed till a total of 6 acquisition transactions have been conducted in all the sensors.

The sequence of acquisition begin by one finger of one hand. This is selected randomly to avoid habituation. This finger is acquired in all the sensors following the order decided at the beginning. When that finger is acquired in all the sensors six times (or trying to be acquired but a Failure To Acquire error happen), then a new finger of this hand is required. When all the fingers (i.e. thumb, index and middle fingers) of this hand have been acquired, the fingers of the other hand are requested to be presented.

Considering this process, fingerprint images are classified as follows:

- 'FTP' that means that the image has a NFIQ higher than 4 or any other kind of processing error occurred.
- 'CI' that means that the image has been compared to the image obtained at the enrolment phase but the comparison fails.
- 'FTE' that means that the image has not been compared to any image due to the fact that a Failure To Enrol (FTE) happens and no image can be considered as a good reference to be compared.
- Successful acquired images for which no additional code is used.

## 3.3. ESTABLISHMENT OF THE GROUND TRUTH

The collection of such a large database implies a lengthy process and the need of human supervision. Even using trained operators, the possibility of test subjects changing fingers or hands, or even placing the finger wrongly in the sensor is high. The acquisition of samples that may be wrongly labelled may derive in wrong calculations and erroneous performance rates.

Therefore, the acquisition process has installed a mechanism to assure the ground truth, minimizing the impact to the database collection, but avoiding mislabelling of the samples acquired. Such mechanism has been based on the execution of a comparison algorithm with a certain threshold.

This is a very important piece of information, as the application of such threshold has an impact on the scores obtained. In few words, mated comparisons (also known as mated) will never present a comparison score below the threshold, as such cases have been discarded during the acquisition process. This presents a serious impact to the FMR (False Match Rate), as the FMR for scores below the threshold will be 0.

In order to minimize such impact, the threshold chosen has been relaxed enough, as to avoid most of the mislabelling, but not forcing a 0 FMR for a large set of threshold, which will impact seriously on the overall performance result.

In addition, as such a mechanism is based on a comparison algorithm, and the evaluation has two evaluation algorithms, the threshold for the second algorithm has also been applied off-line. Therefore, the results won't be biased by the performance of one of the algorithms.

The thresholds chosen for the ground truth determination have been 20 for the NBIS algorithm, and 45 for the NEU (i.e. Neurotechnology) algorithm.

# 4. COMPOSITION OF THE DATABASE

This section describes which information contains the database at the current status. Firstly, the demographic characteristics of the users who have provided the image for this report are given. Then, a report about the number of images and the results obtained for at the acquisition process are explained.

## 4.1. COMPOSITION OF THE DATABASE

### 4.1.1. Users

The content of the database is composed by fingerprint images provided by a total amount of users of 589 individuals. These people has the following characteristics:

- Gender distribution
  - Males: 336 individuals (57.05 %)
  - Females: 253 individuals (42.95 %)
- Age distribution
  - Less than 30 years old: 496 individuals (84.21 %)
  - Between 30 to 50 years old: 59 individuals (10.02 %)
  - More than 50 years old: 34 individuals (5.77 %)
- Technical knowledge distribution
  - Habituated to IT products: 563 individuals (95.59 %)
  - Non-habituated to IT products: 26 individuals (4.41 %)
- Biometric system habituation distribution
  - Habituated to biometric products: 204 individuals (34.635 %)
  - Non-habituated to biometric products: 385 individuals (65.365 %)

### 4.1.2. Visits

Considering this test crew, the frequency between visits can be seen in Figure 10. A total of 589 test subjects have conducted the first visit whereas 553 have already completed the captured process.

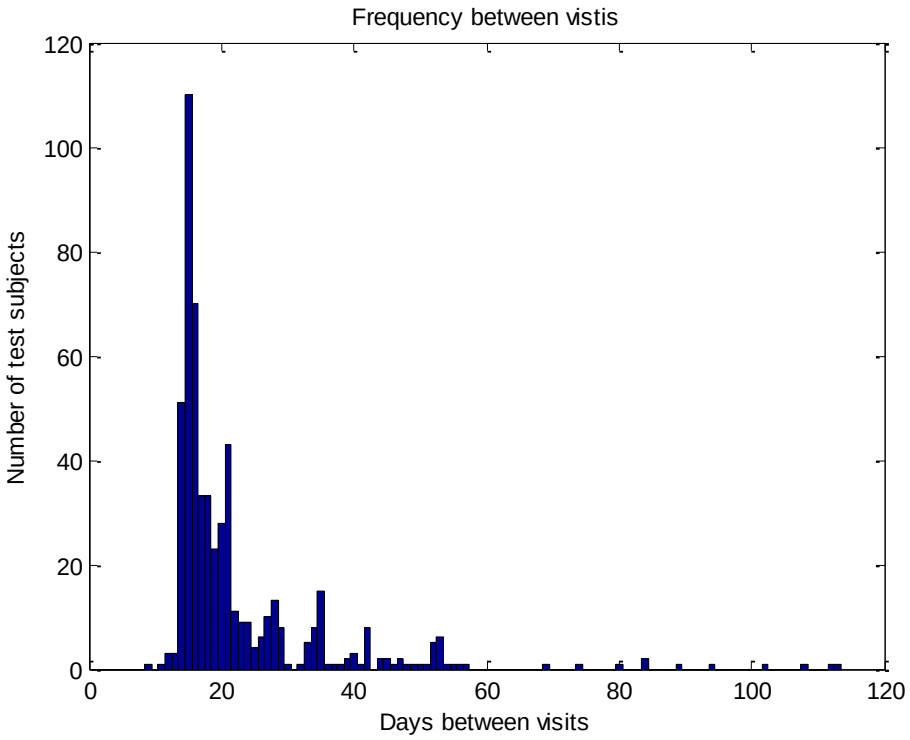



**Figure 10. Days between visits**

### 4.1.3. FINGERPRINT IMAGES

The number of fingerprint images that currently includes the database for 589 users are a total of 188216 images.

- NXT = 64354 images
- FPC = 65100 images
- UPK = 58762 images

Nevertheless, some of them have been discarded by the operator using visual inspection. Therefore, the number of fingerprint images that have been used for the performance analysis are a total of 186593 images.

- NXT = 63493 images
- FPC = 64613 images
- UPK = 58487 images

# PART I

# PERFORMANCE ANALISIS REPORT

# ORIGINAL DATABASE

# 5. QUALITY ANALYSIS

This section shows the quality analysis results of the database captured for the three sensors. The quality analysis has been done using the NFIQ quality score provided by NIST [4]. This score measures the quality of a fingerprint image obtaining a value between 1 and 5. NFIQ = 1 means that the quality of the image is very good whereas NFIQ = 5 means that the quality of the image is very bad.

## 5.1. NFIQ DISTRIBUTION

The NFIQ distribution has been separated based on the enrolment and capturing processes due to different quality threshold were selected for each process. The quality threshold for enrolment was NFIQ <=3 and the quality threshold for the capturing process was NFIQ <=4. Images that have higher NFIQ than the specified thresholds were considered errors.

### 5.1.1. Enrolment NFIQ distribution

Figure 11 shows the NFIQ distribution for enrolment. In spite of the enrolment policy that only images that obtain an NFIQ > = 3 were accepted, the distribution graphic provides data for values between 1 and 5.

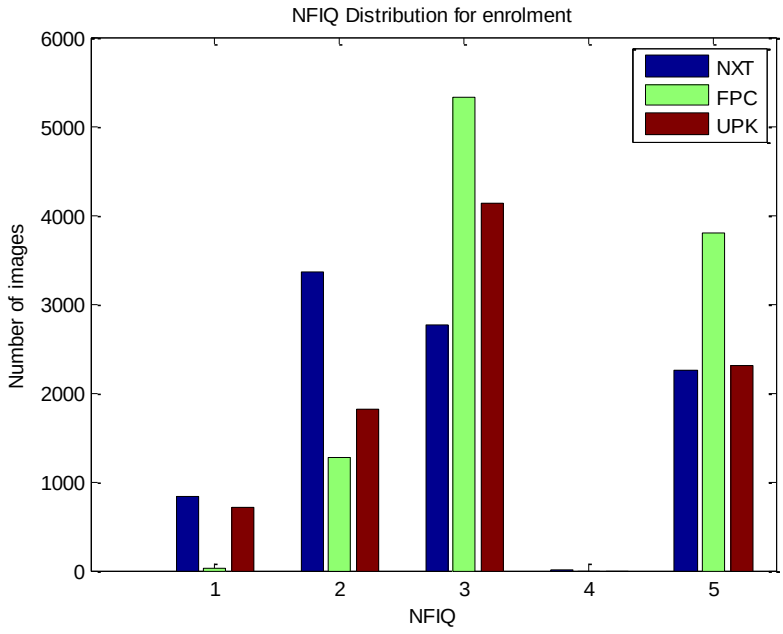



**Figure 11. NFIQ Distribution for enrolment**

### 5.1.2. Acquisition NFIQ distribution

Figure 12 shows the distribution of NFIQ for the acquisition process. This distribution includes all images that have been captured at this process regardless of any error that could be happen later, when images are compared to its corresponding biometric reference.

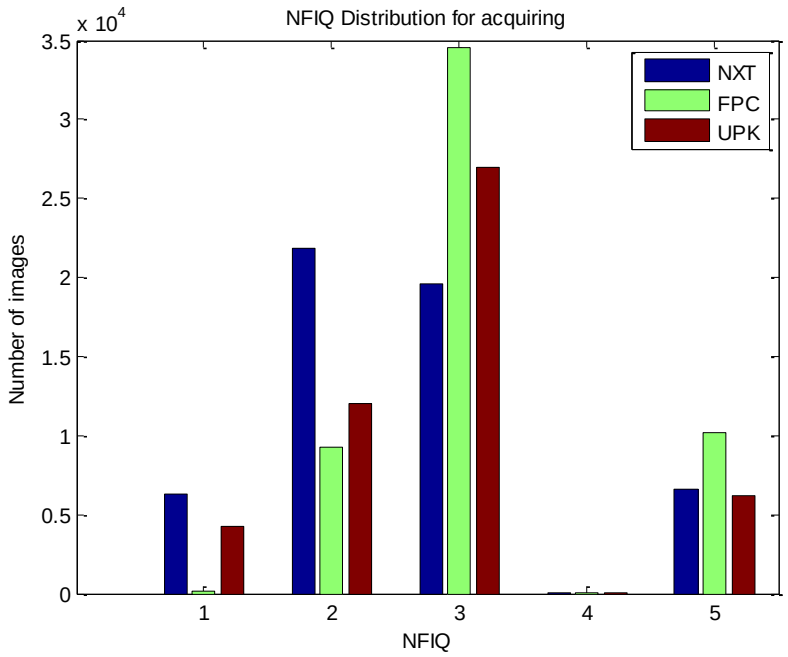



**Figure 12. NFIQ Distribution for capturing process**

## 5.2. QUALITY FAILURES

Taking into account the enrolment and capturing policies explained in sections 3.2.1 and 3.2.2 respectively, quality errors that happen due to quality thresholds are shown in Table 4 for enrolment and in Table 5 for the acquisition processes. The quality threshold for enrolment is NFIQ <=3 and the quality threshold for the acquisition process is NFIQ <=4. Images that have higher NFIQ are considered errors.

It is important to note that these errors are common for the two algorithms that have been analysed.

**Table 4. Quality failures obtained during the enrolment process**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Quality errors (NFIQ >3)** | 2252 | 3797 | 2313 |
| **Total number of enrolment images** | 9205 | 10418 | 8973 |
| **Quality error rate for enrolment** | 24.46 % | 36.44 % | 25.77 % |

**Table 5. Quality failures obtained during the capturing process**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Quality errors (NFIQ >4)** | 6614 | 10183 | 6232 |
| **Total number of acquisition images** | 54288 | 54195 | 49514 |
| **Quality error rate for capturing** | 12.18 % | 18.79 % | 12.58 % |

# 6. PERFORMANCE ANALYSIS

This section explains performance results when processing the database of the full size images using two algorithms: NBIS and Neurotechnology. In particular, error rates and throughput rates will be shown.

Regarding error rates, these metrics are given separately for enrolment (FTE error) and acquisition process (FTA error). For the comparison process the following curves will be shown:

- Distribution curves per each fingerprint sensor
- FNMR vs. FMR curves per each fingerprint sensor
- ROC curves for the three fingerprint sensors
- DET curves for the three fingerprint sensors
- Additional rates: EER, FMR100, FMR1000,FMR10000

It is important to note that most of these curves and results have been done adapting the software provided by Biosecure Tool [5] for calculating this kind of results.

In relation to throughput rates, the metrics that have been obtained have been the following:

- Enrolment time, which has been calculated considering the time that takes to obtain the biometric references.
- Acquisition time, which has been calculated considering the time that takes to obtain the biometric probes.
- Mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference of the same user, same finger.
- Non-mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference that do not belong of the same user.

## 6.1. PERFORMANCE RESULTS FOR NBIS ALGORITHM

### 6.1.1. Error rates for NBIS

#### 6.1.1.1. Enrolment and acquisition results

FTE and FTA errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 6 and Table 7. These errors may happen due to the enrolment and capturing processes have not been successfully completed according the

procedures explained in sections 3.2.1 and 3.2.2. In this case, the algorithm applied for enrolling and acquiring the samples has been NBIS.

**Table 6. FTE errors using NBIS algorithm**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Number of correct templates** | 3,217 | 2,826 | 3,116 |
| **FTE errors** | 317 | 708 | 418 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 8.97 % | 20.03 % | 11.82 % |

**Table 7. FTA errors using NBIS algorithm**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Number of correct samples** | 34,251 | 26,333 | 34,012 |
| **FTA in Visits** | 6,527 | 10,068 | 6,174 |
| **FTP in Visits** | 32 | 8 | 0 |
| **CI** | 11,217 | 12,575 | 6,837 |
| **FTA errors** | 17,776 | 22,651 | 13,011 |
| **Total number of acquisition attempts** | 52,027 | 48,984 | 47,023 |
| **FTA rate** | 34.17 % | 46.24 % | 27.66 % |

It is important to highlight that the FTA rate has been obtained considering the number of attempts. However, the number of attempts have been different depending on the fingerprint sensor.

#### 6.1.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 8.

**Table 8. Number of comparisons conducted using NBIS**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Mated comparisons** | 34,251 | 26,333 | 34,012 |
| **Non-mated comparisons** | 110,151,216 | 74,390,725 | 105,947,381 |

##### 6.1.1.2.1. Distribution curves for NXT sensor

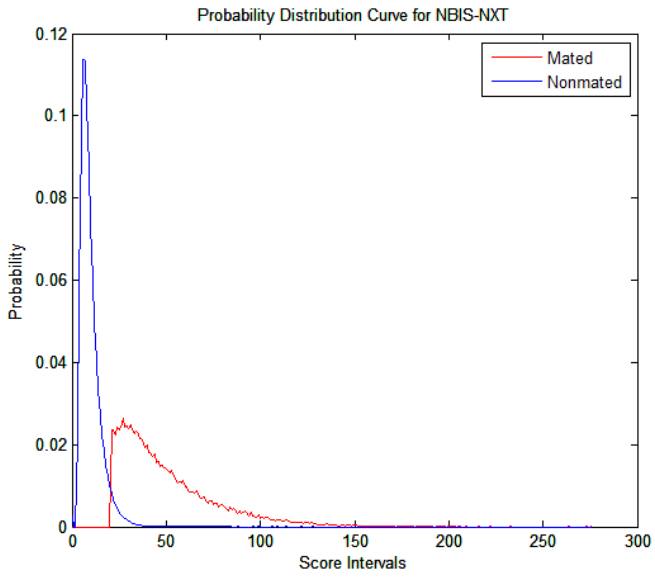
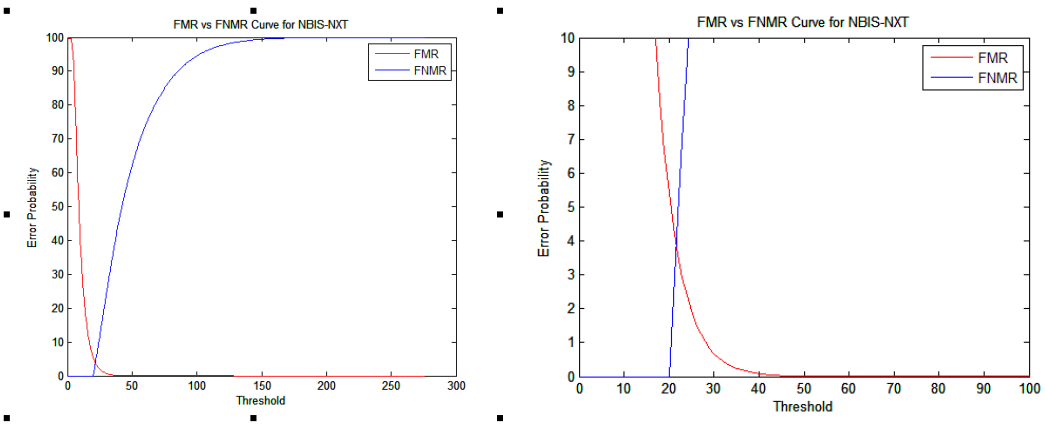



**Figure 13. Distribution curves for NXT sensor using NBIS algorithm**

#### 6.1.1.2.2. FMR vs FNMR graph for NXT sensor




(a) (b)

**Figure 14. FMR vs. FNMR curves for NXT sensor using NBIS algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.1.1.2.3. Distribution curves for FPC sensor

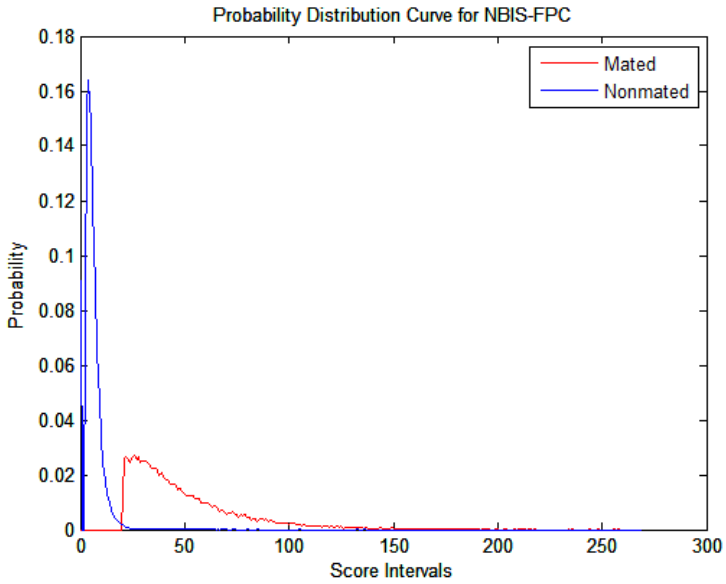
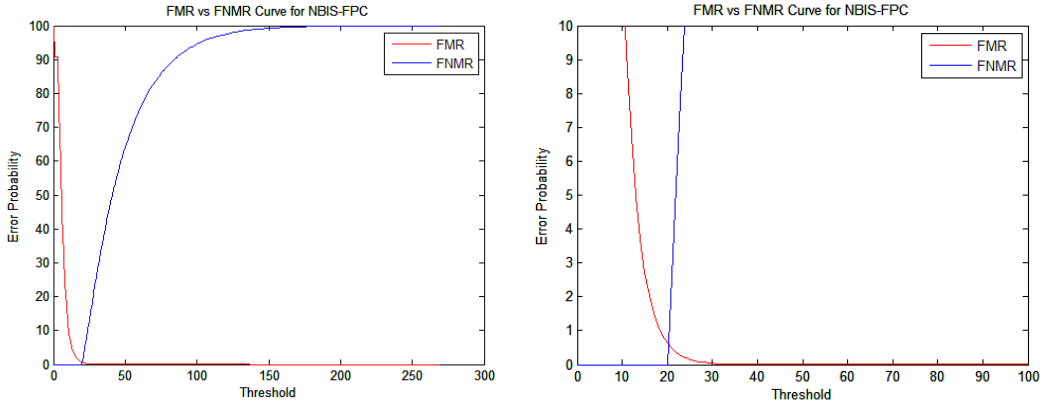



**Figure 15. Distribution curves for FPC sensor using NBIS algorithm**

#### 6.1.1.2.4. FMR vs FNMR graph for FPC sensor




(a) (b)

**Figure 16. FMR vs FNMR curves for FPC sensor using NBIS algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.1.1.2.5. Distribution curves for UPK sensor

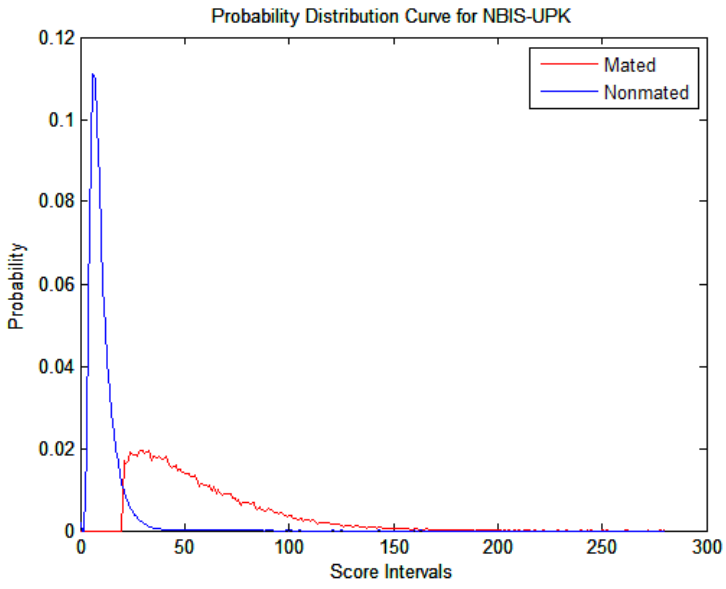
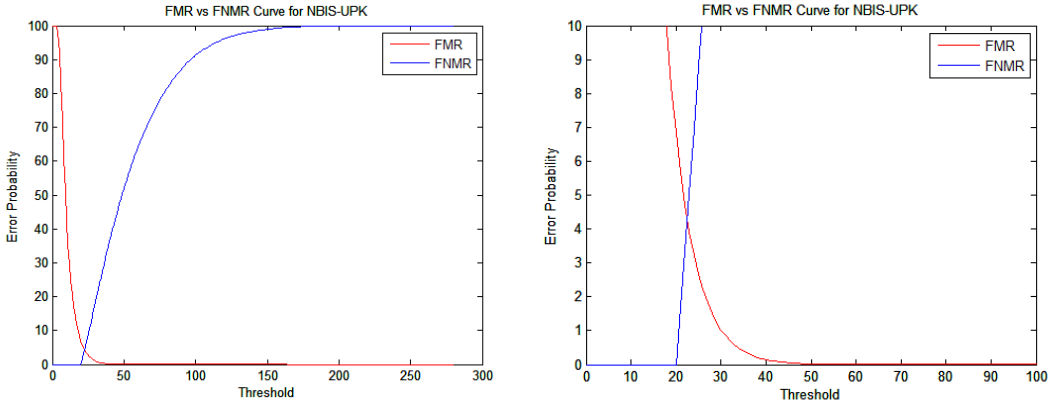



**Figure 17. Distribution curves for UPK sensor using NBIS algorithm**

#### 6.1.1.2.6. FMR vs FNMR graph for UPK sensor




(a) (b)

**Figure 18. FMR vs FNMR curves for UPK sensor using NBIS algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.1.1.2.7. DET curves

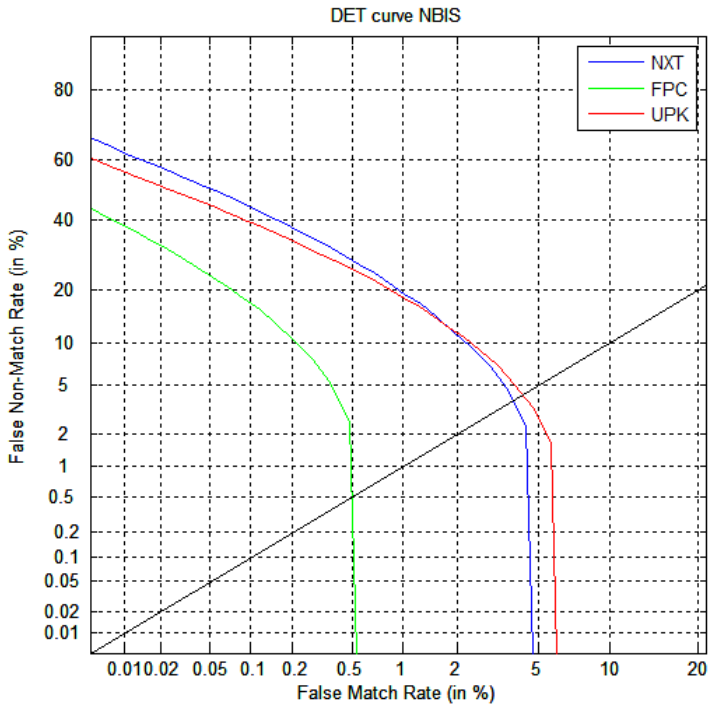



**Figure 19. DET curves for the fingerprint sensors using NBIS algorithm**

#### 6.1.1.2.8. ROC curves

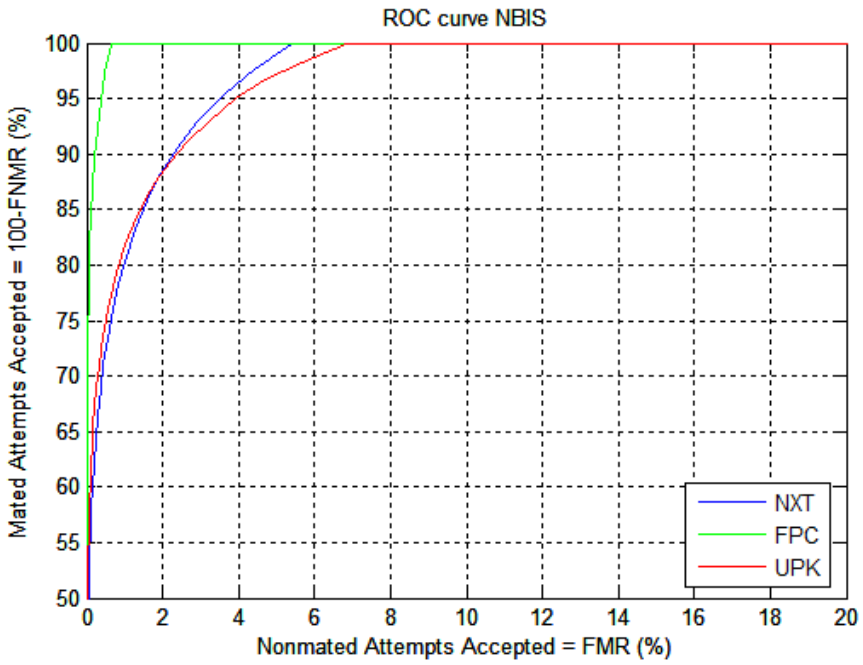



**Figure 20. ROC Curves using NBIS algorithm**

#### 6.1.1.2.9. Additional rates

In addition to previous sections, Table 9 provides relevant error rates for the different sensors.

**Table 9. Additional error rates for NBIS**

| Error rate | NXT | FPC | UPK |
|---|---|---|---|
| **EER** | 3.88 % | 0.60 % | 4.26 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | 19.21 % | < 0.01 %* | 18.24 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 43.99 | 15.62 % | 38.09 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 62.01 % | 37.67 % | 55.88 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

### 6.1.2. Throughput rates for NBIS

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for obtaining features extraction vectors at enrolment and acquisition processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for processing images captured with NXT and UPK fingerprint sensors.
- Machine 2: a PC with a processor Intel Core 2 Duo E8500 @ 3'16 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Professional 2009, Service Pack 1 This machine was used for processing images captured with FPC fingerprint sensor.

#### 6.1.2.1. Enrolment results

Table 10 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 10. Throughput rates results for enrolment using NBIS algorithm**

| Enrolment | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 169.60 ms | 149.83 ms | 320.32 ms |
| **Standard deviation** | ± 99.41 ms | ± 53.84 ms | ± 135.64 ms |
| **Minimum** | 69 ms | 98 ms | 160 ms |
| **Maximum** | 1,594 ms | 584 ms | 2,770 ms |
| **Number of enrolments** | 3,217 | 2,826 | 3,116 |

#### 6.1.2.2. Acquisition results

Table 11 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 11. Throughput rates results for acquisition using NBIS algorithm**

| Acquisition | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 48.18 ms | 52.73 ms | 184.24 ms |
| **Standard deviation** | ± 9.65 ms | ± 5.08 ms | ± 96.02 ms |
| **Minimum** | 12 ms | 26 ms | 92 ms |
| **Maximum** | 322 ms | 96 ms | 1,262 ms |
| **Number of acquisitions** | 47,729 | 44,119 | 43,340 |

#### 6.1.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 12 shows measurements obtained for mated comparisons and

Table 13 for non-mated comparisons.

**Table 12. Throughput rates results for mated comparisons using NBIS algorithm**

| Mated Comparisons | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 33.67 ms | 11.69 ms | 31.68 ms |
| **Standard deviation** | ± 48.15 ms | ± 26.31 ms | ± 48.87 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms |
| **Maximum** | 801 ms | 412 ms | 1,182 ms |
| **Number of comparisons** | 34,251 | 26,333 | 34,012 |

**Table 13. Throughput rates results for non-mated comparisons using NBIS algorithm**

| Non-mated Comparisons | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 2.92 ms | 0.48 ms | 3.97 ms |
| **Standard deviation** | ± 9.11 ms | ± 3.17 ms | ± 11.4 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,213 ms | 522 ms | 1,256 ms |
| **Number of comparisons** | 110,151,216 | 74,390,725 | 105,947,381 |

## 6.2. PERFORMANCE RESULTS FOR NEUROTECHNOLOGY ALGORITHM

### 6.2.1. Error rates for Neurotechnology

#### 6.2.1.1. Enrolment and acquisition results

FTE and FTA errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 14 and Table 15. These errors may happen due to the enrolment and capturing processes have not been successfully completed according the procedures explained in sections 3.2.1 and 3.2.2. In this case, the algorithm applied for enrolling and acquiring the samples has been Neurotechnology.

**Table 14. FTE errors using Neurotechnology algorithm**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Number of correct templates** | 3,230 | 2,903 | 3,131 |
| **FTE errors** | 304 | 631 | 403 |
| **Total number of enrolment attempts** | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 8.60 % | 17.85 % | 11.40 % |

**Table 15. FTA errors using Neurotechnology algorithm**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Number of correct samples** | 43,264 | 37,128 | 40,032 |
| **FTA in Visits** | 6,571 | 10,068 | 9,071 |
| **FTP in Visits** | 1,655 | 959 | 502 |
| **CI real** | 1,118 | 1,903 | 1,023 |
| **FTA errors** | 9,344 | 12,930 | 10,596 |
| **Total number of acquisition attempts** | 52,608 | 50,058 | 50,628 |
| **FTA rate** | 17.76 % | 25.83 % | 20.93 % |

#### 6.2.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 16.

**Table 16. Number of comparisons conducted using Neurotechnology**

| | NXT | FPC | UPK |
|---|---|---|---|
| **Mated comparisons** | 43,262 | 37,128 | 40,032 |
| **Non-mated comparisons** | 139,680,082 | 107,742,554 | 125,118,621 |

##### 6.2.1.2.1. Distribution curves for NXT sensor

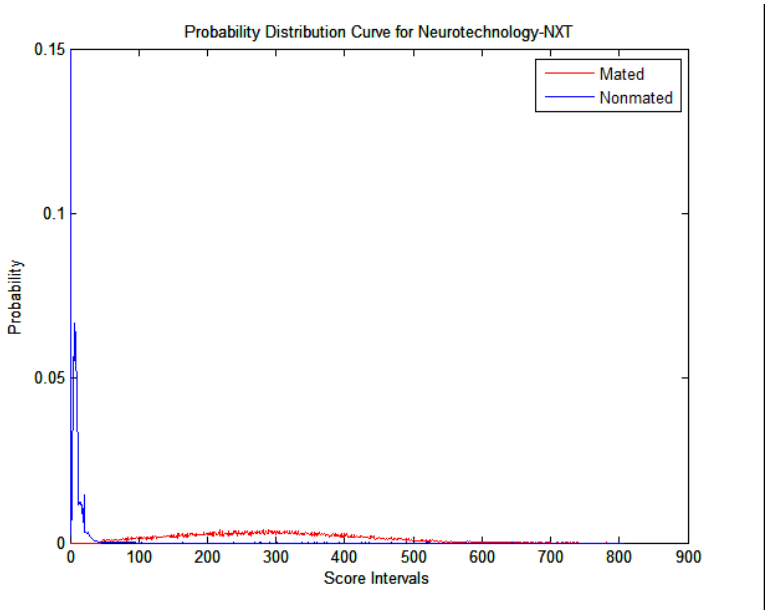
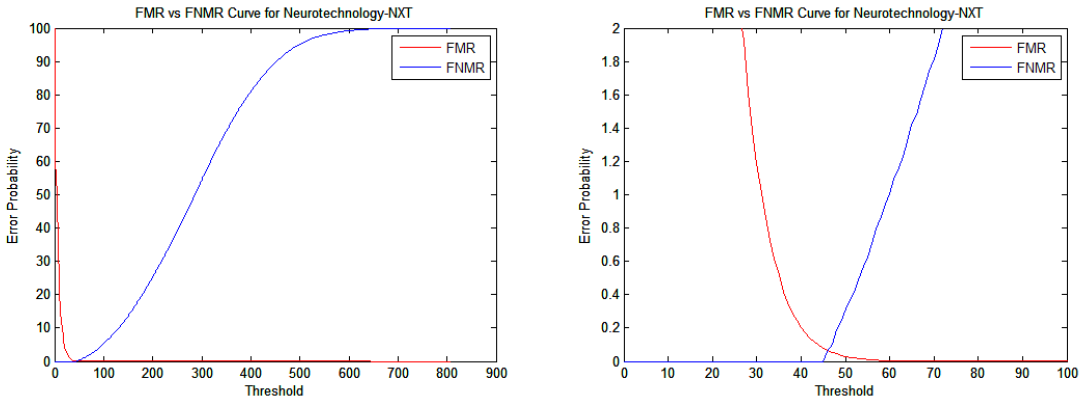



**Figure 21. Distribution curves for NXT sensor using Neurotechnology algorithm**

#### 6.2.1.2.2. FMR vs FNMR graph for NXT sensor




(a) (b)

**Figure 22. FMR vs. FNMR curves for NXT sensor using Neurotechnology algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.2.1.2.3. Distribution curves for FPC sensor

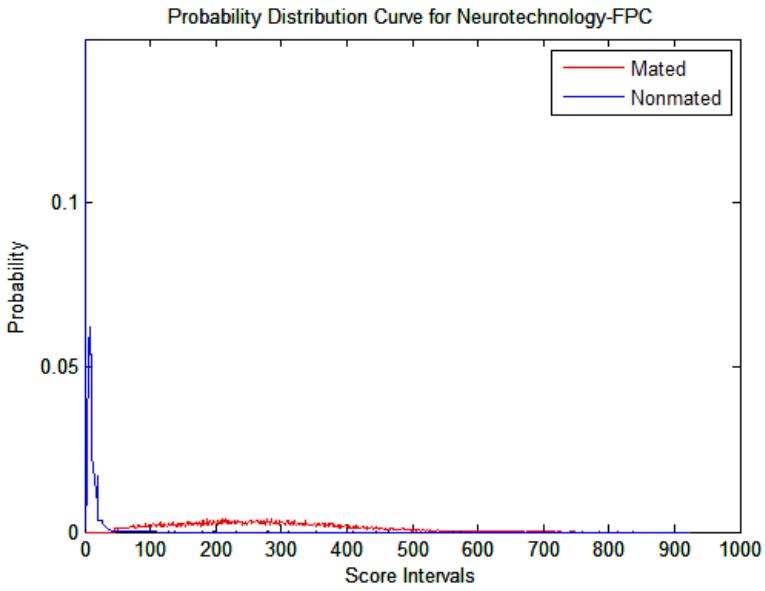
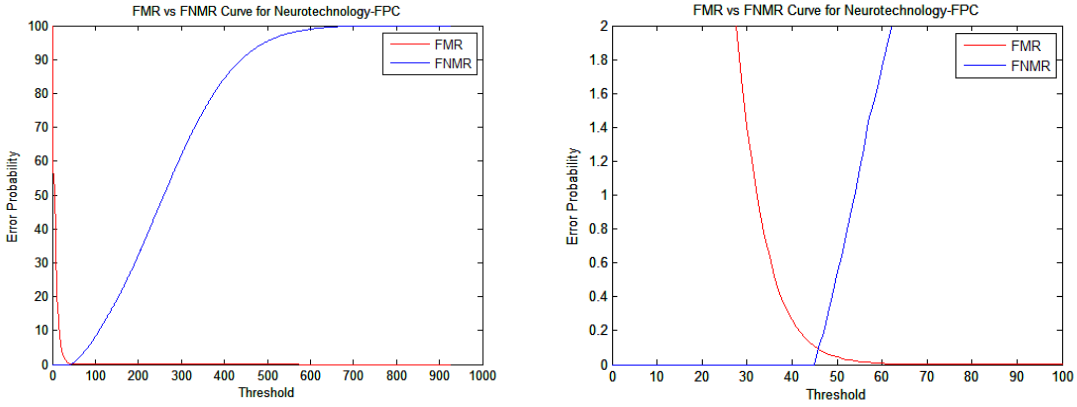



**Figure 23. Distribution curves for FPC sensor using Neurotechnology algorithm**

#### 6.2.1.2.4. FMR vs FNMR graph for FPC sensor




(a) (b)

**Figure 24. FMR vs FNMR curves for FPC sensor using Neurotechnology algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.2.1.2.5. Distribution curves for UPK sensor

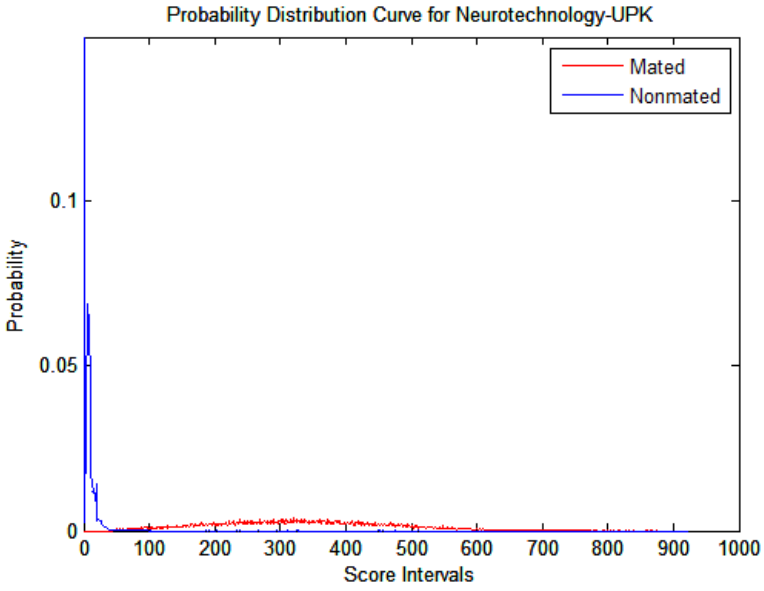
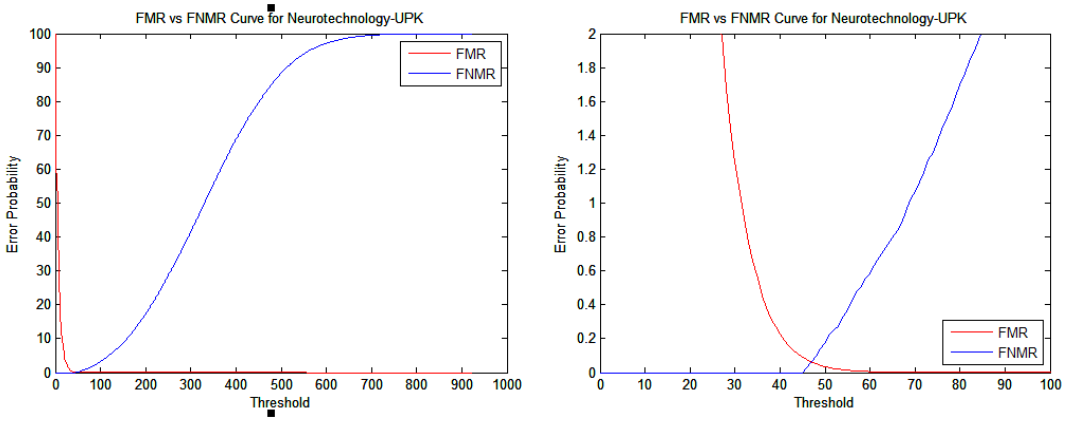



**Figure 25. Distribution curves for UPK sensor using Neurotechnology algorithm**

#### 6.2.1.2.6. FMR vs FNMR graph for UPK sensor




(a) (b)

**Figure 26. FMR vs FNMR curves for UPK sensor using Neurotechnology algorithm**

**(a) Complete graph**
**(b) Zoom of the relevant area**

#### 6.2.1.2.7. DET curves

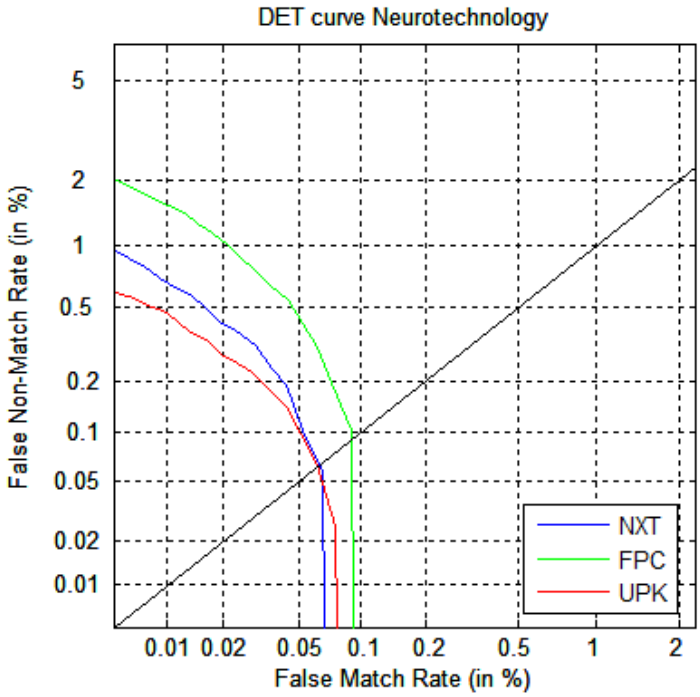



**Figure 27. DET curves for the fingerprint sensors using Neurotechnology algorithm**

#### 6.2.1.2.8. ROC curves

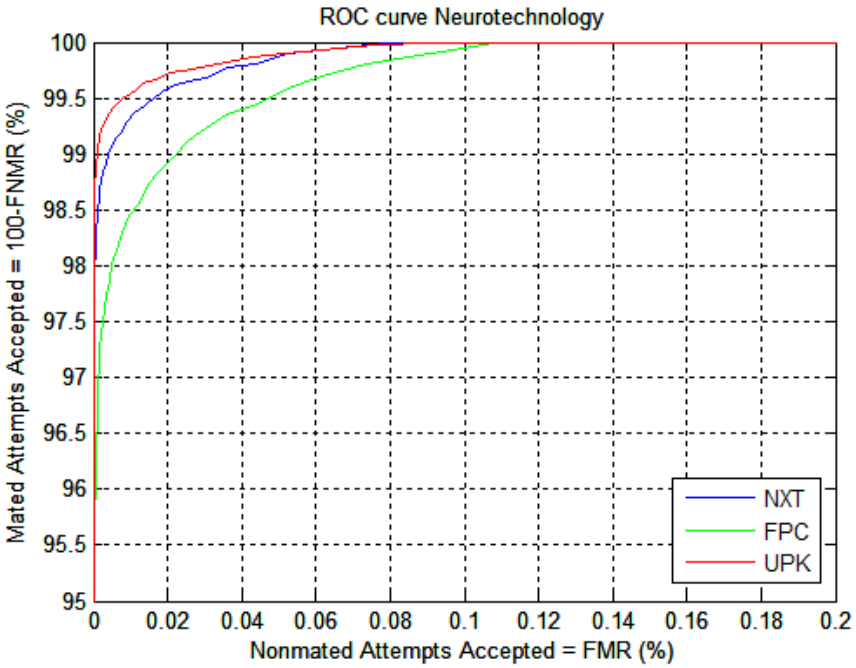



**Figure 28. ROC Curves using Neurotechnology algorithm**

#### 6.2.1.2.9. Additional rates

In addition to previous sections, Table 17 provides relevant error rates for the different sensors.

**Table 17. Additional error rates for Neurotechnology**

| Error rate | NXT | FPC | UPK |
|---|---|---|---|
| **EER** | 0.0639 % | 0.0925 % | 0.0616% |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | <0.01%* | <0.01%* |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01 %* | <0.01%* | <0.01%* |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 0.628 % | 1.54 % | 0.42 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

### 6.2.2. Throughput rates for Neurotechnology

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the Neurotechnology algorithm.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for obtaining features extraction vectors at enrolment and acquisition processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for processing images captured with NXT and UPK fingerprint sensors.
- Machine 2: a PC with a processor Intel Core 2 Duo E8500 @ 3'16 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Professional 2009, Service Pack 1 This machine was used for processing images captured with FPC fingerprint sensor.

#### 6.2.2.1. Enrolment results

Table 18 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 18. Throughput rates results for enrolment using Neurotechnology algorithm**

| Enrolment | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 2,219 ms | 2,200 ms | 2,215 ms |
| **Standard deviation** | ± 94.28 ms | ± 136.25 ms | ± 56.04 ms |
| **Minimum** | 521 ms | 230 ms | 778 ms |
| **Maximum** | 4,452 ms | 4,463 ms | 3,340 ms |
| **Number of enrolments** | 3,230 | 2,903 | 3,131 |

#### 6.2.2.2. Acquisition results

Table 19 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 19. Throughput rates results for acquisition using Neurotechnology algorithm**

| Acquisition | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 1,101 ms | 1,043 ms | 1,090 ms |
| **Standard deviation** | ± 66.75 ms | ± 36.12 ms | ± 84.04 ms |
| **Minimum** | 78 ms | 239 ms | 165 ms |
| **Maximum** | 1,416 ms | 1,187 ms | 1,530 ms |
| **Number of acquisitions** | 46,431 | 43,168 | 44,531 |

#### 6.2.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 20 shows measurements obtained for mated comparisons and Table 21 for non-mated comparisons.

**Table 20. Throughput rates results for mated comparisons using Neurotechnology algorithm**

| Mated Comparisons | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 2.17 ms | 1.07 ms | 1.55 ms |
| **Standard deviation** | ± 1.81 ms | ± 1.157 ms | ± 0.17 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms |
| **Maximum** | 20 ms | 32 ms | 22 ms |
| **Number of comparisons** | 43,262 | 37,128 | 40,032 |

**Table 21. Throughput rates results for non-mated comparisons using Neurotechnology algorithm**

| Non-mated Comparisons | NXT | FPC | UPK |
|---|---|---|---|
| **Arithmetic mean** | 2.20 ms | 0.86 ms | 2.00 ms |
| **Standard deviation** | ± 1.96 ms | ± 0.55 ms | ± 1.65 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms |
| **Maximum** | 2,396 ms | 70 ms | 95 ms |
| **Number of comparisons** | 139,680,082 | 107,742,554 | 125,118,621 |

# PART II

# PERFORMANCE ANALISIS REPORT

# CROPPED DATABASES

# 7. CROPPED DATABASES

This section describes the approach for generating cropped images using the images collected by different fingerprint sensors: NB-3010-U sensor, FPC1011F3 sensor and Upek Eikon Touch 510 sensor. This method have been done based on three sizes that are going to be studied:

- 12x12 $mm^2$
- 10x10 $mm^2$
- 8x8 $mm^2$

Firstly, the approach to obtain the images will be explained. Then an example of the cropped images for the different sizes per each fingerprint sensor will be shown.

## 7.1. CROPPING APPROACH

There are several approaches to obtain a cropped images depending on the selection of the centre of the cropped image:

1. Select the centre considering the centre of the ROI (region of interest).
2. Select the centre considering the centre of the original image.
3. Select a random centre considering a limited area.

All of them have been illustrated in Figure 29. However, not all the methods models the expected behaviour of the users. The first method reduces the active area but it is based on the idea that a user always place the finger in the same position of the sensor. This is not realistic, especially for small sensors, in which it is difficult to place the centre of the fingerprint on the centre of the active area.

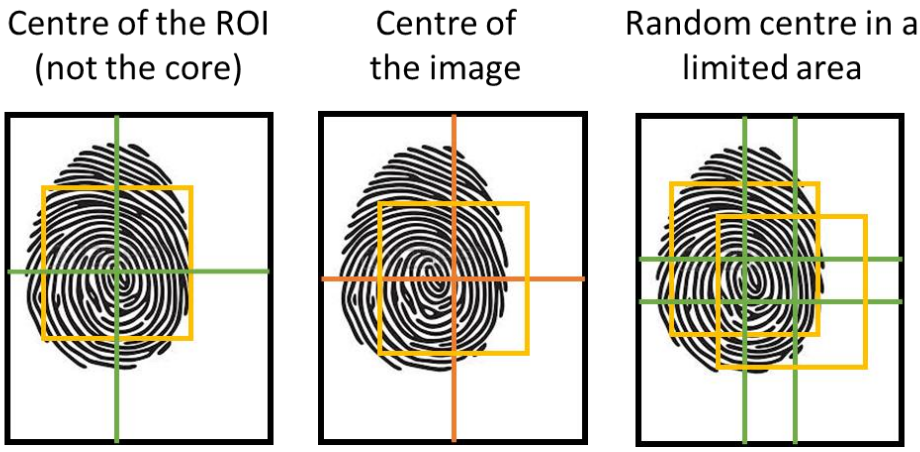



**Figure 29. Different approaches for cropping the original image**

The second method has the same problem of the first method. The variability of the fingerprint placement is insufficiently, considering the variability that has been observed for small sensors.

Finally, the third method is the more realistic method because it is based on the idea that a user tries to place the fingerprint on the centre of the active area but there is a variability due to the difficulty to find it in small sensors. Therefore, this is the method that have been used for cropping the images.

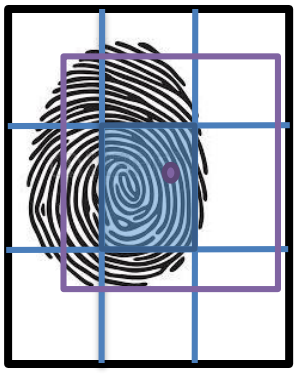


**Figure 30. Area for selecting the centre of the cropped image**

In particular, this method consists on selecting the centre of the cropped image considering a random position in a limited area as it is shown in Figure 30. The limited area has been chosen based on the 10x10 $mm^2$ size and the possible variations considering this size. The possibilities considering the 12x12 $mm^2$ size entail a low variability of the user placement and considering the 8x8 $mm^2$ size entail a high variability of the user placement (see Figure 31).

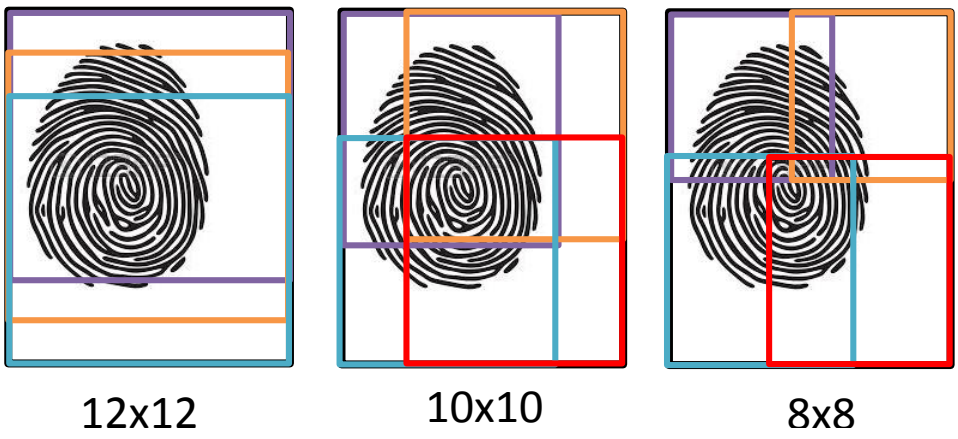



**Figure 31. Selection of the limited area**

Once the centre has been randomly selected in the original image, then this image is cut according to the different sizes. The results are shown in Figure 32

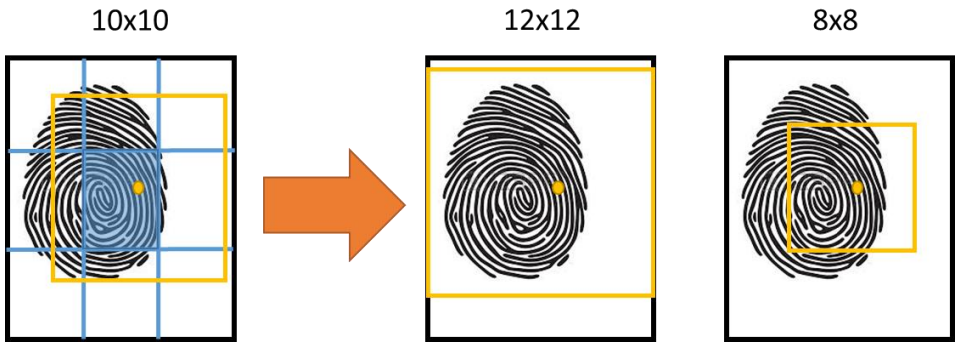



**Figure 32. Approach to generate the different sizes for the cropped images**

## 7.2. COMPOSITION OF THE CROPPED DATABASES

Regarding to images, the number of fingerprint images that compose the cropped database depend on the number of samples that have overcome the ground truth mechanism (see section 3.3) for each of the sensor and algorithm. Therefore the number of images for each of the cropped databases is lower than the ones for the original database.

- For NXT fingerprint sensor:
  - NXT Full size = 64613 images
  - Cropped NXT- NBIS = 40466 images
  - Cropped NXT- Neurotechnology = 50587 images

- For FPC fingerprint sensor:
  - FPC Full size = 63493 images
  - Cropped FPC- NBIS = 32133 images
  - Cropped FPC- Neurotechnology = 43638 images

- For FPC fingerprint sensor:
  - UPK Full size = 58487 images
  - Cropped UPK- NBIS = 42871 images
  - Cropped UPK- Neurotechnology = 42871images

**It is important to note that, due to the fact that the original image of the FPC sensor is 10,6 x 14,0, the cropped database referred as FPC 12x12 has, in fact, images of 10,6 x 12,0.**

### 7.2.1. NXT Cropped images

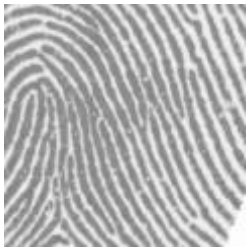
| NXT 12x17 mm² | NXT 12x12 mm² | NXT 10x10 mm² | NXT 8x8 mm² |
|---|---|---|---|
|  |  |  |  |
| 180x256 pixels | 180x180 pixels | 150x150 pixels | 120x120 pixels |

### 7.2.2. FPC Cropped images

| FPC 10.6x14 mm$^2$ | FPC 12x12 mm$^2$ | FPC10x10 mm$^2$ | FPC 8x8 mm$^2$ |
|---|---|---|---|
|  |  |  |  |
| 152x200 pixels | 152x172 pixels [2] | 143x143 pixels | 114x114 pixels |

[2] As it can be seen, the FPC 12x12 images are in fact 10,6x12,0, as the original image obtained from the sensor is 10,6 x 14,0

### 7.2.3. UPK Cropped images

| UPK 12.8x18 mm² | UPK 12x12 mm² | UPK 10x10 mm² | UPK 8x8 mm² |
|---|---|---|---|
|  |  |  |  |
| 192x270 pixels | 180x180 pixels | 150x150 pixels | 120x120 pixels |

# 8. QUALITY ANALYSIS OF THE CROPPED DATABASES

This section shows the quality analysis results of the cropped databases generated from the full-size database. This analysis includes the total number of images that have been reported in the previous section for NBIS algorithm considering the different sizes.

In a similar way to the full size database, this quality analysis has been done using the NFIQ quality score provided by NIST [4].

## 8.1. QUALITY ANALYSIS

### 8.1.1. NFIQ Distribution for NXT sensor

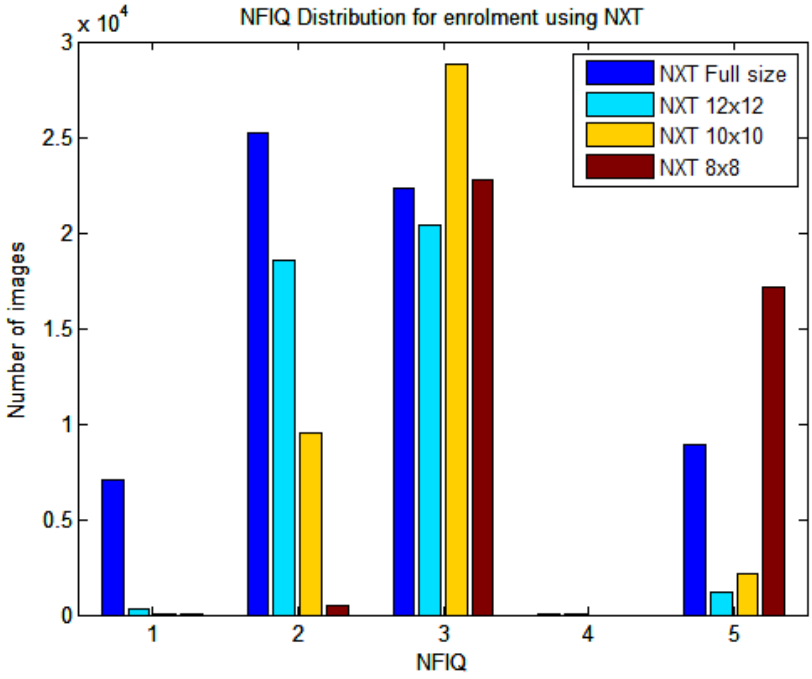



**Figure 33. NFIQ Distribution using NXT sensor**

### 8.1.2. NFIQ Distribution for FPC sensor

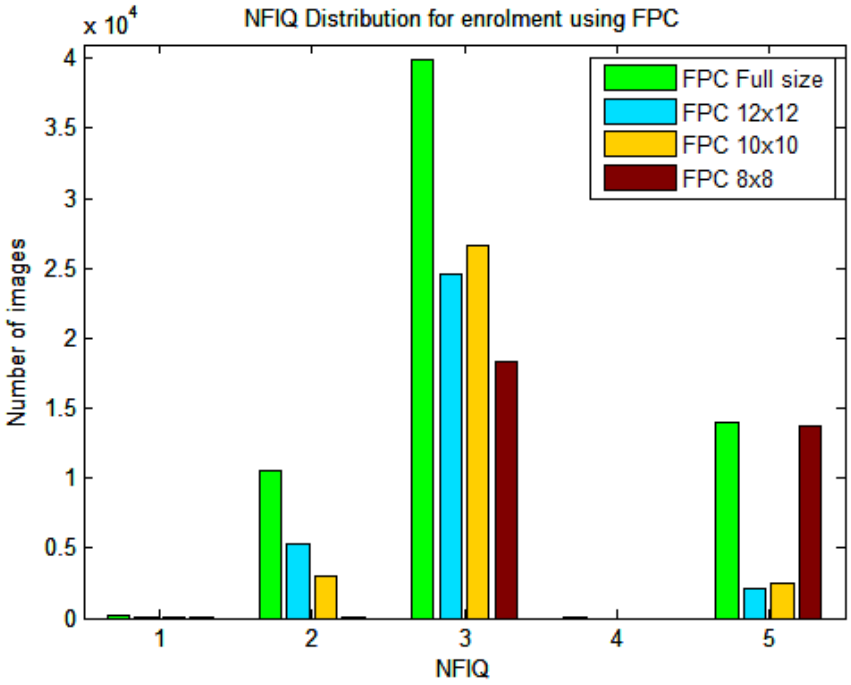



**Figure 34. NFIQ Distribution for enrolment using FPC sensor**

### 8.1.3. NFIQ Distribution

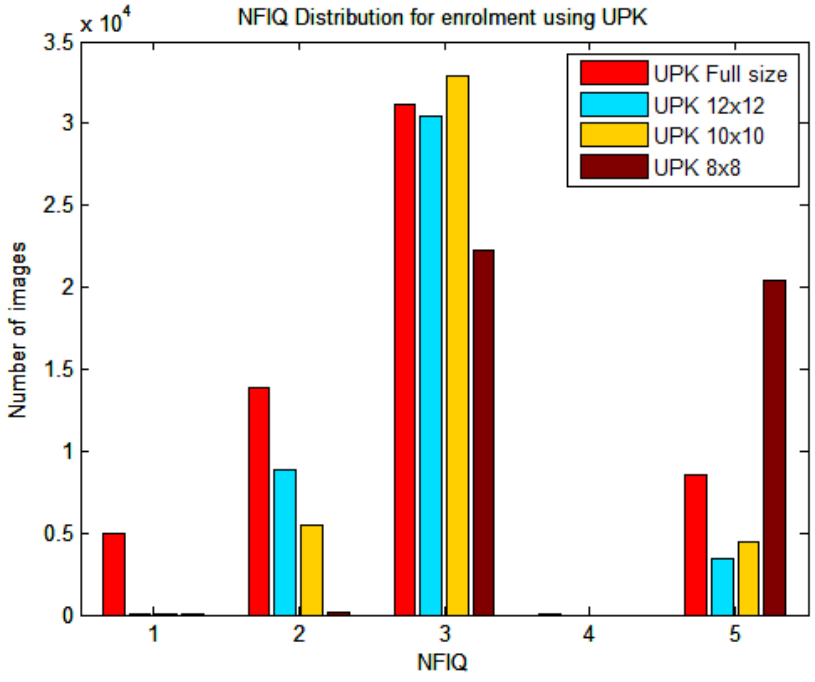



**Figure 35. NFIQ Distribution for enrolment using UPK sensor**

# PART II-A

# PERFORMANCE ANALISIS REPORT

## FULL SIZES IMAGES vs. CROPPED SIZES IMAGES

# 9. PERFORMANCE ANALISIS FULL SIZE VS. CROPPED IMAGES

## 9.1. INTRODUCTION

This section explains performance analysis results considering the different algorithms: NBIS and Neurotechnology. In particular, error rates and throughput rates will be shown.

Regarding error rates, these metrics are given separately for enrolment (FTE error) and acquisition process (FTA error) and then, for the comparison process. For the comparison process the following curves will be shown:

- ROC curves for the three fingerprint sensors
- DET curves for the three fingerprint sensors
- Additional rates: EER, FMR100, FMR1000,FMR10000

In addition, the following curves will be provided in the annexes:

- Distribution curves per each fingerprint sensor
- FNMR vs. FMR curves per each fingerprint sensor

In relation to throughput rates, the metrics that have been obtained have been the following:

- Enrolment time, which has been calculated considering the time that takes to obtain the biometric references.
- Acquisition time, which has been calculated considering the time that takes to obtain the biometric probes.
- Mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference of the same user, same finger.
- Non-mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference that do not belong of the same user.

An important issue to consider is that the quality check and ground truth mechanism was applied in the full size database, and those images not concealing with those requirements have been discarded for the cropped images analysis. In other terms, this means that the ground truth mechanism is not applied again during this tests, and therefore, the FTA cases detected are additional to the ones of the full-size case. In order not to confuse the reader, we will consider Failure to Process (FTP) rates, instead of the FTA rates, knowing that the number of cases in a real scenario should be the sum of both the FTA and FTP cases.

## 9.2. PERFORMANCE RESULTS FOR NBIS

### 9.2.1. Performance results for NBIS - NXT

#### 9.2.1.1. Error rates for NBIS – NXT

##### 9.2.1.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.1.1.1). A total 3,217 correct templates have been generated and 317 FTE errors have happened. Therefore, the FTE rate for NXT sensor using NBIS algorithm has been 8.97 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 22.

**Table 22. FTP errors for NBIS - NXT**

| | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|
| **Number of correct samples** | 33,508 | 33,507 | 33,495 |
| **FTP errors** | 0 | 1 | 13 |
| **Total number of acquisition attempts** | 33,508 | 33,508 | 33,508 |
| **FTP rate** | 0.00 % | 0.0029 % | 0.0038 % |

##### 9.2.1.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 23.

**Table 23. Number of comparisons conducted using NBIS - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 34,251 | 33,508 | 33,507 | 33,495 |
| **Non-mated comparisons** | 110,151,216 | 107,761,728 | 107,758,512 | 107,719,920 |

#### 9.2.1.1.3. DET curves

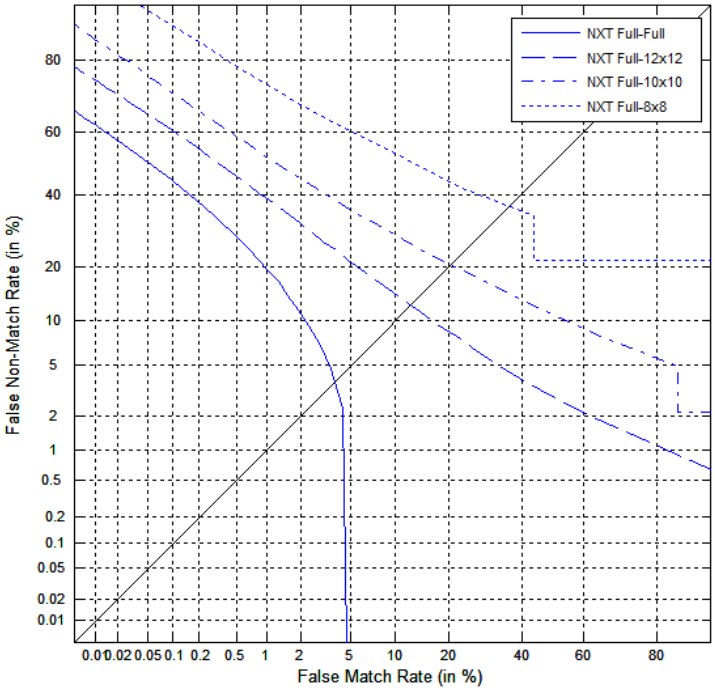



**Figure 36. DET curves for the fingerprint sensors using NBIS – NXT**

#### 9.2.1.1.4. ROC curves

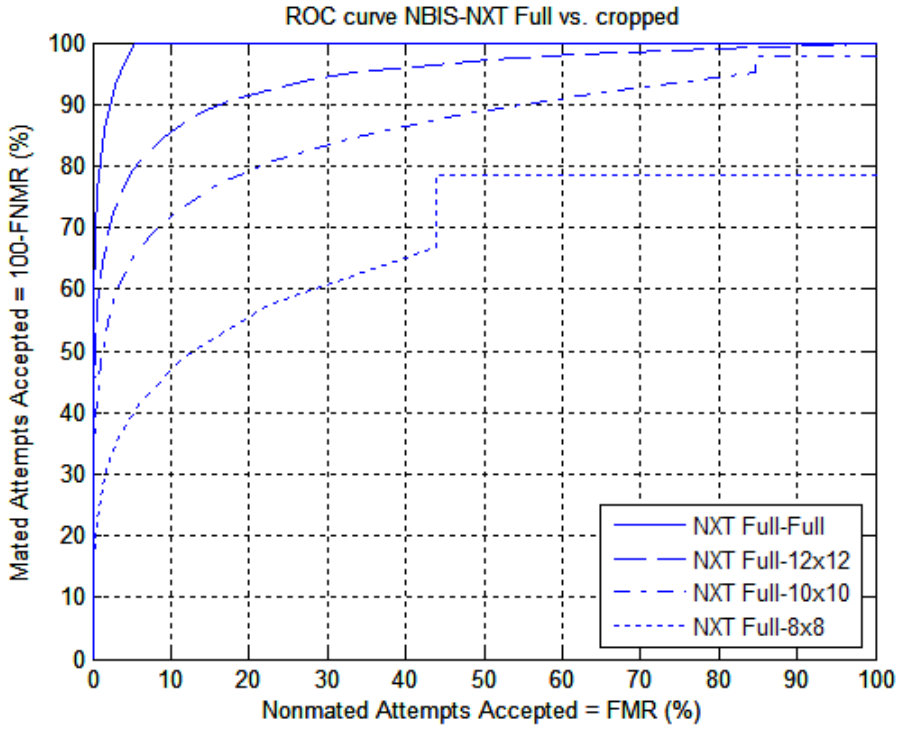



**Figure 37. ROC Curves using NBIS – NXT**

#### 9.2.1.1.5. Additional rates

In addition to previous sections, Table 24 provides relevant error rates for the different sensors.

**Table 24. Additional error rates for NBIS - NXT**

| Error rate | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **EER** | 3.88 % | 12.43 % | 20.49 % | 36.47 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | 19.21 % | 38.19 % | 51.82 % | 73.73 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 43.99 % | 58.92 % | 70.21 % | 85.78 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 62.01 % | 74.43 % | 83.22 % | 93.13 % |

#### 9.2.1.2. Throughput rates for NBIS - NXT

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the NXT fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the original database and for making comparisons.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2.40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the cropped databases.

##### 9.2.1.2.1. Enrolment results

Time measurements to obtain biometric references for NXT using NBIS algorithm are the following:

- Arithmetic mean: 169.60 ms
- Standard deviation: ± 99.41 ms
- Minimum: 69 ms
- Maximum: 1,594 ms

##### 9.2.1.2.2. Acquisition results

Table 25 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 25. Throughput rates results for acquisition using NBIS - NXT**

| Acquisition | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 48.18 ms | 37.48 ms | 32.03 ms | 19.72 ms |
| **Standard deviation** | ± 9.65 ms | ± 9.16 ms | ± 8.11 ms | ± 5.11 ms |
| **Minimum** | 12 ms | 14 ms | 10 ms | 6 ms |
| **Maximum** | 322 ms | 79 ms | 68 ms | 45 ms |
| **Number of acquisitions** | 47,729 | 33,508 | 33,507 | 33,495 |

#### 9.2.1.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 26 shows measurements obtained for mated comparisons and Table 27 for non-mated comparisons.

**Table 26. Throughput rates results for mated comparisons using NBIS - NXT**

| Mated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 33.67 ms | 27.63 ms | 3.62 ms | 0.42 ms |
| **Standard deviation** | ± 48.15 ms | ± 49.59 ms | ± 13.83 ms | ± 2.91 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 801 ms | 943 ms | 571 ms | 199 ms |
| **Number of comparisons** | 34,251 | 33,508 | 33,507 | 33,495 |

**Table 27. Throughput rates results for non-mated comparisons using NBIS - NXT**

| Non-mated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.92 ms | 3.57 ms | 0.61 ms | 0.19 ms |
| **Standard deviation** | ± 9.11 ms | ± 11.14 ms | ± 3.04 ms | ± 0.59 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,213 ms | 2,828 ms | 1,252 ms | 527 ms |
| **Number of comparisons** | 110,151,216 | 107,761,728 | 107,761,728 | 107,719,920 |

### 9.2.2. Performance results for NBIS - FPC

#### 9.2.2.1. Error rates for NBIS - FPC

##### 9.2.2.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.1.1.1). A total 2,826 correct templates have been generated and 708 FTE errors have happened. Therefore, the FTE rate for FPC sensor using NBIS algorithm has been 20.03 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 28.

**Table 28. FTP errors for NBIS - FPC**

| | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|
| **Number of correct samples** | 25,512 | 25,512 | 25,511 |
| **FTP errors** | 0 | 0 | 1 |
| **Total number of acquisition attempts** | 25,512 | 25,512 | 25,512 |
| **FTP rate** | 0.00 % | 0.00 % | 0.0039 % |

##### 9.2.2.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 29.

**Table 29. Number of comparisons conducted using NBIS - FPC**

| | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 26,333 | 25,512 | 25,512 | 25,511 |
| **Non-mated comparisons** | 74,390,725 | 72,071,400 | 72,071,400 | 72,068,575 |

#### 9.2.2.1.3. DET curves

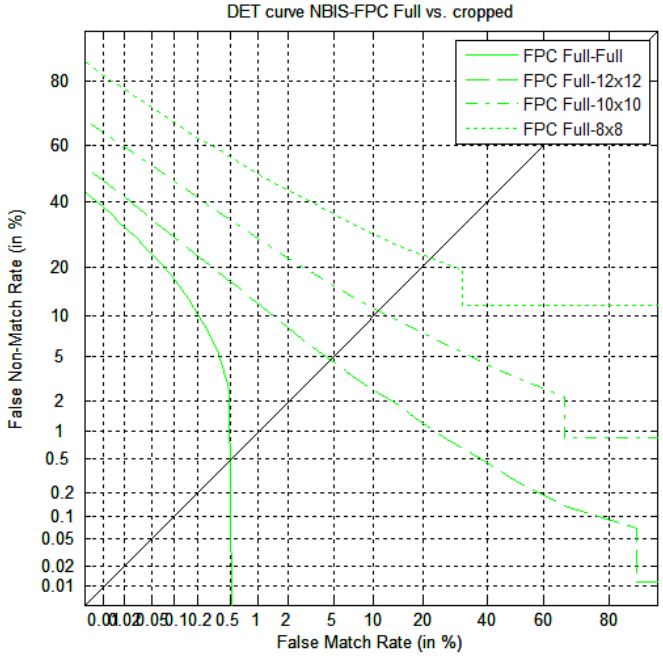



**Figure 38. DET curves for the fingerprint sensors using NBIS – FPC**

#### 9.2.2.1.4. ROC curves

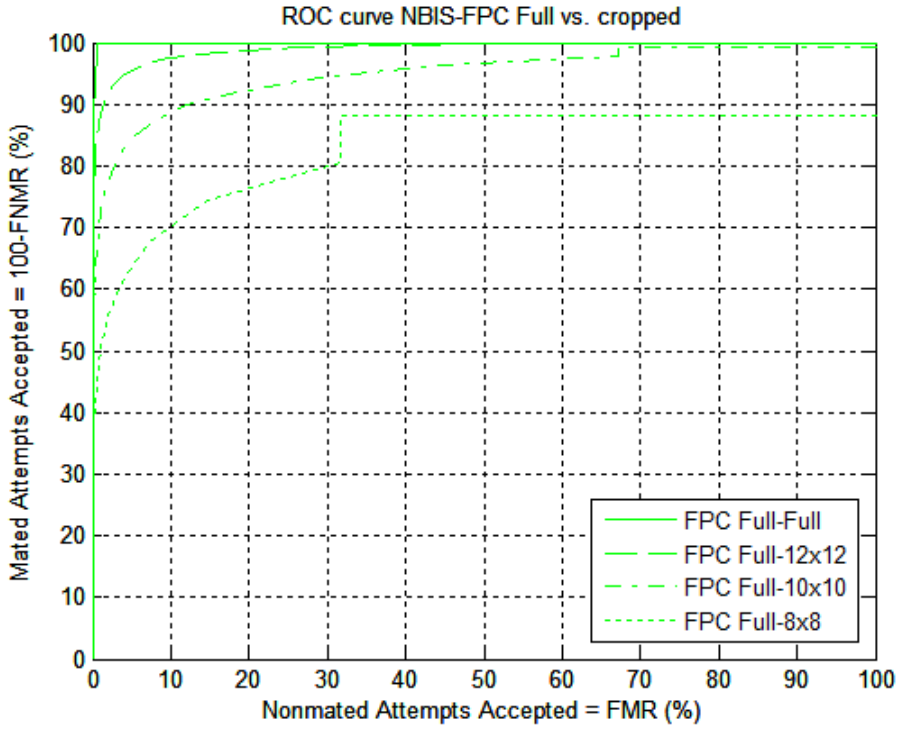



**Figure 39. ROC Curves using NBIS – FPC**

#### 9.2.2.1.5. Additional rates

In addition to previous sections, Table 30 provides relevant error rates for the different sensors.

**Table 30. Additional error rates for NBIS - FPC**

| Error rate | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **EER** | 0.60 % | 4.72 % | 10.88 % | 22.62 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 11.54 % | 27.30 % | 49.50 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 15.62 % | 28.02 % | 45.37 % | 66.87 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 37.67 % | 46.05 % | 64.35 % | 80.67 % |

### 9.2.2.2. Throughput rates for NBIS - FPC

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the FPC fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2 Duo E8500 @ 3.16 GHz and a RAM memory of 4GB. This PC has installed Windows 7 Professional 2009, SP1. This machine was used for extracting the feature vectors of the original database.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2.40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the cropped databases and for making comparisons.

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* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 9.2.2.2.1. Enrolment results

Time measurements to obtain biometric references for FPC using NBIS algorithm are the following:

- Arithmetic mean: 169.60 ms
- Standard deviation: ± 99.41 ms
- Minimum: 69 ms
- Maximum: 1,594 ms

#### 9.2.2.2.2. Acquisition results

Table 31 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 31. Throughput rates results for acquisition using NBIS - FPC**

| Acquisition | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 52.73 ms | 43.88 ms | 38.92 ms | 29.07 ms |
| **Standard deviation** | ± 5.08 ms | ± 6.78 ms | ± 6.26 ms | ± 3.82 ms |
| **Minimum** | 26 ms | 29 ms | 22 ms | 16 ms |
| **Maximum** | 96 ms | 71 ms | 62 ms | 49 ms |
| **Number of acquisitions** | 44,119 | 25,512 | 22,512 | 22,511 |

#### 9.2.2.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 32 shows measurements obtained for mated comparisons and Table 33 for non-mated comparisons.

**Table 32. Throughput rates results for mated comparisons using NBIS - FPC**

| Mated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 11.69 ms | 8.31 ms | 2.39 ms | 0.20 ms |
| **Standard deviation** | ± 26.31 ms | ± 22.12 ms | ± 10.89 ms | ± 1.64 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 412 ms | 327 ms | 752 ms | 128 ms |
| **Number of comparisons** | 26,333 | 25,512 | 25,512 | 25,511 |

**Table 33. Throughput rates results for non-mated comparisons using NBIS - FPC**

| Nonmated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 0.48 ms | 0.32 ms | 0.08 ms | 0.006 ms |
| **Standard deviation** | ± 3.17 ms | ± 2.52 ms | ± 1.07 ms | ± 0.182 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 522 ms | 787 ms | 438 ms | 238 ms |
| **Number of comparisons** | 74,390,725 | 72,071,400 | 72,071,400 | 72,068,575 |

#### 9.2.3. Performance results for NBIS - UPK

##### 9.2.3.1. Error rates for NBIS - UPK

###### 9.2.3.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.1.1.1). A total 3,116 correct templates have been generated and 418 FTE errors have happened. Therefore, the FTE rate for UPK sensor using NBIS algorithm has been 11.82 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 34.

**Table 34. FTP errors for NBIS – UPK**

| | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|
| **Number of correct samples** | 33,720 | 33,718 | 33,689 |
| **FTP** | 0 | 2 | 31 |
| **Total number of acquisition attempts** | 33,720 | 33,720 | 33,720 |
| **FTP rate** | 0.00 % | 0.005 % | 0.092 % |

###### 9.2.3.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 35.

**Table 35. Number of comparisons conducted using NBIS - UPK**

| | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 34,012 | 33,720 | 33,718 | 33,689 |
| **Non-mated comparisons** | 105,947,381 | 102,799,756 | 102,793,524 | 102,703,182 |

#### 9.2.3.1.3. DET curves

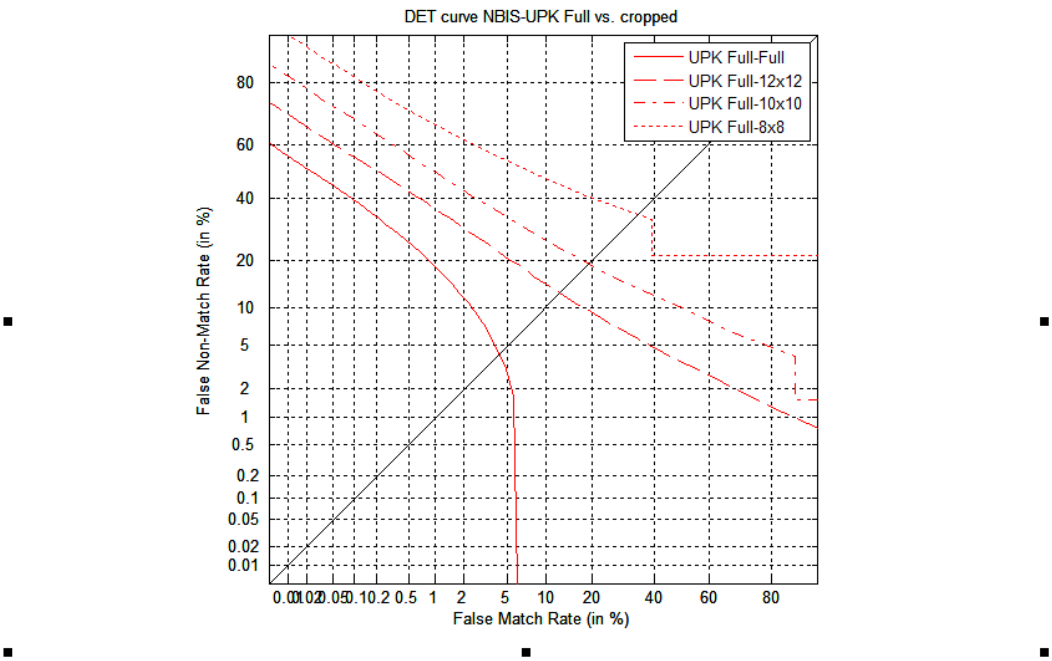


**Figure 40. DET curves for the fingerprint sensors using NBIS – UPK**

#### 9.2.3.1.4. ROC curves

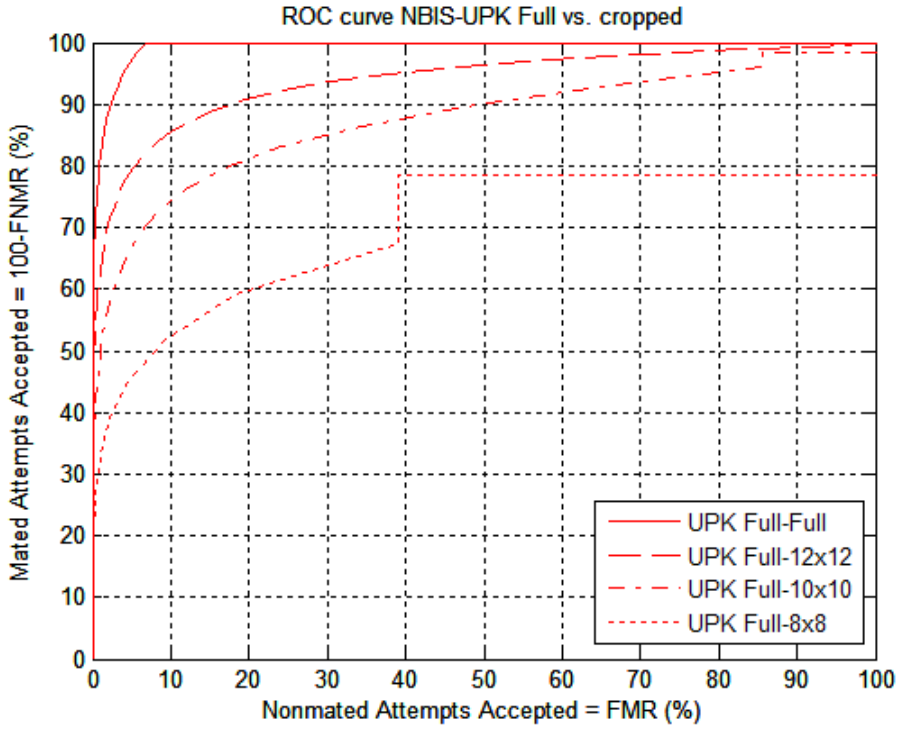


**Figure 41. ROC Curves using NBIS – UPK**

#### 9.2.3.1.5. Additional rates

In addition to previous sections, Table 36 provides relevant error rates for the different sensors.

**Table 36. Additional error rates for NBIS - UPK**

| Error rate | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **EER** | 4.26 % | 12.62 % | 19.15 % | 34.46 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | 18.24 % | 34.87 % | 47.12 % | 65.11 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 38.09 % | 54.94 % | 68.95 % | 79.18 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 55.88 % | 69.47 % | 81.13 % | 90.21 % |

### 9.2.3.2. Throughput rates for NBIS - UPK

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the UPK fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2Duo E6750 @ 2.67 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Ultimate 2009, SP1. This machine was used for extracting the feature vectors of the original database.
- Machine 2: a PC with a processor Intel Core 2Duo E6750 @ 2.67 GHz and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the cropped databases and for making the comparisons of the full vs. 8x8 $mm^2$ and some of the full vs. 12x12 $mm^2$ feature vectors.
- Machine 3: a laptop with a processor Intel Core i7-5500U @ 2’40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used making the comparisons of the full vs. 10x10 $mm^2$ and some of the full vs. 12x12 $mm^2$ feature vectors.

#### 9.2.3.2.1. Enrolment results

Time measurements to obtain biometric references for UPK using NBIS algorithm are the following:

- Arithmetic mean: 320.32 ms
- Standard deviation: ± 135.64 ms
- Minimum: 160 ms
- Maximum: 2,770 ms

#### 9.2.3.2.2. Acquisition results

Table 37 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 37. Throughput rates results for acquisition using NBIS - UPK**

| Acquisition | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 31.68 ms | 103.08 ms | 86.77 ms | 32.61 ms |
| **Standard deviation** | ± 48.87 ms | ± 100.22 ms | ± 133.44 ms | ± 2.16 ms |
| **Minimum** | 0 ms | 41 ms | 27 ms | 12 ms |
| **Maximum** | 1,182 ms | 9,990 ms | 12,732 ms | 66 ms |
| **Number of acquisitions** | 34,012 | 33,720 | 33,718 | 33,689 |

#### 9.2.3.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 38 shows measurements obtained for mated comparisons and Table 38 for non-mated comparisons.

**Table 38. Throughput rates results for mated comparisons using NBIS - UPK**

| Mated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 31.68 ms | 18.47 ms | 2.51 ms | 0.187 ms |
| **Standard deviation** | ± 48.87 ms | ± 37.64 ms | ± 10.74 ms | ± 1.781 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,182 ms | 634 ms | 917 ms | 189 ms |
| **Number of comparisons** | 34,012 | 33,720 | 33,718 | 33,689 |

**Table 39. Throughput rates results for non-mated comparisons using NBIS - UPK**

| Nonmated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 3.97 ms | 2.59 ms | 0.48 ms | 0.072 ms |
| **Standard deviation** | ± 11.4 ms | ± 8.95 ms | ± 2.54 ms | ± 0.39 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,256 ms | 8,103 ms | 1,135 ms | 332 ms |
| **Number of comparisons** | 105,947,381 | 102,799,756 | 102,793,524 | 102,703,182 |

## 9.3. PERFORMANCE RESULTS FOR NEUROTECHNOLOGY

### 9.3.1. Performance results for Neurotechnology - NXT

#### 9.3.1.1. Error rates for Neurotechnology – NXT

##### 9.3.1.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.2.1.1). A total 3,230 correct templates have been generated and 304 FTE errors have happened. Therefore, the FTE rate for NXT sensor using Neurotechnology algorithm has been 8.60 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 40.

**Table 40. FTP errors for Neurotechnology - NXT**

| | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|
| **Number of correct samples** | 39,326 | 30,079 | 11,651 |
| **FTP errors** | 4,303 | 13,550 | 31,978 |
| **Total number of acquisition attempts** | 43,629 | 43,629 | 43,629 |
| **FTP rate** | 9.86 % | 31.06 % | 73.29 % |

##### 9.3.1.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 41.

**Table 41. Number of comparisons conducted using Neurotechnology - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 43,262 | 39,315 | 30,077 | 11,650 |
| **Non-mated comparisons** | 139,680,082 | 126,983,665 | 97,125,093 | 37,621,080 |

#### 9.3.1.1.3. DET curves

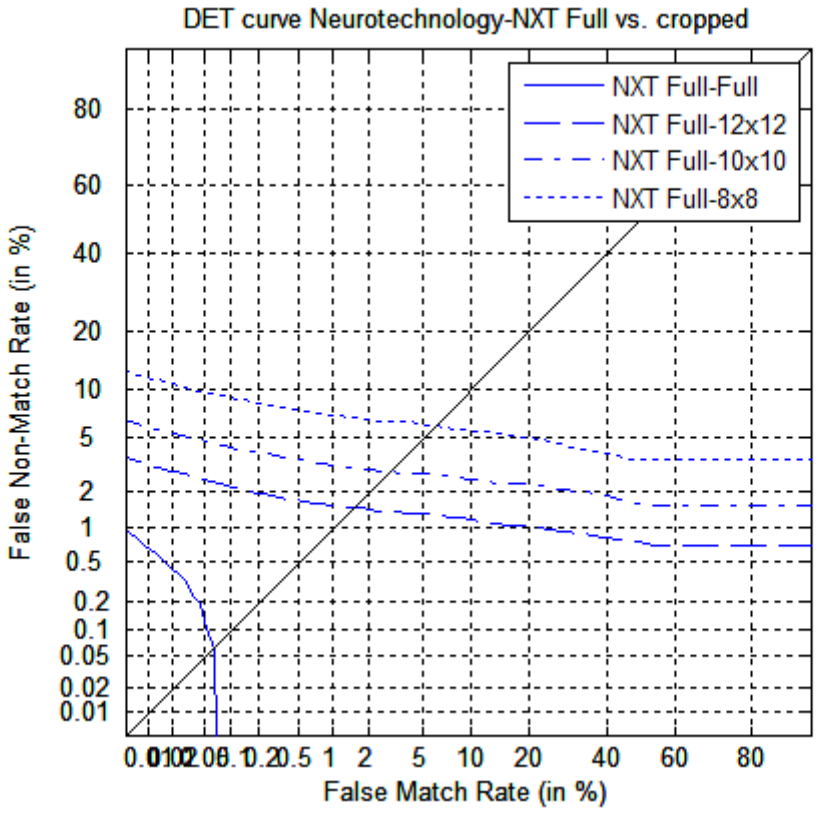


**Figure 42. DET curves for the fingerprint sensors using Neurotechnology - NXT**

#### 9.3.1.1.4. ROC curves

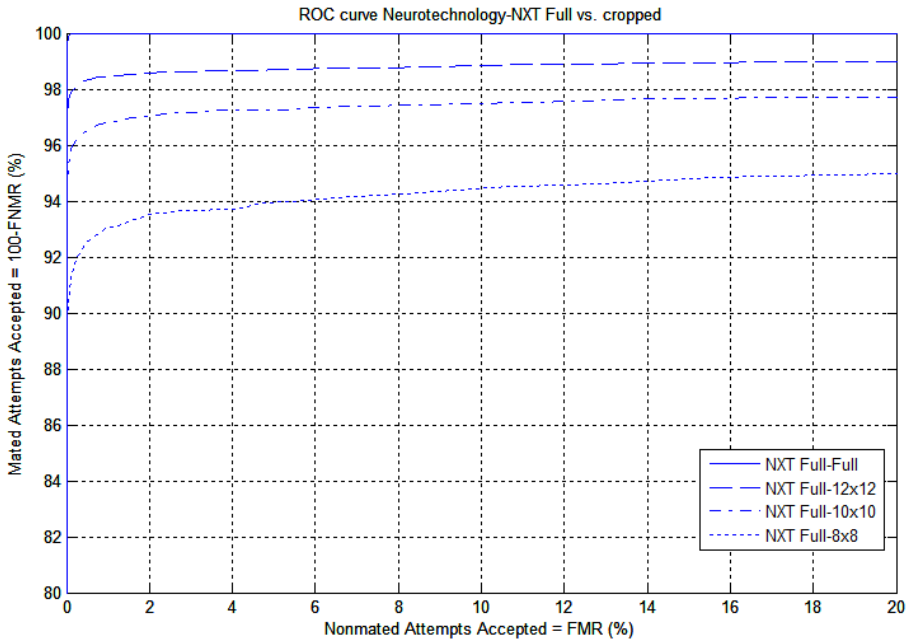


**Figure 43. ROC Curves using Neurotechnology – NXT**

#### 9.3.1.1.5. Additional rates

In addition to previous sections, Table 42 provides relevant error rates for the different sensors.

**Table 42. Additional error rates for Neurotechnology - NXT**

| Error rate | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **EER** | 0.0639 % | 1.47 % | 2.85 % | 5.97 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 1.51 % | 3.15 % | 6.91 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01%* | 2.14 % | 4.17 % | 8.74 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 0.628 % | 3.17 % | 5.89 % | 11.43 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 9.3.1.2. Throughput rates for Neurotechnology - NXT

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the Neurotechnology algorithm and the NXT fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the original database and the 8x8 and 12x12 $mm^2$ cropped databases. Also, it was used for making the comparisons of the original database and the full vs. 12x12 $mm^2$ feature vectors.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2'40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the 10x10 $mm^2$ database and for making the comparisons of the full vs. 10x10 $mm^2$ feature vectors.
- Machine 3: a PC with a processor Intel Core i7-4790 @ 3.60 GHz and a RAM memory of 12GB. This PC has installed Windows 8.1, 2013. This machine was used for making the comparisons of the full vs. 8x8 $mm^2$ feature vectors.

##### 9.3.1.2.1. Enrolment results

Time measurements to obtain biometric references for NXT using Neurotechnology algorithm are the following:

- Arithmetic mean: 2,219 ms
- Standard deviation: ±94.28 ms
- Minimum: 521 ms
- Maximum: 4,452 ms

##### 9.3.1.2.2. Acquisition results

Table 43 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 43. Throughput rates results for acquisition using Neurotechnology - NXT**

| Acquisition | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1,101 ms | 1,449 ms | 1,106 ms | 1,603 ms |
| **Standard deviation** | ± 66.75 ms | ± 516.97 ms | ± 16.60 ms | ± 551.99 ms |
| **Minimum** | 78 ms | 119 ms | 52 ms | 410 ms |
| **Maximum** | 1416 ms | 2,513 ms | 1,220 ms | 2,355 ms |
| **Number of acquisitions** | 46,431 | 39,326 | 30,079 | 11,651 |

#### 9.3.1.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 44 shows measurements obtained for mated comparisons and Table 45 for non-mated comparisons.

**Table 44. Throughput rates results for mated comparisons using Neurotechnology - NXT**

| Mated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.17 ms | 1.41 ms | 1.04 ms | 0.09 ms |
| **Standard deviation** | ± 1.81 ms | ± 0.79 ms | ± 4.13 ms | ± 0.30 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 20 ms | 10 ms | 228 ms | 11 ms |
| **Number of comparisons** | 43,262 | 39,315 | 30,077 | 11,650 |

**Table 45. Throughput rates results for non-mated comparisons using Neurotechnology - NXT**

| Nonmated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.20 ms | 1.20 ms | 0.83 ms | 0.019 ms |
| **Standard deviation** | ± 1.96 ms | ± 0.66 ms | ± 3.65 ms | ± 0.32 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 23,96 ms | 24 ms | 412 ms | 11 ms |
| **Number of comparisons** | 139,680,082 | 126,983,665 | 97,125,093 | 37,621,080 |

### 9.3.2. Performance results for Neurotechnology - FPC

#### 9.3.2.1. Error rates for Neurotechnology - FPC

##### 9.3.2.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.2.1.1). A total 2,903 correct templates have been generated and 631 FTE errors have happened. Therefore, the FTE rate for FPC sensor using Neurotechnology algorithm has been 17.85 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 46.

**Table 46. FTP errors for Neurotechnology - FPC**

| | FPC _12x12 | FPC _10x10 | FPC _8x8 |
|---|---|---|---|
| **Number of correct samples** | 37,017 | 37,017 | 3,7017 |
| **FTP errors** | 0 | 0 | 0 |
| **Total number of acquisition attempts** | 37,017 | 37,017 | 37,017 |
| **FTP rate** | 0 % | 0 % | 0 % |

##### 9.3.2.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 47.

**Table 47. Number of comparisons conducted using Neurotechnology - FPC**

| | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 37,128 | 36,733 | 36,571 | 36,733 |
| **Non-mated comparisons** | 107,742,554 | 107,423,618 | 107,000,449 | 107,423,618 |

#### 9.3.2.1.3. DET curves

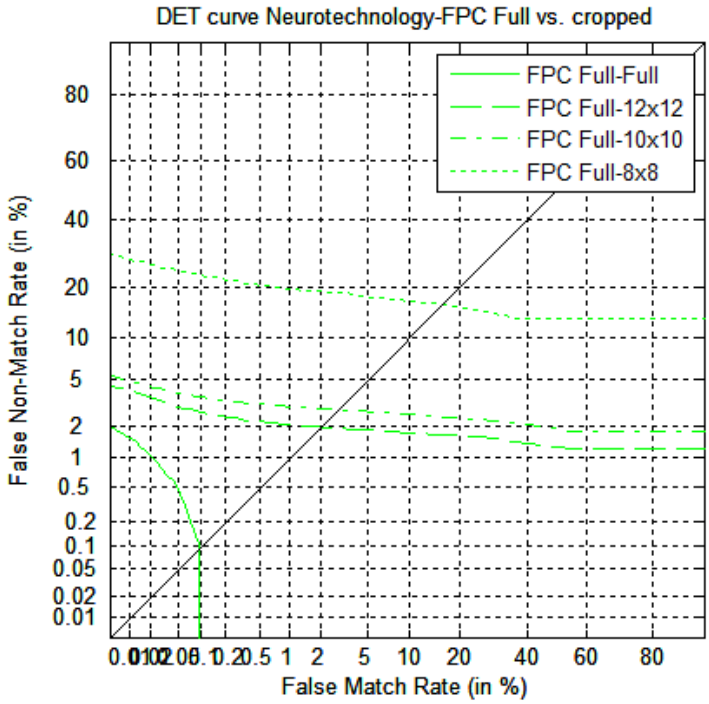


**Figure 44. DET curves for the fingerprint sensors using Neurotechnology – FPC**

#### 9.3.2.1.4. ROC curves

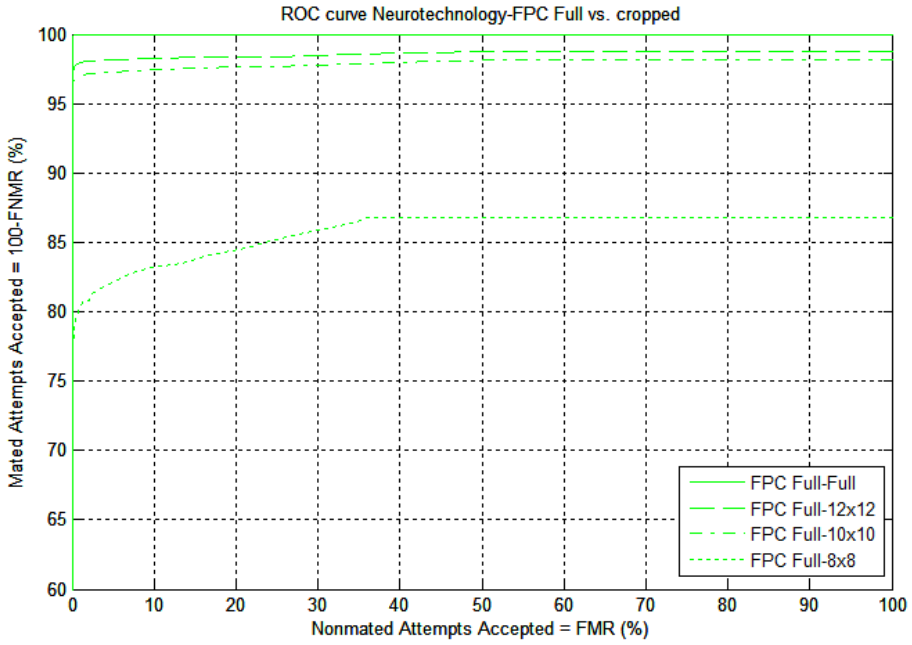


**Figure 45. ROC Curves using Neurotechnology – FPC**

#### 9.3.2.1.5. Additional rates

In addition to previous sections, Table 48 provides relevant error rates for the different sensors.

**Table 48. Additional error rates for Neurotechnology - FPC**

| Error rate | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **EER** | 0.0925 % | 1.96 % | 2.80 % | 16.04 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 2.04 % | 2.97 % | 19.53 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01%* | 2.61 % | 3.53 % | 22.67 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 1.54 % | 3.95 % | 4.75 % | 27.03 % |

### 9.3.2.2. Throughput rates for Neurotechnology - FPC

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the FPC fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2Duo E8500 @ 3.16 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Professional 2009, SP1. This machine was used for extracting the features vectors and for making some comparisons of the original database.
- Machine 2: a laptop with a processor Intel core i7-3517U @ 1.9 GHz and a RAM memory of 4 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for making the rest of comparisons of the original database.

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* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

- Machine 3: a laptop with a processor Intel Core i7-5500U @ 2'40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the all cropped databases and for making comparisons of the full vs. 8x8 $mm^2$ and the full vs. 10x10 $mm^2$ feature vectors.
- Machine 4: a PC with a processor Intel Core i7-4790 @ 3.60 GHz and a RAM memory of 12 GB. This PC has installed Windows 8.1, 2013. This machine was used for making the comparisons of the full vs. 12x12 $mm^2$ feature vectors.

#### 9.3.2.2.1. Enrolment results

Time measurements to obtain biometric references for FPC using Neurotechnology algorithm are the following:

- Arithmetic mean: 2,200 ms
- Standard deviation: ±136.25 ms
- Minimum: 230 ms
- Maximum: 4,463 ms

#### 9.3.2.2.2. Acquisition results

Table 49 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 49. Throughput rates results for acquisition using Neurotechnology - FPC**

| Acquisition | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1,043 ms | 3,325 ms | 3,325 ms | 3,274 ms |
| **Standard deviation** | ± 36.12 ms | ± 13.29 ms | ± 39.61 ms | ± 334.6 ms |
| **Minimum** | 239 ms | 3,202 ms | 2,194 ms | 1,080 ms |
| **Maximum** | 1,187 ms | 3,410 ms | 3,394 ms | 3,395 ms |
| **Number of acquisitions** | 43,168 | 37,017 | 370,17 | 37,017 |

#### 9.3.2.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 50 shows measurements obtained for mated comparisons and Table 51 for non-mated comparisons.

**Table 50. Throughput rates results for mated comparisons using Neurotechnology - FPC**

| Mated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1.07 ms | 0.14 ms | 0.85 ms | 0.25 ms |
| **Standard deviation** | ± 1.157 ms | ±1.147 ms | ± 0.73 ms | ± 4.08 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 32 ms | 210 ms | 39 ms | 294 ms |
| **Number of comparisons** | 37,128 | 36,733 | 36,571 | 36,733 |

**Table 51. Throughput rates results for Non-mated comparisons using Neurotechnology - FPC**

| Nonmated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 0.86 ms | 0.036 ms | 0.73 ms | 0.19 ms |
| **Standard deviation** | ± 0.55 ms | ± 0.55 ms | ± 0.80 ms | ± 4.61 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 70 ms | 1,142 ms | 869 ms | 1,429 ms |
| **Number of comparisons** | 107,742,554 | 107,423,618 | 107,000,449 | 107,423,618 |

#### 9.3.3. Performance results for Neurotechnology - UPK

##### 9.3.3.1. Error rates for Neurotechnology - UPK

###### 9.3.3.1.1. Enrolment and acquisition results

For enrolment, results are similar to those obtained for the original database (See section 6.2.1.1). A total 3,131 correct templates have been generated and 403 FTE errors have happened. Therefore, the FTE rate for UPK sensor using Neurotechnology algorithm has been 11.40 %.

FTP errors that have happened correspond to those errors to generate the features vector from the cropped images. These error are given in Table 52.

**Table 52. FTP errors for Neurotechnology – UPK**

| | UPK _12x12 | UPK _10x10 | UPK _8x8 |
|---|---|---|---|
| **Number of correct samples** | 33,861 | 36,211 | 11,537 |
| **FTP errors** | 2,350 | 0 | 24,674 |
| **Total number of acquisition attempts** | 36,211 | 36,211 | 36,211 |
| **FTP rate** | 6.49 % | 0.00 % | 68.14 % |

###### 9.3.3.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 53.

**Table 53. Number of comparisons conducted using Neurotechnology - UPK**

| | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 40,032 | 31,828 | 34,023 | 10,772 |
| **Non-mated comparisons** | 125,118,621 | 105,986,963 | 113,687,507 | 36,111,575 |

#### 9.3.3.1.3. DET curves

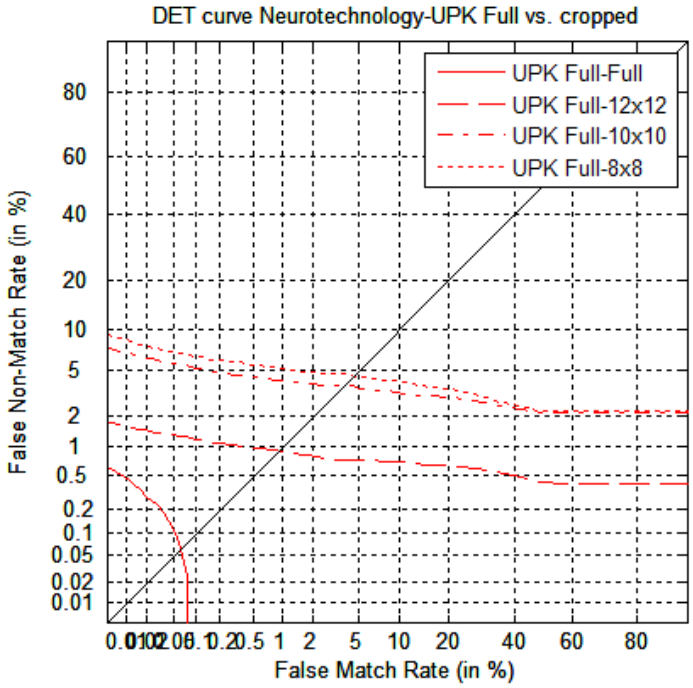


**Figure 46. DET curves for the fingerprint sensors using Neurotechnology – UPK**

#### 9.3.3.1.4. ROC curves

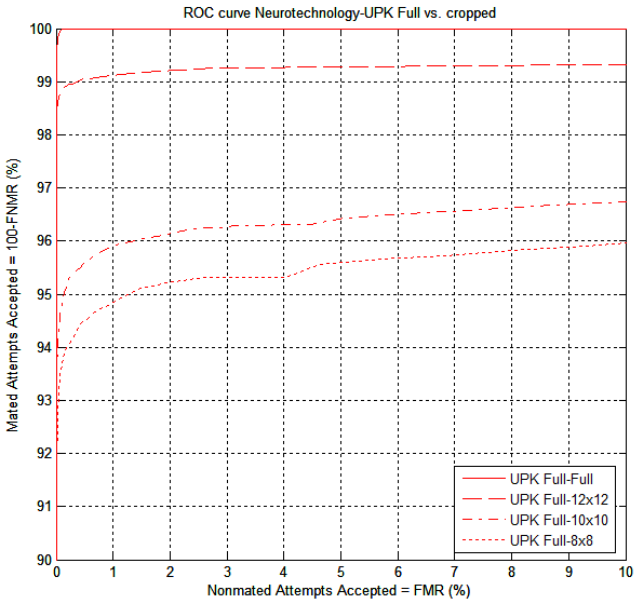


**Figure 47. ROC Curves using Neurotechnology – UPK**

#### 9.3.3.1.5. Additional rates

In addition to previous sections, Table 54 provides relevant error rates for the different sensors.

**Table 54. Additional error rates for Neurotechnology - UPK**

| Error rate | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **EER** | 0.0616% | 0.90 % | 3.70 % | 4.48 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 0.86 % | 4.06 % | 5.106 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01%* | 1.16 % | 5.09 % | 6.32 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 0.42 % | 1.58 % | 6.72 % | 8.31 % |

### 9.3.3.2. Throughput rates for Neurotechnology - UPK

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the UPK fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2Duo E6750@ 2.66 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Ultimate, 2009. This machine was used for extracting the feature vectors and making comparisons of the original database. Also, it was used extracting the feature vectors of the 8x8 $mm^2$ database and for making comparisons of the full vs. 8x8 $mm^2$ and some of the full vs. 10x10 $mm^2$ feature vectors.
- Machine 2: a PC with a processor Intel Core i7-4790 @ 3.60 GHz and a RAM memory of 12 GB. This PC has installed Windows 8.1, 2013. This machine was used for extracting the feature vectors of the 10x10 $mm^2$ and 12x12 $mm^2$ cropped databases and for making comparisons of the full vs. 12x2 $mm^2$ feature vectors.

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* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

- Machine 3: a laptop with a processor Intel core i7-3517U @ 1.9 GHz and a RAM memory of 4 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for making the rest of comparisons of the full vs. 10x10 $mm^2$ feature vectors.

#### 9.3.3.2.1. Enrolment results

Time measurements to obtain biometric references for UPK using Neurotechnology algorithm are the following:

- Arithmetic mean: 2,215 ms
- Standard deviation: ± 56.04 ms
- Minimum: 778 ms
- Maximum: 3,340 ms

#### 9.3.3.2.2. Acquisition results

Table 55 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 55. Throughput rates results for acquisition using Neurotechnology - UPK**

| Acquisition | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1,090 ms | 1,105 ms | 1,106 ms | 1,102 ms |
| **Standard deviation** | ± 84.04 ms | ± 13.01 ms | ± 9.76 ms | ± 26.37 ms |
| **Minimum** | 165 ms | 885 ms | 615 ms | 60 ms |
| **Maximum** | 1,530 ms | 1,153 ms | 1,143 ms | 1,261 ms |
| **Number of acquisitions** | 44,531 | 33,861 | 36,211 | 11,537 |

#### 9.3.3.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 56 shows measurements obtained for mated comparisons and Table 57 for non-mated comparisons.

**Table 56. Throughput rates results for mated comparisons using Neurotechnology - UPK**

| Mated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.00 ms | 0.36 ms | 0.87 ms | 0.89 ms |
| **Standard deviation** | ± 1.65 ms | ± 0.5 ms | ± 1.52 ms | ± 0.527 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 95 ms | 17 ms | 198 ms | 26 ms |
| **Number of comparisons** | 125,118,621 | 31,828 | 34,023 | 10,772 |

**Table 57. Throughput rates results for non-mated comparisons using Neurotechnology - UPK**

| Nonmated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.00 ms | 0.19 ms | 0.73 ms | 0.59 ms |
| **Standard deviation** | ± 1.65 ms | ± 0.39 ms | ± 1.51 ms | ± 0.72 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 95 ms | 28 ms | 2526 ms | 785 ms |
| **Number of comparisons** | 125,118,621 | 105,986,963 | 113,687,507 | 36,111,575 |

# PART II-B

# PERFORMANCE ANALISIS REPORT

## CROPPED SIZES IMAGES vs. CROPPED SIZES IMAGES

# 10. PERFORMANCE ANALYSIS CROPPED VS. CROPPED IMAGES

## 10.1. INTRODUCTION

This section explains performance analysis results considering the different algorithms: NBIS and Neurotechnology. In particular, error rates and throughput rates will be shown.

Regarding error rates, these metrics are given separately for enrolment (FTE error) and acquisition process (FTA error) and then, for the comparison process. For the comparison process the following curves will be shown:

- ROC curves for the three fingerprint sensors
- DET curves for the three fingerprint sensors
- Additional rates: EER, FMR100, FMR1000,FMR10000

In addition, the following curves will be provided in the annexes:

- Distribution curves per each fingerprint sensor
- FNMR vs. FMR curves per each fingerprint sensor

In relation to throughput rates, the metrics that have been obtained have been the following:

- Enrolment time, which has been calculated considering the time that takes to obtain the biometric references.
- Acquisition time, which has been calculated considering the time that takes to obtain the biometric probes.
- Mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference of the same user, same finger.
- Non-mated comparison time, which is the time that takes to compare a biometric probe to the biometric reference that do not belong of the same user.

As in the case of the full-size vs. cropped comparisons, an important issue to consider is that the quality check and ground truth mechanism was applied in the full size database, and those images not concealing with those requirements have been discarded for the cropped images analysis. In other terms, this means that the ground truth mechanism is not applied again during this tests, and therefore, the FTA cases detected are additional to the ones of the full-size case. In order not to confuse the reader, we will consider Failure to Process (FTP) rates, instead of the FTA rates, knowing that the number of cases in a real scenario should be the sum of both the FTA and FTP cases.

## 10.2. PERFORMANCE RESULTS FOR NBIS

### 10.2.1. Performance results for NBIS - NXT

#### 10.2.1.1. Error rates for NBIS – NXT

##### 10.2.1.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 58 and Table 59. In this case, the algorithm applied for enrolling and acquiring the samples has been NBIS.

**Table 58. FTE errors for NBIS - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 3,217 | 2,558 | 914 | 62 |
| **FTE errors** | 317 | 976 | 2,620 | 3,472 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 8.97 % | 27.61 % | 74.13 % | 98.24 % |

**Table 59. FTP errors for NBIS - NXT**

| | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|
| **Number of correct samples** | 27,073 | 9,714 | 655 |
| **FTP errors** | 0 | 1 | 13 |
| **Total number of acquisition attempts** | 27,073 | 9,715 | 668 |
| **FTP rate** | 0.00 % | 0.01 % | 1.94 % |

#### 10.2.1.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 60.

**Table 60. Number of comparisons conducted using NBIS - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 34,251 | 27,073 | 9,714 | 655 |
| **Non-mated comparisons** | 110,151,216 | 69,225,661 | 8,868,882 | 39,955 |

#### 10.2.1.1.3. DET curves

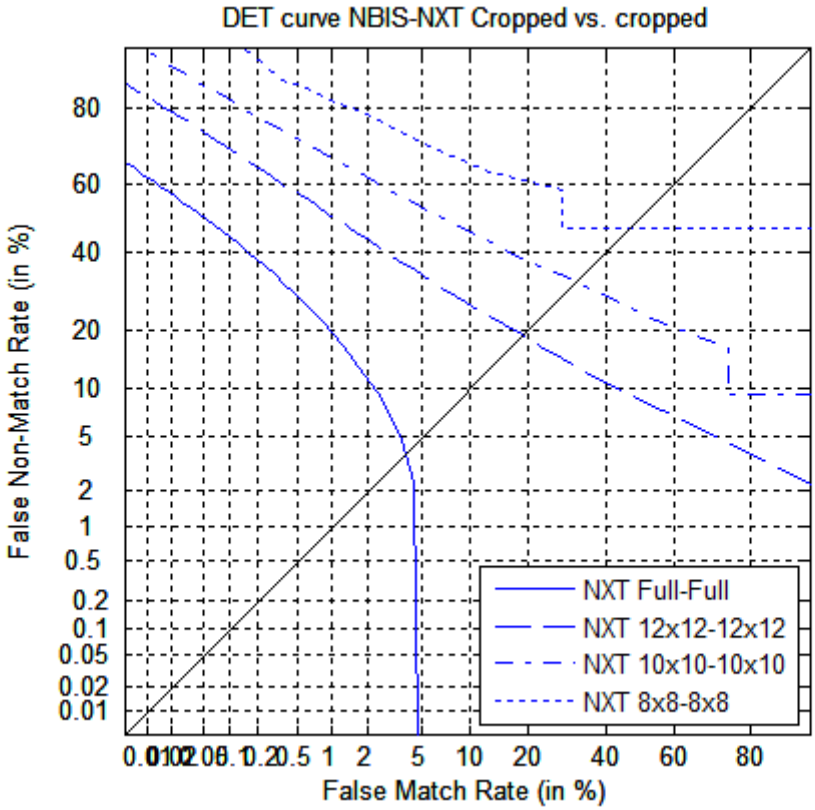


**Figure 48. DET curves for the fingerprint sensors using NBIS – NXT**

#### 10.2.1.1.4. ROC curves

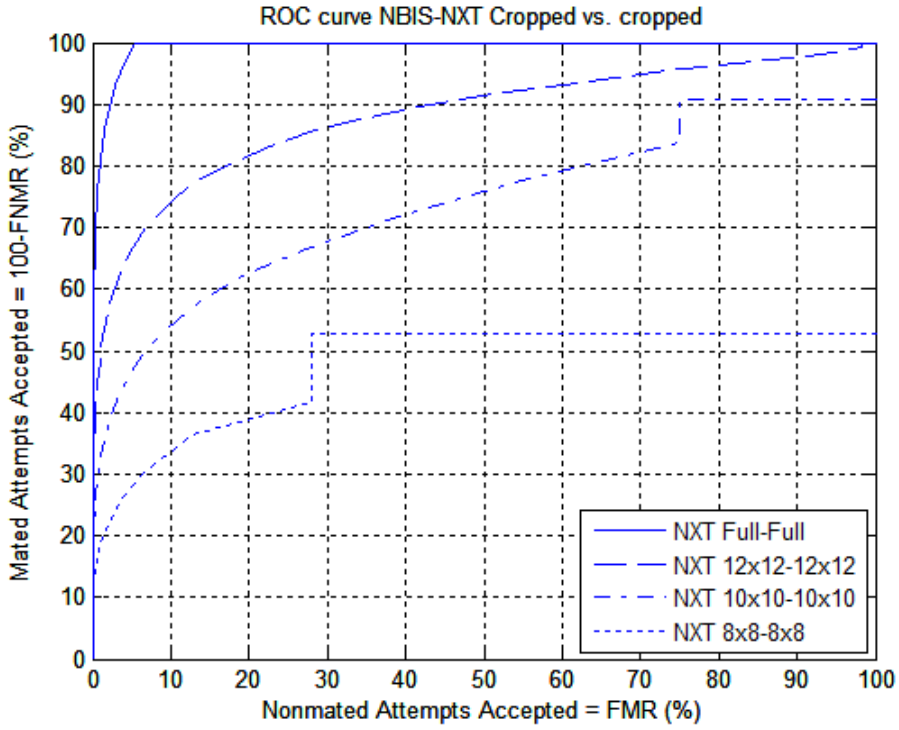


**Figure 49. ROC Curves using NBIS – NXT**

#### 10.2.1.1.5. Additional rates

In addition to previous sections, Table 61 provides relevant error rates for the different sensors.

**Table 61. Additional error rates for NBIS - NXT**

| Error rate | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **EER** | 3.88 % | 18.89 % | 31.62 % | 47.17 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | 19.21 % | 49.60 % | 67.10 % | 81.22 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 43.99 | 69.48 % | 80.57 % | 90.07 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 62.01 % | 81.87 % | 89.20 % | 96.33 % |

#### 10.2.1.2. Throughput rates for NBIS - NXT

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the NXT fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors and for making comparisons of the original database.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2.40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors and for making comparisons of the cropped databases.

##### 10.2.1.2.1. Enrolment results

Table 62 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 62. Throughput rates results for enrolment using NBIS - NXT**

| Enrolment | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 169.60 ms | 163.85 ms | 85.29 ms | 47.74 ms |
| **Standard deviation** | ± 99.41 ms | ± 80.08 ms | ± 35.38 ms | ± 9.78 ms |
| **Minimum** | 69 ms | 63 ms | 46 ms | 32 ms |
| **Maximum** | 1,594 ms | 830 ms | 437 ms | 72 ms |
| **Number of enrolments** | 3,217 | 2,558 | 914 | 62 |

#### 10.2.1.2.2. Acquisition results

Table 63 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 63. Throughput rates results for acquisition using NBIS - NXT**

| Acquisition | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 48.18 ms | 37.48 ms | 32.03 ms | 19.72 ms |
| **Standard deviation** | ± 9.65 ms | ± 9.16 ms | ± 8.11 ms | ± 5.11 ms |
| **Minimum** | 12 ms | 14 ms | 10 ms | 6 ms |
| **Maximum** | 322 ms | 79 ms | 68 ms | 45 ms |
| **Number of acquisitions** | 47,729 | 33,494 | 33,507 | 33,495 |

#### 10.2.1.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 64shows measurements obtained for mated comparisons and Table 65

**Table** 65 for non-mated comparisons.

**Table 64. Throughput rates results for mated comparisons using NBIS - NXT**

| Mated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 33.67 ms | 21.56 ms | 3.27 ms | 0.126 ms |
| **Standard deviation** | ± 48.15 ms | ± 40.12 ms | ± 13.36 ms | ± 1.26 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 801 ms | 997 ms | 199 ms | 28 ms |
| **Number of comparisons** | 34,251 | 27,073 | 9,714 | 655 |

**Table 65. Throughput rates results for non-mated comparisons using NBIS - NXT**

| Nonmated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.92 ms | 2.97 ms | 0.30 ms | 0.004 ms |
| **Standard deviation** | ± 9.11 ms | ± 10.35 ms | ± 2.93 ms | ± 0.11 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,213 ms | 2,274 ms | 469 ms | 28 ms |
| **Number of comparisons** | 110,151,216 | 69,225,661 | 8,868,882 | 39,955 |

### 10.2.2. Performance results for NBIS - FPC

#### 10.2.2.1. Error rates for NBIS - FPC

##### 10.2.2.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 66 and Table 67. These errors may happen due to the enrolment and capturing processes have not been successfully completed. In this case, the algorithm applied for enrolling and acquiring the samples has been NBIS.

**Table 66. FTE errors for NBIS - FPC**

| | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 2,826 | 1,119 | 11,79 | 191 |
| **FTE errors** | 708 | 2,415 | 2,355 | 3,343 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 20.03 % | 68.33 % | 66.64 % | 94.59 % |

**Table 67. FTP errors for NBIS - FPC**

| | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|
| **Number of correct samples** | 22,408 | 11,397 | 1,940 |
| **FTP errors** | 0 | 0 | 1 |
| **Total number of acquisition attempts** | 22,408 | 11,397 | 1,941 |
| **FTP rate** | 0.00 % | 0.00 % | 0.051 % |

#### 10.2.2.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 68.

**Table 68. Number of comparisons conducted using NBIS - FPC**

| | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 26,333 | 22,408 | 11,397 | 1,940 |
| **Non-mated comparisons** | 74,390,725 | 54,092,912 | 13,425,666 | 368,600 |

#### 10.2.2.1.3. DET curves

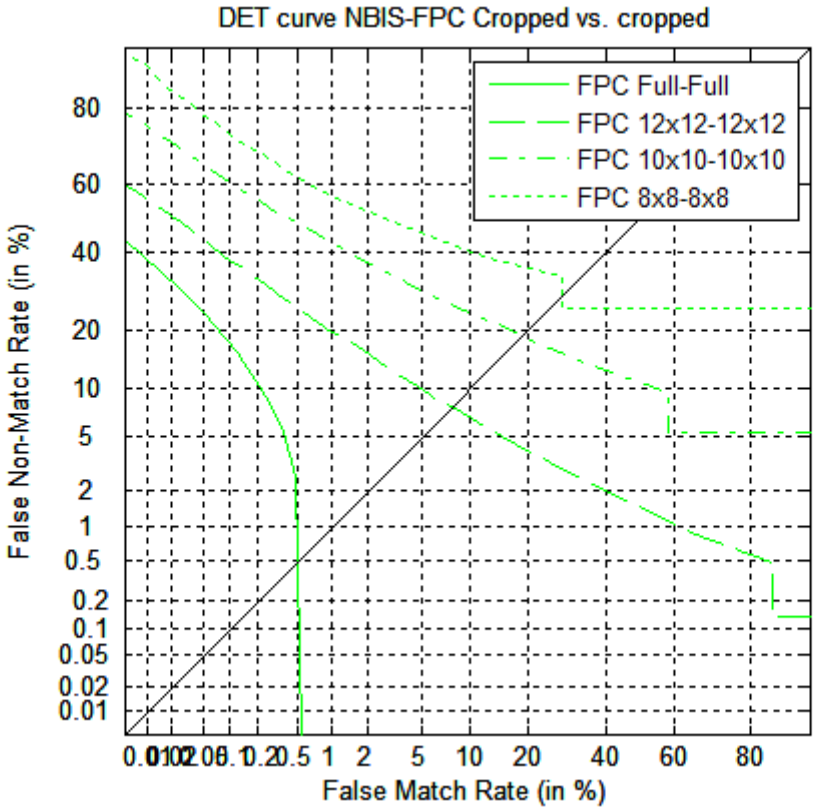


**Figure 50. DET curves for the fingerprint sensors using NBIS – FPC**

#### 10.2.2.1.4. ROC curves

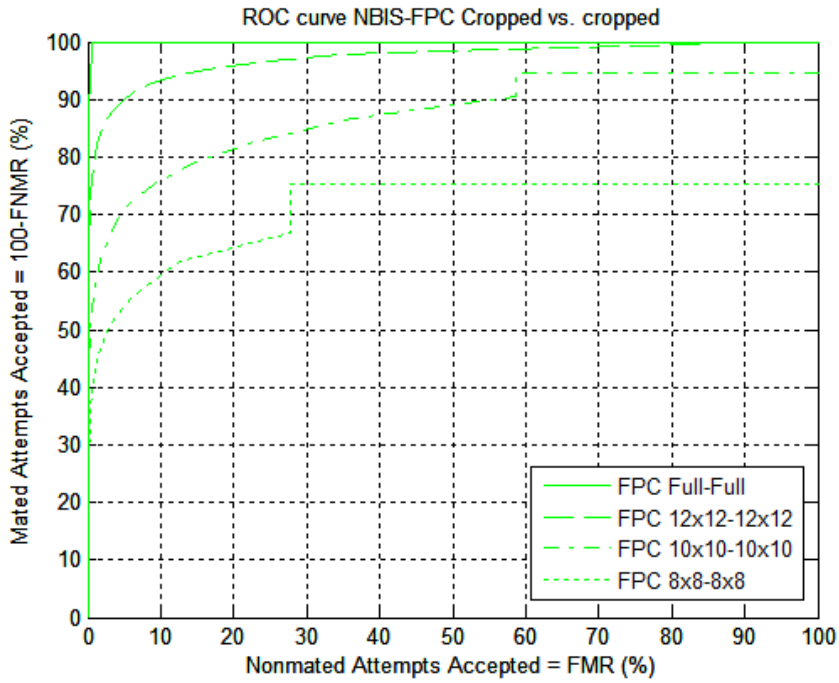


**Figure 51. ROC Curves using NBIS – FPC**

#### 10.2.2.1.5. Additional rates

In addition to previous sections, Table 69 provides relevant error rates for the different sensors.

**Table 69. Additional error rates for NBIS - FPC**

| Error rate | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **EER** | 0.60 % | 7.79 % | 19.02 % | 27.82 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 19.70 % | 40.95 % | 53.35 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 15.62 % | 37.38 % | 59.53 % | 70.92 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 37.67 % | 54.19 % | 75.18 % | 87.47 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 10.2.2.2. Throughput rates for NBIS - FPC

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the FPC fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2 Duo E8500 @ 3.16 GHz and a RAM memory of 4GB. This PC has installed Windows 7 Professional 2009, SP1. This machine was used for extracting the feature vectors and for making comparisons of the original database.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2.40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors and for making comparisons of the cropped databases.

##### 10.2.2.2.1. Enrolment results

Table 70 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 70. Throughput rates results for enrolment using NBIS - FPC**

| Enrolment | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 149.83 ms | 113.17 ms | 91.31 ms | 62.75 ms |
| **Standard deviation** | ± 53.84 ms | ± 42.84 ms | ± 25.40 ms | ± 11.55 ms |
| **Minimum** | 98 ms | 63 ms | 51 ms | 41 ms |
| **Maximum** | 584 ms | 546 ms | 384 ms | 126 ms |
| **Number of enrolments** | 2,826 | 2,415 | 1,179 | 191 |

#### 10.2.2.2.2. Acquisition results

The following table shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 71. Throughput rates results for acquisition using NBIS - FPC**

| Acquisition | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 52.73 ms | 43.88 ms | 38.92 ms | 29.07 ms |
| **Standard deviation** | ± 5.08 ms | ± 6.78 ms | ± 6.26 ms | ± 3.82 ms |
| **Minimum** | 26 ms | 29 ms | 22 ms | 16 ms |
| **Maximum** | 96 ms | 71 ms | 62 ms | 49 ms |
| **Number of acquisitions** | 44,119 | 25,512 | 22,512 | 22,511 |

#### 10.2.2.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 72 shows measurements obtained for mated comparisons and Table 73 for non-mated comparisons.

**Table 72. Throughput rates results for mated comparisons using NBIS - FPC**

| Mated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 11.69 ms | 7.01 ms | 1.93 ms | 0.21 ms |
| **Standard deviation** | ± 26.31 ms | ± 20.51 ms | ± 9.88 ms | ± 1.72 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 412 ms | 373 ms | 330 ms | 35 ms |
| **Number of comparisons** | 26,333 | 22,408 | 11,397 | 1,940 |

**Table 73. Throughput rates results for non-mated comparisons using NBIS - FPC**

| Nonmated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 0.48 ms | 0.29 ms | 0.56 ms | 0.002 ms |
| **Standard deviation** | ± 3.17 ms | ± 2.43 ms | ± 0.97 ms | ± 0.13 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 522 ms | 582 ms | 430 ms | 29 ms |
| **Number of comparisons** | 74,390,725 | 54,092,912 | 13,425,666 | 368,600 |

### 10.2.3. Performance results for NBIS - UPK

#### 10.2.3.1. Error rates for NBIS - UPK

##### 10.2.3.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 74 and Table 75. In this case, the algorithm applied for enrolling and acquiring the samples has been NBIS.

**Table 74. FTE errors for NBIS - UPK**

| | UPK | UPK _12x12 | UPK _10x10 | UPK _8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 3,116 | 2334 | 852 | 56 |
| **FTE errors** | 418 | 1200 | 2,682 | 3,478 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 11.82 % | 33.95 % | 75.89 % | 98.41 % |

**Table 75. FTP errors for NBIS – UPK**

| | UPK _12x12 | UPK _10x10 | UPK _8x8 |
|---|---|---|---|
| **Number of correct samples** | 25,616 | 9,470 | 632 |
| **FTP errors** | 0 | 2 | 31 |
| **Total number of acquisition attempts** | 25,616 | 9,472 | 663 |
| **FTP rate** | 0.00 % | 0.02 % | 4.67 % |

#### 10.2.3.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 76.

**Table 76. Number of comparisons conducted using NBIS - UPK**

| | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 34,012 | 25,616 | 9,470 | 632 |
| **Non-mated comparisons** | 105,947,381 | 59,762,128 | 8,058,970 | 34,760 |

#### 10.2.3.1.3. DET curves

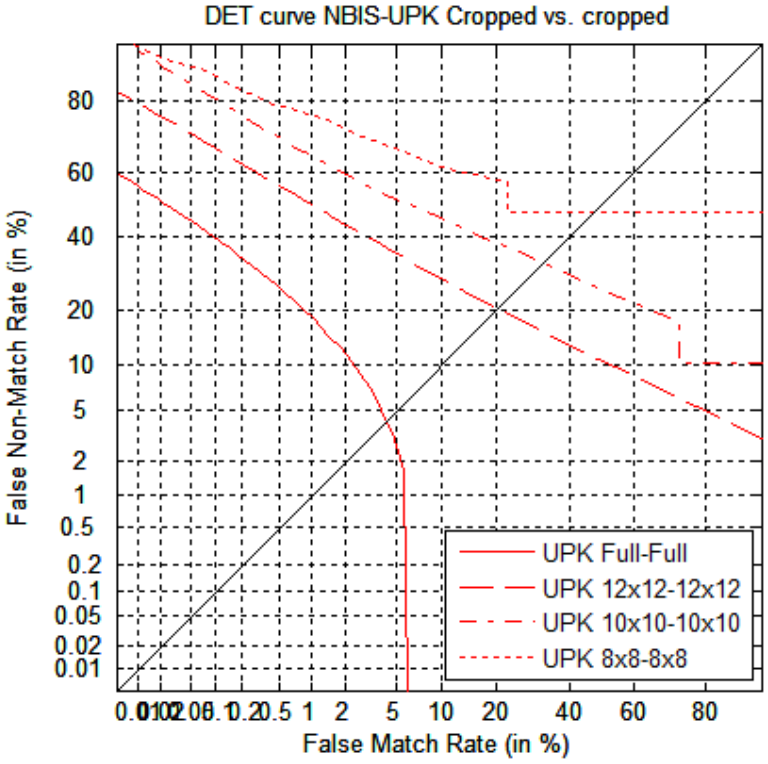


**Figure 52. DET curves for the fingerprint sensors using NBIS – UPK**

#### 10.2.3.1.4. ROC curves

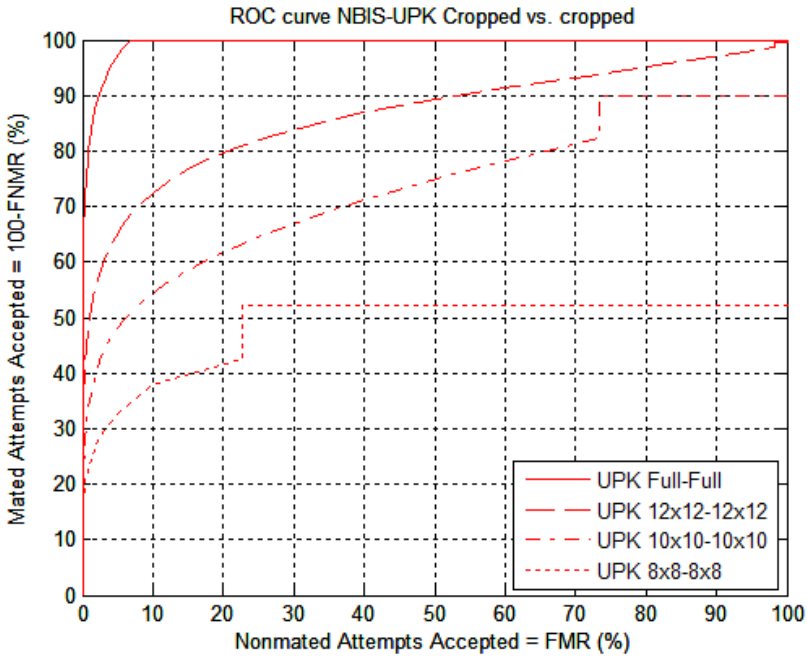


**Figure 53. ROC Curves using NBIS – UPK**

#### 10.2.3.1.5. Additional rates

In addition to previous sections, Table 77 provides relevant error rates for the different sensors.

**Table 77. Additional error rates for NBIS - UPK**

| Error rate | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **EER** | 4.26 % | 20.23 % | 32.16 % | 47.94 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | 18.24 % | 50 % | 64.66 % | 75.15 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | 38.09 % | 66.41 % | 80.11 % | 84.65 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 55.88 % | 78.81 % | 89.08 % | 89.08 % |

#### 10.2.3.2. Throughput rates for NBIS - UPK

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the UPK fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2Duo E6750 @ 2.67 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Ultimate 2009, SP1. This machine was used for extracting the feature vectors and making comparisons of the original database.
- Machine 2: a PC with a processor Intel Core 2Duo E6750 @ 2.67 GHz and a RAM memory of 4 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors and for making the comparisons of the cropped databases.

##### 10.2.3.2.1. Enrolment results

Table 78 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 78. Throughput rates results for enrolment using NBIS - UPK**

| Enrolment | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 320.32 ms | 349.13 ms | 161.84 ms | 78.07 ms |
| **Standard deviation** | ± 135.64 ms | ± 510.80 ms | ± 59.72 ms | ± 14.14 ms |
| **Minimum** | 160 ms | 121 ms | 100 ms | 67 ms |
| **Maximum** | 2,770 ms | 16,870 ms | 752 ms | 153 ms |
| **Number of enrolments** | 3,116 | 2,334 | 852 | 56 |

#### 10.2.3.2.2. Acquisition results

Table 79 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 79. Throughput rates results for acquisition using NBIS - UPK**

| Acquisition | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 184.24 ms | 103.08 ms | 86.77 ms | 32.61 ms |
| **Standard deviation** | ± 96.02 ms | ± 100.22 ms | ± 133.44 ms | ± 2.16 ms |
| **Minimum** | 92 ms | 41 ms | 27 ms | 12 ms |
| **Maximum** | 1,262 ms | 9,990 ms | 12,732 ms | 66 ms |
| **Number of acquisitions** | 43,340 | 36,211 | 36,209 | 36,180 |

#### 10.2.3.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 80 shows measurements obtained for mated comparisons and Table 81 for non-mated comparisons.

**Table 80. Throughput rates results for mated comparisons using NBIS - UPK**

| Mated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 31.68 ms | 22.17 ms | 3.41 ms | 0.106 ms |
| **Standard deviation** | ± 48.87 ms | ± 45.37 ms | ± 17.03 ms | ± 1.198 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,182 ms | 782 ms | 654 ms | 26 ms |
| **Number of comparisons** | 34,012 | 25,616 | 9,470 | 632 |

**Table 81. Throughput rates results for non-mated comparisons using NBIS - UPK**

| Nonmated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 3.97 ms | 3.67 ms | 0.44 ms | 0.004 ms |
| **Standard deviation** | ± 11.4 ms | ± 13.07 ms | ± 5.25 ms | ± 0.14 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 1,256 ms | 4,720 ms | 4,750 ms | 26 ms |
| **Number of comparisons** | 105,947,381 | 59,762,128 | 8,058,970 | 34,760 |

## 10.3. PERFORMANCE RESULTS FOR NEUROTECHNOLOGY

### 10.3.1. Performance results for Neurotechnology - NXT

#### 10.3.1.1. Error rates for Neurotechnology – NXT

##### 10.3.1.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 82 and Table 83. In this case, the algorithm applied for enrolling and acquiring the samples has been Neurotechnology.

**Table 82. FTE errors for Neurotechnology - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 3,230 | 2,906 | 1,892 | 425 |
| **FTE errors** | 304 | 628 | 1642 | 3109 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 8.60 % | 17.77 % | 46.46 % | 87.97 % |

**Table 83. FTP errors for Neurotechnology - NXT**

| | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|
| **Number of correct samples** | 36,097 | 19,837 | 2,653 |
| **FTP errors** | 4,303 | 13,550 | 31,978 |
| **Total number of acquisition attempts** | 40,400 | 33,387 | 34,631 |
| **FTP rate** | 10.65 % | 40.58 % | 92.34 % |

#### 10.3.1.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 84.

**Table 84. Number of comparisons conducted using Neurotechnology - NXT**

| | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 43,262 | 36,097 | 19,837 | 2,653 |
| **Non-mated comparisons** | 139,680,082 | 104,861,785 | 37,511,767 | 1,124,872 |

#### 10.3.1.1.3. DET curves

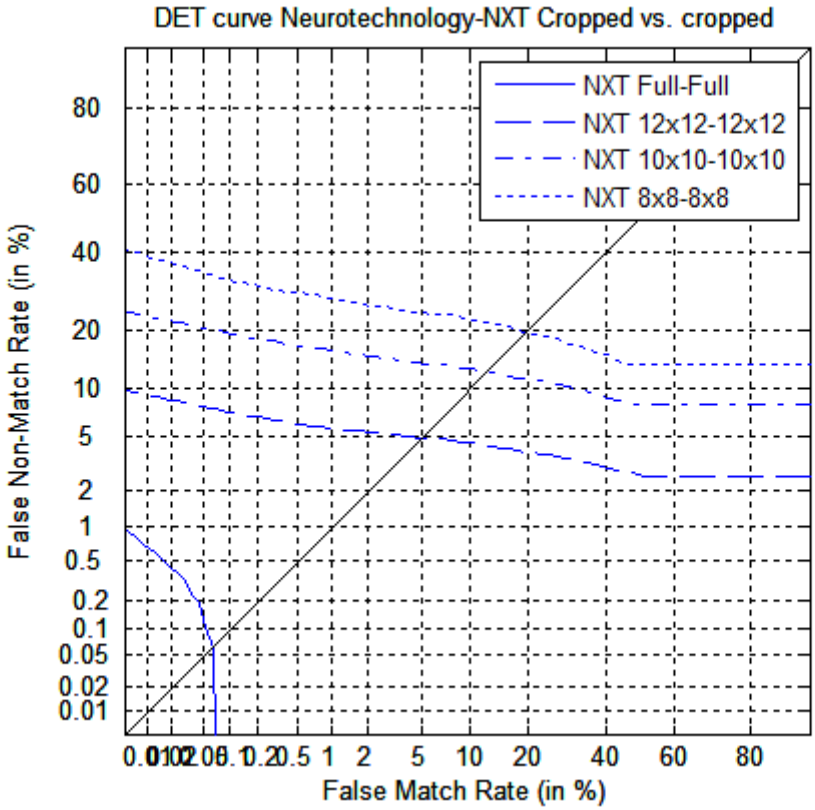


**Figure 54. DET curves for the fingerprint sensors using Neurotechnology - NXT**

#### 10.3.1.1.4. ROC curves

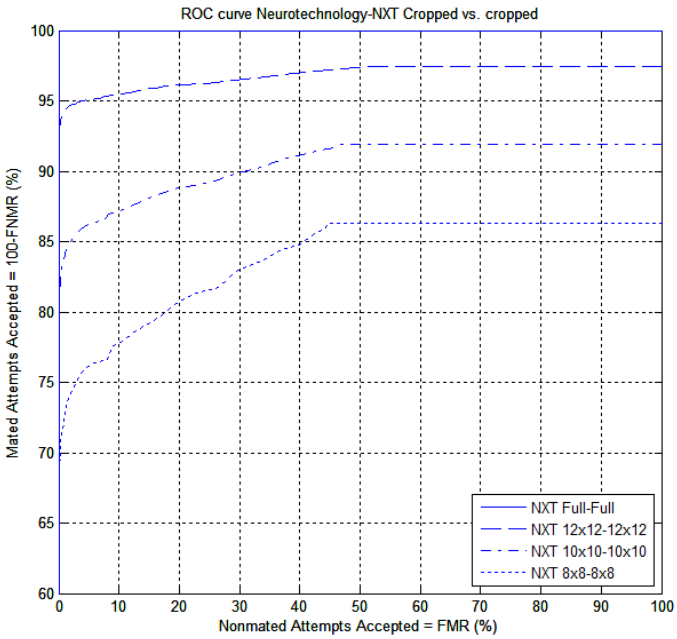


**Figure 55. ROC Curves using Neurotechnology – NXT**

#### 10.3.1.1.5. Additional rates

In addition to previous sections, Table 85 provides relevant error rates for the different sensors.

**Table 85. Additional error rates for Neurotechnology - NXT**

| Error rate | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **EER** | 0.0639 % | 4.89 % | 12.43 % | 19.42 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 5.63 % | 15.75 % | 27.25 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01%* | 7.09 % | 19.23 % | 32.07 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 0.628 % | 9.04 % | 22.99 % | 38.44 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 10.3.1.2. Throughput rates for Neurotechnology - NXT

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the Neurotechnology algorithm and the NXT fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a laptop with a processor Intel core i7-3517U @ 1.9 GHz (up to 2.4 GHz) and a RAM memory of 4GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the original database the 8x8 and 12x12 $mm^2$ databases. Also, it was used for making the comparisons of the original database and the 12x12 vs. 12x12 $mm^2$ feature vectors.
- Machine 2: a laptop with a processor Intel Core i7-5500U @ 2'40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors of the 10x10 $mm^2$ database and for making the comparisons of the 10x10 vs. 10x10 $mm^2$ feature vectors.
- Machine 3: a PC with a processor Intel Core i7-4790 @ 3.60 GHz and a RAM memory of 12 GB. This PC has installed Windows 8.1, 2013. This machine was used for making the comparisons of the 8x8 vs. 8x8 $mm^2$ feature vectors.

##### 10.3.1.2.1. Enrolment results

Table 86 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 86. Throughput rates results for enrolment using Neurotechnology - NXT**

| Enrolment | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2,219 ms | 4,461 ms | 2,235 ms | 2,236 ms |
| **Standard deviation** | ± 1101 ms | ± 249.85 ms | ± 172.60 ms | ± 170.56 ms |
| **Minimum** | 521 ms | 4197 ms | 208 ms | 1,058 ms |
| **Maximum** | 4,452 ms | 9,029 ms | 4,452 ms | 4,435 ms |
| **Number of enrolments** | 3,230 | 2,906 | 1,892 | 425 |

#### 10.3.1.2.2. Acquisition results

Table 87 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 87. Throughput rates results for acquisition using Neurotechnology - NXT**

| Acquisition | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1,101 ms | 1,449 ms | 1,106 ms | 1,603 ms |
| **Standard deviation** | ± 66.75 ms | ± 516.97 ms | ± 16.60 ms | ± 551.99 ms |
| **Minimum** | 78 ms | 119 ms | 52 ms | 410 ms |
| **Maximum** | 1,416 ms | 2,513 ms | 1,220 ms | 2,355 ms |
| **Number of acquisitions** | 46,431 | 39,32 | 30,079 | 11,651 |

#### 10.3.1.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 88 shows measurements obtained for mated comparisons and Table 89 for non-mated comparisons.

**Table 88. Throughput rates results for mated comparisons using Neurotechnology - NXT**

| Mated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.17 ms | 0.99 ms | 0.29 ms | 0.0007 ms |
| **Standard deviation** | ± 1.81 ms | ± 0.52 ms | ± 0.48 ms | ± 0.027 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 20 ms | 5 ms | 14 ms | 1 ms |
| **Number of comparisons** | 43,262 | 36,097 | 19,837 | 2,653 |

**Table 89. Throughput rates results for non-mated comparisons using Neurotechnology - NXT**

| Nonmated comparisons | NXT | NXT_12x12 | NXT_10x10 | NXT_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.20 ms | 0.84 ms | 0.18 ms | 0.001 ms |
| **Standard deviation** | ± 1.96 ms | ± 0.46 ms | ± 0.73 ms | ± 0.04 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 2,396 ms | 17 ms | 1157 ms | 9 ms |
| **Number of comparisons** | 139,680,082 | 104,861,785 | 37,511,767 | 1,124,872 |

#### 10.3.2. Performance results for Neurotechnology - FPC

##### 10.3.2.1. Error rates for Neurotechnology - FPC

###### 10.3.2.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 90 and Table 91. In this case, the algorithm applied for enrolling and acquiring the samples has been Neurotechnology.

**Table 90. FTE errors for Neurotechnology - FPC**

| | FPC | FPC _12x12 | FPC _10x10 | FPC _8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 2,903 | 2,911 | 2,735 | 1,251 |
| **FTE errors** | 631 | 623 | 799 | 1,089 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 17.85 % | 17.63 % | 22.61 % | 30.81 % |

**Table 91. FTP errors for Neurotechnology - FPC**

| | FPC _12x12 | FPC _10x10 | FPC _8x8 |
|---|---|---|---|
| **Number of correct samples** | 36,529 | 34,696 | 15,903 |
| **FTP errors** | 0 | 0 | 0 |
| **Total number of acquisition attempts** | 36,529 | 34,696 | 15,903 |
| **FTP rate** | 0.00 % | 0.00 % | 0.00 % |

#### 10.3.2.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 92.

**Table 92. Number of comparisons conducted using Neurotechnology - FPC**

| | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 37,128 | 36,529 | 34,696 | 15,903 |
| **Non-mated comparisons** | 107,742,554 | 106,299,390 | 94,858,864 | 19,878,750 |

#### 10.3.2.1.3. DET curves

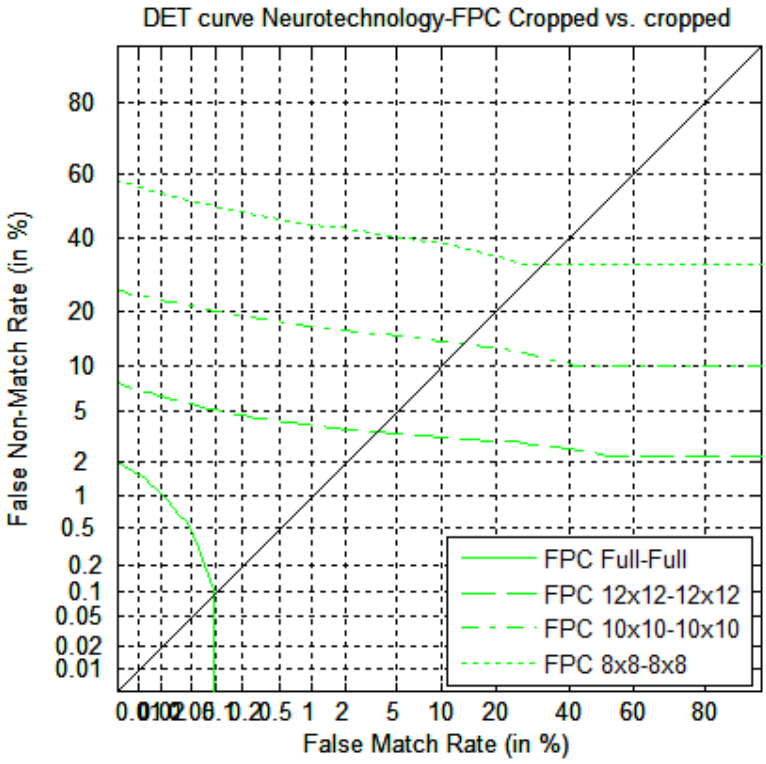


**Figure 56. DET curves for the fingerprint sensors using Neurotechnology – FPC**

#### 10.3.2.1.4. ROC curves

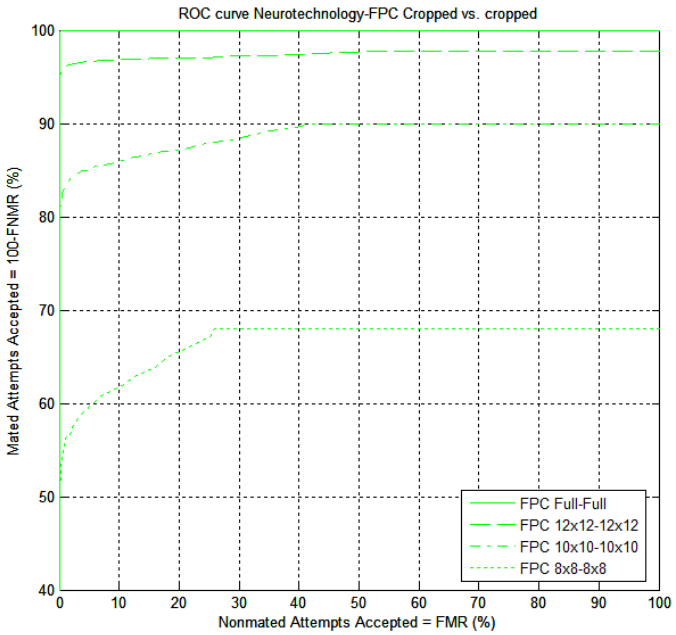


**Figure 57. ROC Curves using Neurotechnology – FPC**

#### 10.3.2.1.5. Additional rates

In addition to previous sections, Table 93 provides relevant error rates for the different sensors.

**Table 93. Additional error rates for Neurotechnology - FPC**

| Error rate | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **EER** | 0.0925 % | 3.49 % | 13.48 % | 31.96 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 3.91 % | 16.70 % | 44.11 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01*% | 4.99 % | 19.775 % | 49.64 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 1.54 % | 6.86 % | 23.53 % | 56.05 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 10.3.2.2. Throughput rates for Neurotechnology - FPC

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the FPC fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel core 2Duo E8500 @ 3.16 GHz and a RAM memory of 4 GB which has installed Windows 7 Professional 2007. This machine was used for extracting the feature vectors and making some comparisons of the original database.
- Machine 2: a laptop with a processor Intel core i7-3517U @ 1.9 GHz and a RAM memory of 4 GB. This PC has installed Windows 8.1 Professional, 2013. This machine was used for making some comparisons of the original database.
- Machine 3: a laptop with a processor Intel Core i7-5500U @ 2'40 GHz and a RAM memory of 8 GB. This PC has installed Windows 8.1 Professional 2013. This machine was used for extracting the feature vectors and for making comparisons of the all cropped databases.

##### 10.3.2.2.1. Enrolment results

Table 94 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 94. Throughput rates results for enrolment using Neurotechnology - FPC**

| Enrolment | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2,200 ms | 6,416 ms | 6,449 ms | 6,726 ms |
| **Standard deviation** | ± 136.25 ms | ± 711.22 ms | ± 776.20 ms | ± 553.28 ms |
| **Minimum** | 230 ms | 4,397 ms | 44,06 ms | 6,618 ms |
| **Maximum** | 4,463 ms | 9,985 ms | 10,000 ms | 13,324 ms |
| **Number of enrolments** | 2,903 | 2,911 | 2,735 | 1,251 |

#### 10.3.2.2.2. Acquisition results

Table 95 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 95. Throughput rates results for acquisition using Neurotechnology - FPC**

| Acquisition | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1043 ms | 3,325 ms | 3,325 ms | 3,274 ms |
| **Standard deviation** | ± 36.12 ms | ± 13.29 ms | ± 39.61 ms | ± 334.6 ms |
| **Minimum** | 239 ms | 3,202 ms | 2,194 ms | 1,080 ms |
| **Maximum** | 1,187 ms | 3,410 ms | 3,394 ms | 3,395 ms |
| **Number of acquisitions** | 43,168 | 37,017 | 37,017 | 37,017 |

#### 10.3.2.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 96 shows measurements obtained for mated comparisons and Table 97 for non-mated comparisons.

**Table 96. Throughput rates results for mated comparisons using Neurotechnology - FPC**

| Mated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1.07 ms | 0.63 ms | 0.45 ms | 0.07 ms |
| **Standard deviation** | ± 1.157 ms | ± 2.60 ms | ± 2.62 ms | ± 2.02 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 32 ms | 263 ms | 198 ms | 111 ms |
| **Number of comparisons** | 37,128 | 36,529 | 34,696 | 15,903 |

**Table 97. Throughput rates results for non-mated comparisons using Neurotechnology - FPC**

| Nonmated comparisons | FPC | FPC_12x12 | FPC_10x10 | FPC_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 0.86 ms | 0.48 ms | 0.28 ms | 0.047 ms |
| **Standard deviation** | ± 0.55 ms | ± 2.56 ms | ± 2.16 ms | ± 1.69 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 70 ms | 1,354 ms | 1,519 ms | 1,415 ms |
| **Number of comparisons** | 107,742,554 | 106,299,390 | 94,858,864 | 19,878,750 |

#### 10.3.3. Performance results for Neurotechnology - UPK

##### 10.3.3.1. Error rates for Neurotechnology - UPK

###### 10.3.3.1.1. Enrolment and acquisition results

FTE and FTP errors that have happened for the different fingerprint sensors when for generating the biometric references and probes for later comparisons are given in Table 98 and Table 99. In this case, the algorithm applied for enrolling and acquiring the samples has been Neurotechnology.

**Table 98. FTE errors for Neurotechnology - UPK**

| | UPK | UPK _12x12 | UPK _10x10 | UPK _8x8 |
|---|---|---|---|---|
| **Number of correct templates** | 3,131 | 2,795 | 2,593 | 390 |
| **FTE errors** | 403 | 739 | 941 | 3,144 |
| **Total number of enrolment transactions** | 3,534 | 3,534 | 3,534 | 3,534 |
| **FTE rate** | 11.40 % | 20.91 % | 26.62 % | 88.96 % |

**Table 99. FTP errors for Neurotechnology – UPK**

| | UPK _12x12 | UPK _10x10 | UPK _8x8 |
|---|---|---|---|
| **Number of correct samples** | 29,103 | 28,249 | 2,226 |
| **FTP errors** | 2,350 | 0 | 24,674 |
| **Total number of acquisition attempts** | 31,453 | 28,249 | 26,900 |
| **FTP rate** | 7.47 % | 0.00 % | 91.72 % |

#### 10.3.3.1.2. Comparison results

Comparisons results are provided in the following subsections. The number of comparisons used to obtain these metrics per each fingerprint sensors are given in Table 100.

**Table 100. Number of comparisons conducted using Neurotechnology - UPK**

| | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Mated comparisons** | 40,032 | 29,103 | 28,249 | 2,226 |
| **Non-mated comparisons** | 125,118,621 | 81,313,782 | 73,221,408 | 865,914 |

#### 10.3.3.1.3. DET curves

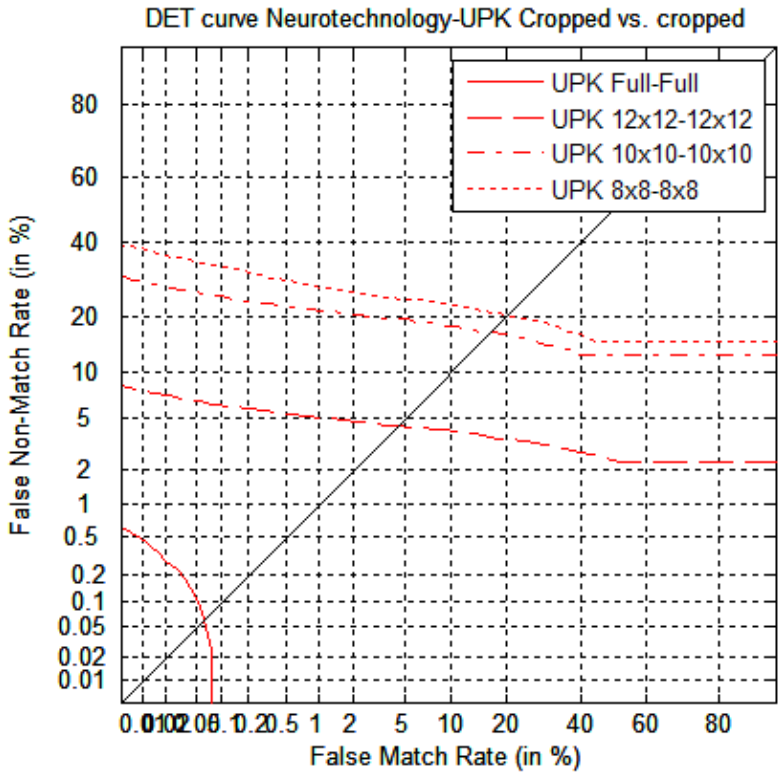


**Figure 58. DET curves for the fingerprint sensors using Neurotechnology – UPK**

#### 10.3.3.1.4. ROC curves

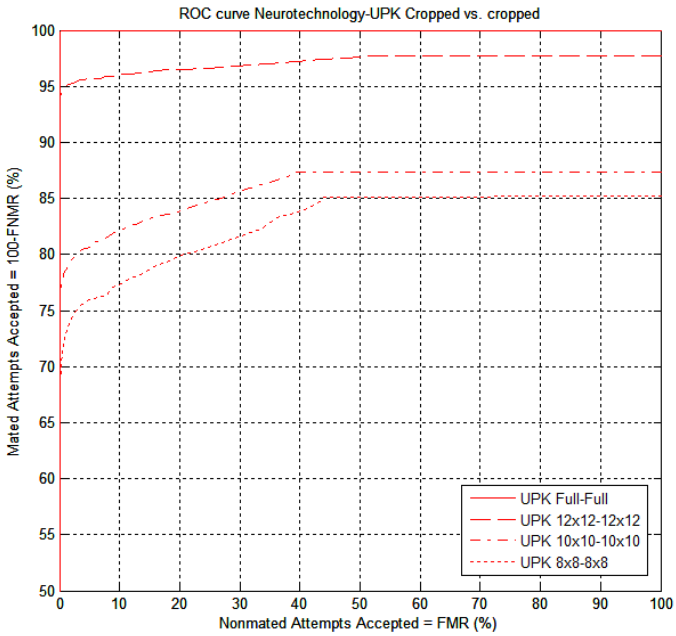


**Figure 59. ROC Curves using Neurotechnology – UPK**

#### 10.3.3.1.5. Additional rates

In addition to previous sections, Table 101 provides relevant error rates for the different sensors.

**Table 101. Additional error rates for Neurotechnology - UPK**

| Error rate | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **EER** | 0.0616% | 4.38 % | 16.58 % | 20.02 % |
| **FMR100 (the lowest FNMR for FMR<=1%)** | <0.01%* | 5.00 % | 21.25 % | 27.04 % |
| **FMR1000 (the lowest FNMR for FMR<=0.1%)** | <0.01%* | 6.08 % | 24.50 % | 32.75 % |
| **FMR10000 (the lowest FNMR for FMR<=0.01%)** | 0.42 % | 7.56 % | 28.56 % | 37.69 % |

* *The lack of precisión in providing this rate is due to the sample rejection by the automatic ground truth checking mechanism during the capturing process.*

#### 10.3.3.2. Throughput rates for Neurotechnology - UPK

This subsection shows throughput rates for the processes that have been conducted during the evaluation considering the NBIS algorithm and the UPK fingerprint sensor.

The application used to process and compare fingerprint images has been developed using Microsoft Visual Studio, .NET framework 4.5 and C# 32 bits.

Moreover, time measurements for the different processes have been calculated using different machines:

- Machine 1: a PC with a processor Intel Core 2Duo E6750 @ 2.66 GHz and a RAM memory of 4 GB. This PC has installed Windows 7 Ultimate, 2009. This machine was used for extracting the feature vectors and making comparisons of the original database. Also, it was used extracting the feature vectors of the 8x8 $mm^2$ database and for making comparisons of the 8x8 vs. 8x8 $mm^2$ feature vectors.
- Machine 2: a PC with a processor Intel Core i7-4790 @ 3.60 GHz and a RAM memory of 12GB. This PC has installed Windows 8.1, 2013. This machine was used for extracting the feature vectors and for making comparisons of the 10x10 $mm^2$ and 12x12 $mm^2$ databases.

##### 10.3.3.2.1. Enrolment results

Table 102 shows the time in milliseconds that takes to obtain the biometric references for the images captured with each fingerprint sensor respectively.

**Table 102. Throughput rates results for enrolment using Neurotechnology - UPK**

| Enrolment | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2,215 ms | 2,223 ms | 2,222 ms | 2,250 ms |
| **Standard deviation** | ± 56.04 ms | ± 90.67 ms | ± 103.20 ms | ± 195.86 ms |
| **Minimum** | 778 ms | 117 ms | 406 ms | 2014 ms |
| **Maximum** | 3,340 ms | 4452 ms | 4,435 ms | 4,456 ms |
| **Number of enrolments** | 3,131 | 2,795 | 2,593 | 390 |

#### 10.3.3.2.2. Acquisition results

Table 103 shows the time in milliseconds that takes to obtain the biometric probes for the images captured with each fingerprint sensor respectively.

**Table 103. Throughput rates results for acquisition using Neurotechnology - UPK**

| Acquisition | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1,090 ms | 1,105 ms | 1,106 ms | 1,102 ms |
| **Standard deviation** | ± 84.04 ms | ± 13.01 ms | ± 9.76 ms | ± 26.37 ms |
| **Minimum** | 165 ms | 885 ms | 615 ms | 60 ms |
| **Maximum** | 1,530 ms | 1,153 ms | 1,143 ms | 1,261 ms |
| **Number of acquisitions** | 44,531 | 33,861 | 36,211 | 11,537 |

#### 10.3.3.2.3. Comparison results

Next tables provided the time in milliseconds that takes to compare the biometric references to biometric probes for the images captured with each fingerprint sensor respectively. Specifically, Table 104 shows measurements obtained for mated comparisons and Table 105 for non-mated comparisons.

**Table 104. Throughput rates results for Mated comparisons using Neurotechnology - UPK**

| Mated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 1.55 ms | 0.16 ms | 0.007 ms | 0.61 ms |
| **Standard deviation** | ± 0.17 ms | ± 0.37 ms | ± 0.08 ms | ± 2.03 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 22 ms | 2 ms | 2 ms | 69 ms |
| **Number of comparisons** | 40,032 | 29,103 | 28,249 | 2,226 |

**Table 105. Throughput rates results for Non-mated comparisons using Neurotechnology - UPK**

| Nonmated comparisons | UPK | UPK_12x12 | UPK_10x10 | UPK_8x8 |
|---|---|---|---|---|
| **Arithmetic mean** | 2.00 ms | 0.06 ms | 0.0021 ms | 0.53 ms |
| **Standard deviation** | ± 1.65 ms | ± 0.24 ms | ± 0.067 ms | ± 1.56 ms |
| **Minimum** | 0 ms | 0 ms | 0 ms | 0 ms |
| **Maximum** | 95 ms | 26 ms | 89 ms | 170 ms |
| **Number of comparisons** | 125,118,621 | 81,313,782 | 73,221,408 | 865,914 |

# PART III

# ANALYSIS OF THE RESULTS OBTAINED

# 11. ANALYSIS OF THE RESULTS OBTAINED

## 11.1. INTRODUCTION

This final part provides the analysis of the results and main conclusions obtained from the figures calculated. These conclusions are sorted in sections as to analyse individually each aspect considered of interest.

## 11.2. COMPARISON AMONG SENSORS ACCORDING TO THE QUALITY OF THE SAMPLES CAPTURED

According to NFIQ, the number of samples overcoming the enrolment threshold is higher for UPK and NXT than for FPC, which presents a high rate of NFIQ=5. Considering those samples overcoming the enrolment quality threshold, the thermal sensor present more NFIQ=1 and NFIQ=2 samples, while the two capacitor sensors present a majority of NFIQ=3.

This tendency is kept also for the samples captured during the visits (i.e. after enrolment). FPC presents a very low number of NFIQ=1 samples, placing the most of the samples at NFIQ=3. UPK presents a growing curve with NFIQ, having more samples at NFIQ=3 than the ones at NFIQ=2, and those are more than the ones at NFIQ=1. In the case of NXT sensor, a majority of the samples present NFIQ=2, with a reasonable high percentage at NFIQ=1. Once again, the sensor presenting a larger number of rejected samples (i.e. NFIQ=5) is FPC.

Although this conclusion is accurate considering the results, it is important to note that scientific community has already determined the need of improving NFIQ as to provide results that are more consistent. But for the time being, NFIQ is the baseline for quality assessment.

According to the quality error rate, the results show that FPC rejects more users than the other two sensors, who behave equivalently, being slightly lower for NXT than for UPK. This gives the impression of a faster adaptation of the user to the NXT sensor, in the same level of easiness than with UPK. The sensor for which the user needed a larger number of attempts (i.e. larger number of images created in the database) is FPC; this creates some concerns about the usability of the sensor among the test crew.

The same tendency is present during the capturing process.

A qualitative result obtained by operators during the acquisition process is that users felt more uncomfortable or have more difficulties in interacting with the sensor having the smaller area (i.e. FPC), as the location of the finger had direct impact to the quality assessment and/or the ground truth assurance mechanism.

## 11.3. PERFORMANCE ALGORITHM-SENSOR PAIRS

The performance of the NBIS algorithm results in a lower FTE rate for NXT with a similar (although higher) rate for UPK and a sensible larger rate for FPC. Regarding the feature extraction of the samples acquired during the capturing process, the first thing to note is the high number of the FTA rate for all sensors, being above 25%, which may raise usability concerns due to the large rejection of samples. Comparing the results for the three sensors, FPC shows a much higher FTA rate (over 45%), while UPK and NXT show similar rates between each other, being lower for UPK, although still over 27%. Therefore, when using NBIS algorithm, the behaviour of FPC may not be considered acceptable, while the one of NXT and UPK should be analysed as to reduce the number of rejections.

Focusing on the recognition rates of the NBIS algorithm for each of the sensors, a similar behaviour can be observed for NXT and UPK (around 4% EER), while FPC shows a better behaviour of below 1% EER.

In overall, considering the large amount of samples rejected from the FPC sensor, a trade-off between usability (lower FTA rates) and accuracy (lower EER figures) shall be analysed according to the target application.

Finally, avoiding differences between machines, it is shown that NBIS takes longer enrolment time for UPK than for NXT and FPC samples. The same behaviour is shown for the feature extraction process, while the comparison among samples present a more homogeneous behaviour among sensors. It is important to note that for the NBIS algorithm, the comparison time for the mated samples is one order or magnitude higher than the comparison time among non-mated samples.

Analysing the performance of the Neurotechnology algorithm, the FTE rates result in a lower error rate for NXT than for UPK and FPC, being the numbers lower than the ones obtained with the NBIS algorithm. Regarding FTA rates, the numbers are also much lower than those of the NBIS algorithm (below 26%, instead of over 45% for FPC). But it still shows a worse behaviour of the FPC sensor compared to the other two ones. Differently from the results of NBIS, in this case the FTA rate is lower for NXT than for UPK. Even though, the rates are still higher than expected (above 15%), although in a much acceptable level than the one with the NBIS algorithm.

Focusing on the recognition rates, Neurotechnology presents much lower error rates than NBIS (lower than 0.1% EER, compared to the 4% of NBIS). The accuracy achieved with each of the sensors is quite similar, being better for UPK and NXT and worse for FPC. That relationship is just the opposite as the one with the NBIS algorithm.

In overall, considering the rejection rates and the accuracy achieved, it can be stated that NXT presents a better behaviour, followed closely by UPK, and finally with worse results for FPC. But in all cases, the FTA rate may compromise usability of a potential deployment.

In the case of Neurotechnology, the time needed for the feature extraction and for the enrolment is equivalent for all 3 sensors, being one order of magnitude higher than the time needed by NBIS. But for comparison, having an equivalent time for mated and non-mated samples, the time consumed is one order of magnitude lower than the one of NBIS. Among sensors, the comparison time for FPC is half of the one needed by NXT or UPK.

## 11.4. PERFORMANCE OF ALGORITHMS

With the results summarized in the previous sub-section, Neurotechnology obtains nearly two orders of magnitude better performance than NBIS, with a comparison time of one order of magnitude less. The major disadvantage of the Neurotechnology algorithm is the time needed for enrolment and for the feature extraction process.

It is important to remember that the mechanism established to guarantee the ground truth has an impact on the error rates, but, nevertheless, for both algorithms the threshold chosen has been relaxed enough as to minimize this effect. Such impact is only on the mated distribution curve, so by analysing the non-mated distribution line, it can be observed how much compact/narrow is in case of Neurotechnology compared to NBIS. Therefore it is clear than the area of intersection between mateds and non-mated will always be larger for NBIS than for Neurotechnology, providing validity to the initial result observed of a better performance in the latter than in the former.

## 11.5. IMPACT OF REDUCED AREA

Considering the NFIQ, the quality of the cropped images is decreasing as the size of the image is reduced. Specially, 8x8 images present an NFIQ=5. For the other sizes, i.e. 12x12 and 10x10 the most common is, in most cases, NFIQ=3.

After analysing all the combinations algorithm/sensor, the main conclusions are equivalent for each case, with slight differences depending on the combination:

- FTE rate increase enormously as the size of the image is reduced. This effect is very important in all cases although for the Neurotechnology/FPC combination cropping to smaller sizes is not so dramatic.
- Regarding FTA, the analysis has only considered the additional errors obtained at the processing of the samples (FTP). This rate has been completely insignificant for the case of the NBIS algorithm, while it has been extremely important in the case of Neurotechnology (the “Too Few Features” exception has occurred multiple times). An exception for this case is the use of the FPC sensor, which has not obtained any FTP error, while the number of FTP with NXT and NEU is extremely high.
- When analysing the accuracy, cropped images present higher error rates than full-size images, being higher the error as the size is reduced. Such errors increase, at least, in an order of magnitude when 8x8 size is considered. For NBIS, 8x8 EER is higher than 40% (being 4% for full-size),

while for Neurotechnology the increase has been from below 0.1% till up to 35%. Intermediate values appear for the intermediate sizes, being always above 20% for NBIS and above 3% for Neurotechnology.

- Regarding computational time, as expected, it shrinks with the size of the image. In the case of the NBIS algorithm this happens for all cases and processes, i.e. enrolment, feature extraction and comparison. But in the case of Neurotechnology, only the comparison time is significantly reduced, while the enrolment and feature extraction processes present equivalent rates among each of the cases.

In few words, the smaller the image, the larger the rejection during acquisition, and the higher the error rates. In most cases, the results show important concerns on the potential usability of a deployment, as well as the accuracy achieved. An initial recommendation from this result is avoiding using small size sensors. In case such sensors are used, then two recommendations shall be followed. The first one is to improve the training of the user in interacting with the sensor, as to reduce the FTE and FTA rates. The second one is to complement the recognition process with other mechanisms, as to improve the accuracy during an operational recognition process.

## 11.6. INTEROPERABILITY BETWEEN FULL SIZE AND REDUCED AREA

When analysing the interoperability between the reduced samples and the biometric references obtained using the full size images, the results obtained are equivalent to the ones noted in the previous section, with some slight differences:

- FTP error rates (mainly obtained by the lack of being able to extract enough minutiae from the cropped images) increase when the area is reduced in the case of the Neurotechnology algorithm (as this algorithm has additional internal quality checks). These rates shall be added to the FTA rates for the acquisition process given in the full-size case.
    - This increase in the FTA error rates is very low in the case of the NBIS algorithm, although for the FPC sensor higher.
- Regarding accuracy, it shows the expected behaviour of an increase in the error rates with the reduction of the image area. The loss of accuracy is very significant, although much less important than the one of cropped vs. cropped comparisons.
- Using the Neurotechnology algorithm, the accuracy decreases in an order of magnitude with the size, but the error rates keep in a reasonable level (lower than 10% EER in most cases).
    - For UPK, the accuracy for 8x8 keeps the same level as the 10x10, although, as said, the FTA rate is much higher, and the overall performance of the 8x8, even for that sensor, is much worse than for the 10x10 case.
- In terms of processing time, the tendency is the one as the case of cropped vs. cropped comparison. The smaller the size, the shorter the time, both for feature extraction and for comparison. Obviously, feature extraction is equivalent as in the previous case, while comparison time is slightly higher

than in the cropped vs. cropped comparison, but still three orders of magnitude shorter than the feature extraction.

As a summary, results show that the behaviour of the system using reduced size samples, is much better if the enrolment has been performed using full size images. Therefore, the recommendation is to use this scheme in those applications where small sensors need to be used, whenever it may be possible to use an external sensor for enrolment.

## 11.7. LESSONS LEARNED

After carrying out the acquisition and obtaining the evaluation report, there are a set of lessons learned, being some of them in the roadmap for future evaluations. The lessons learned have been:

- Using managed/interpreted languages for the evaluation process is fully discouraged, as the latency of the virtual machines involved, not only delays the processing, but also creates further challenges in massive comparisons, such as memory management, garbage collection and core assignment.
- Potentially related to this is the effect in the execution of each of the test with the different laboratories. The timing taken for performing each of the experiments is much higher than the multiplication of each of the processes multiplied by the number of times the process takes (e.g. it takes much longer the whole cross-comparison, than summing the individual times obtained for each of the comparisons). This effect has been more noted in the case of the Neurotechnology algorithm, taking 3 times longer than the NBIS algorithm, while the feature extraction and comparison durations are, more or less, equivalent or even shorter).
- After analysing the results of the NFIQ algorithm, and more precisely some of the samples labelled with bad quality and some others with good quality, the performance of NFIQ as a quality assessment tool provide no consistent results. An analysis of the results without such quality assessment (i.e. just using the processing/comparison algorithms) is encouraged.
    - In addition, a strong support to the teams currently developing a 2nd version of NFIQ, should be given.
- The need of a mechanism to assure ground truth should be mandatory, even considering the impact to the mated distribution curve. Such mechanism shall complement the visual inspection of the capturing process, but should try to have a reduced impact on both, the distribution rates and the user interaction.

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# ANNEX A: Additional performance curves using NBIS algorithm Full vs. Cropped comparisons

## A.1. DET curve including all cropped sizes

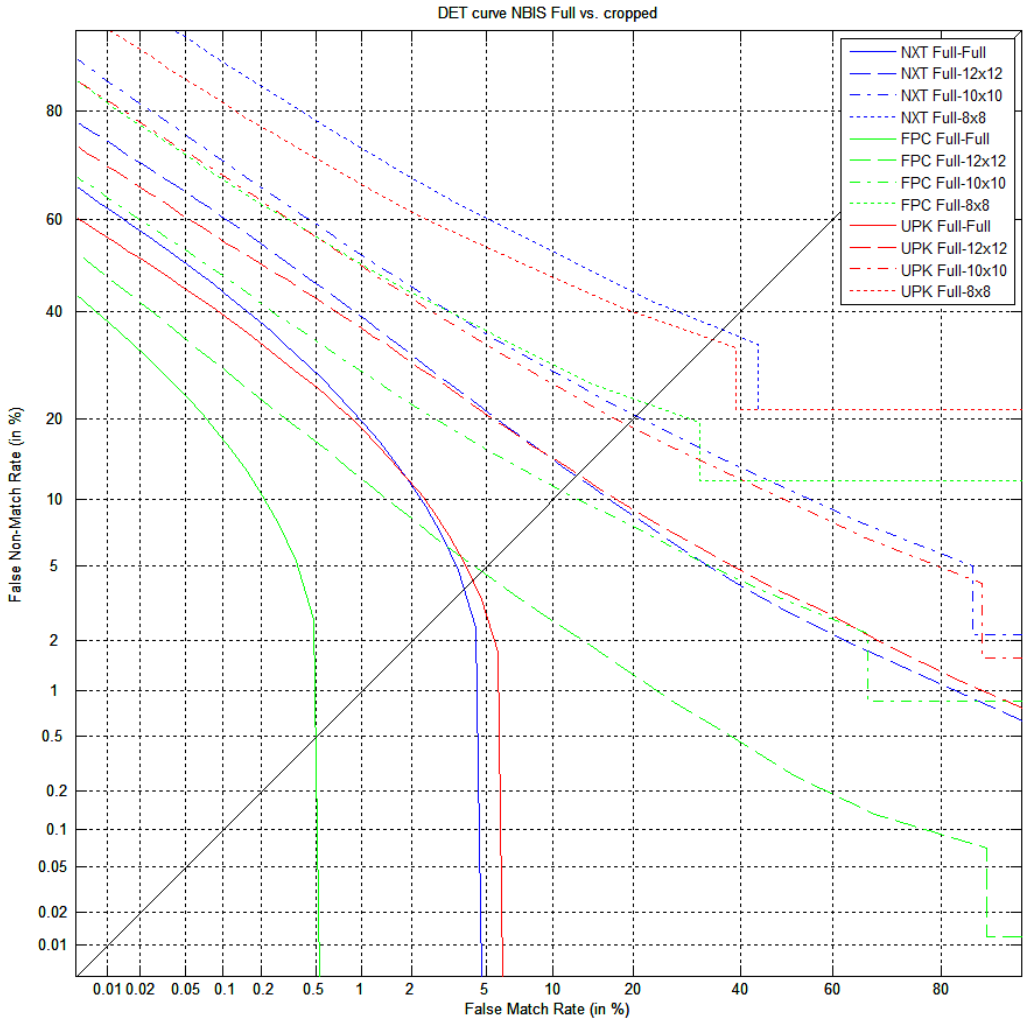


**Figure 60. DET curve using NBIS**

## A.2. ROC curve including all cropped sizes

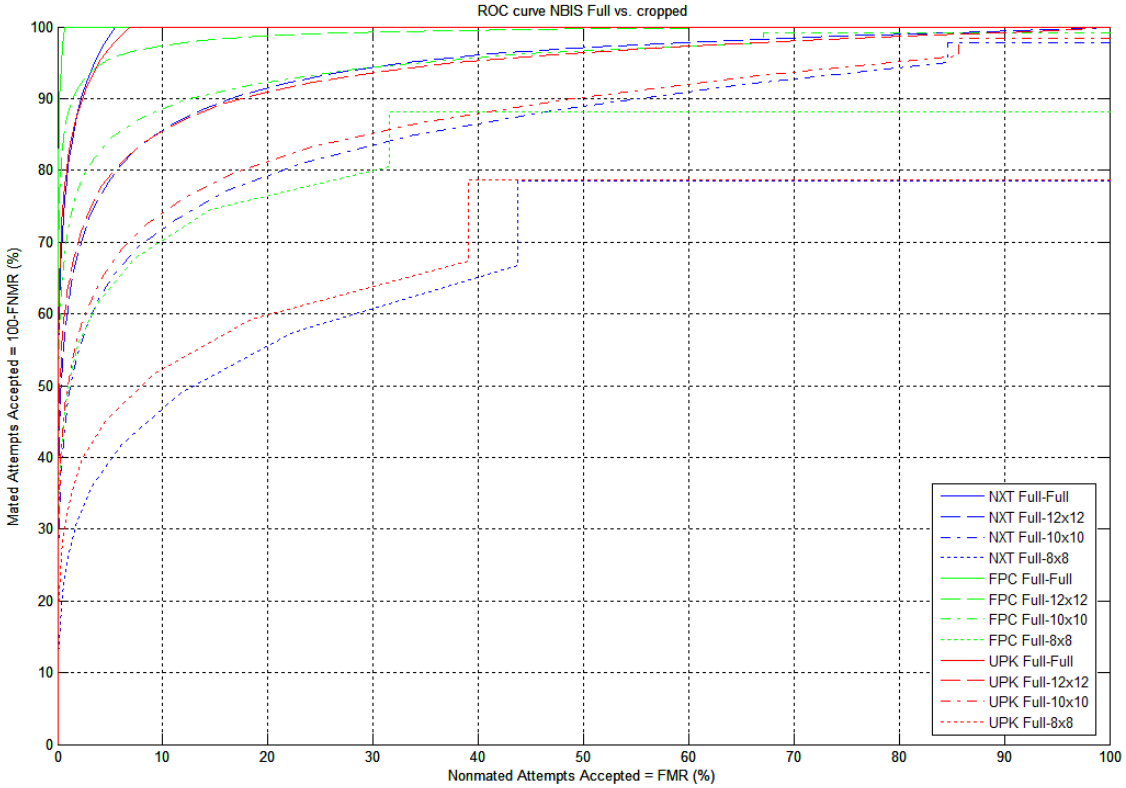


**Figure 61. ROC curve using NBIS**

# ANNEX B: Additional performance curves using Neurotechnology algorithm Full vs. Cropped comparisons

## B.1. DET curve including all cropped sizes

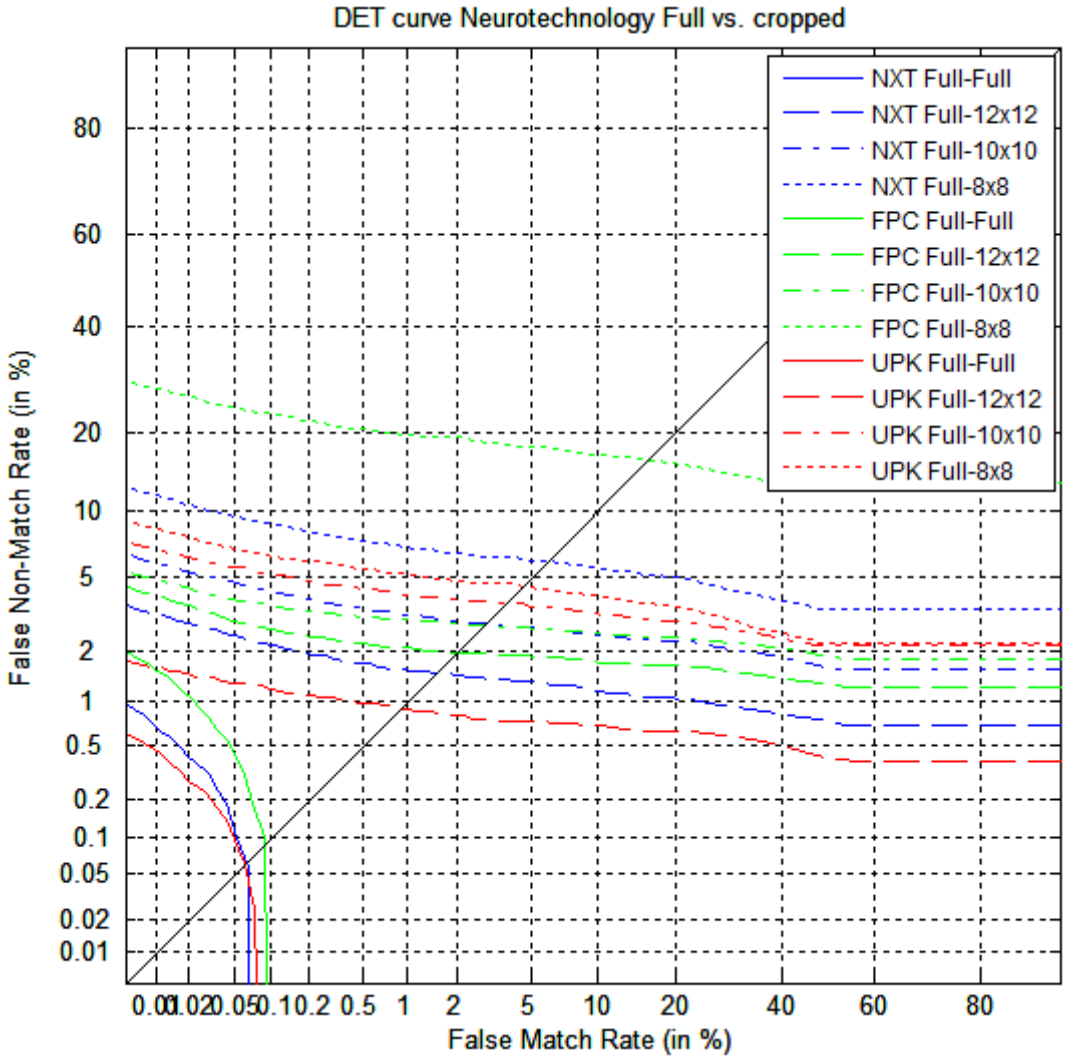


**Figure 62. DET curve using Neurotechnology**

## B.2. Roc curve including all cropped sizes

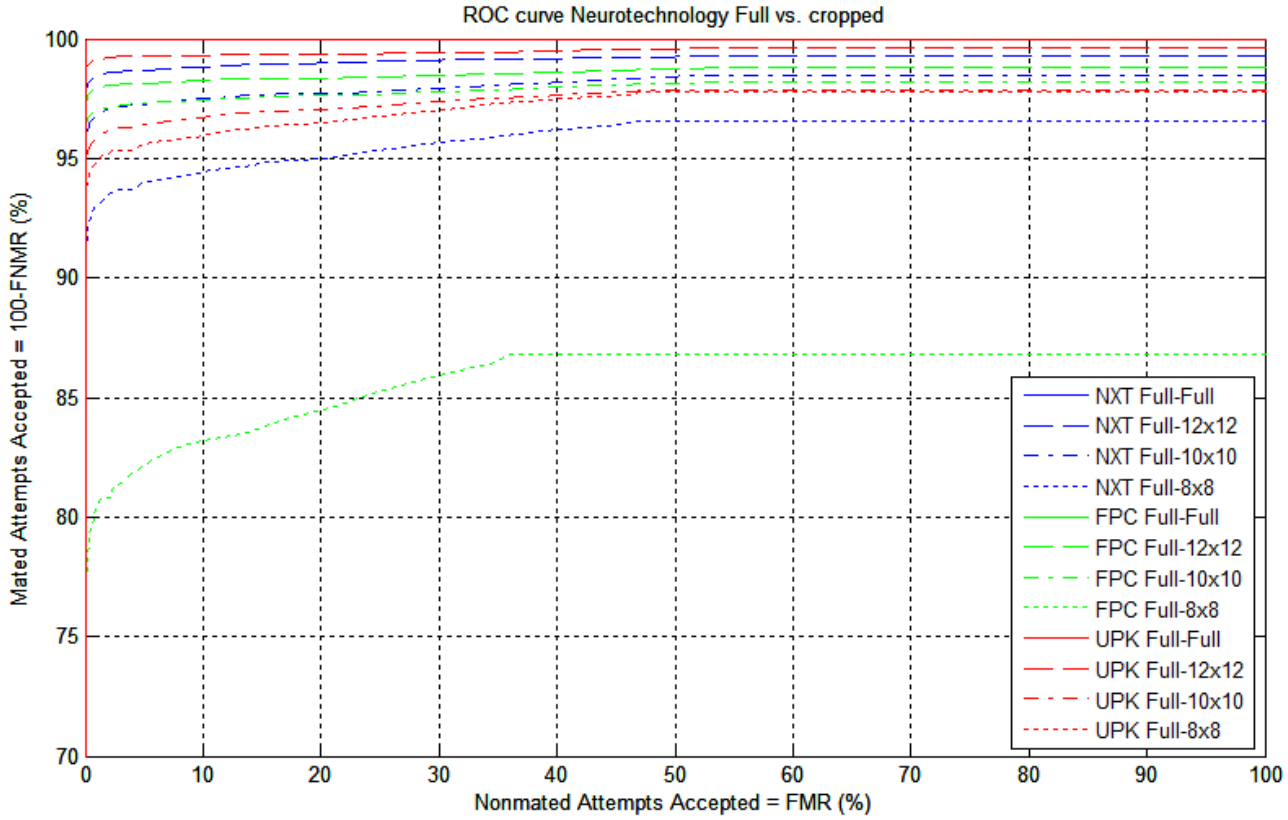


**Figure 63. ROC curve using Neurotechnology**

# ANNEX C: Additional performance curves using NBIS algorithm

## C.1. DET curve including all cropped sizes

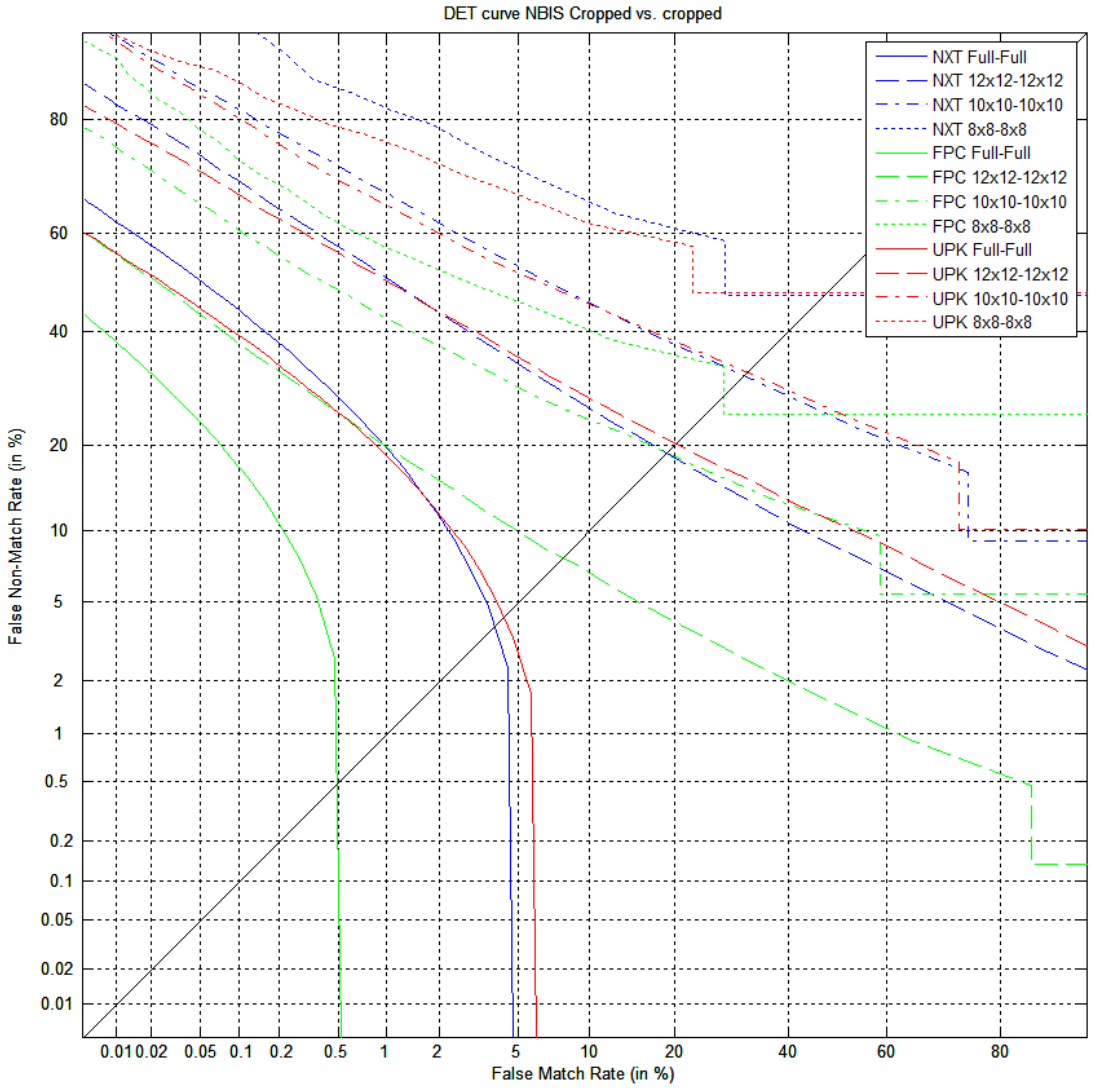


**Figure 64. DET curve using NBIS**

## C.2. ROC curve including all cropped sizes

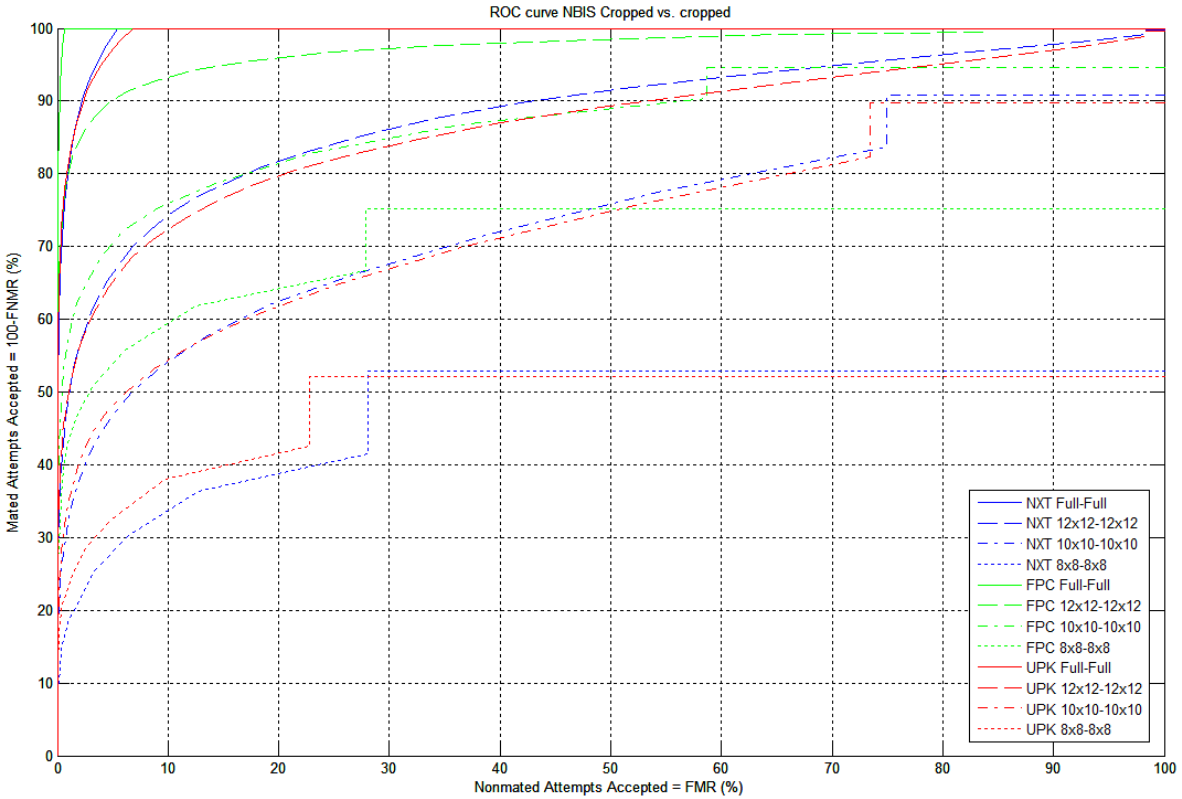


**Figure 65. ROC curve using NBIS**

# ANNEX D: Additional performance curves using Neurotechnology algorithm

## D.1. DET curve including all cropped sizes

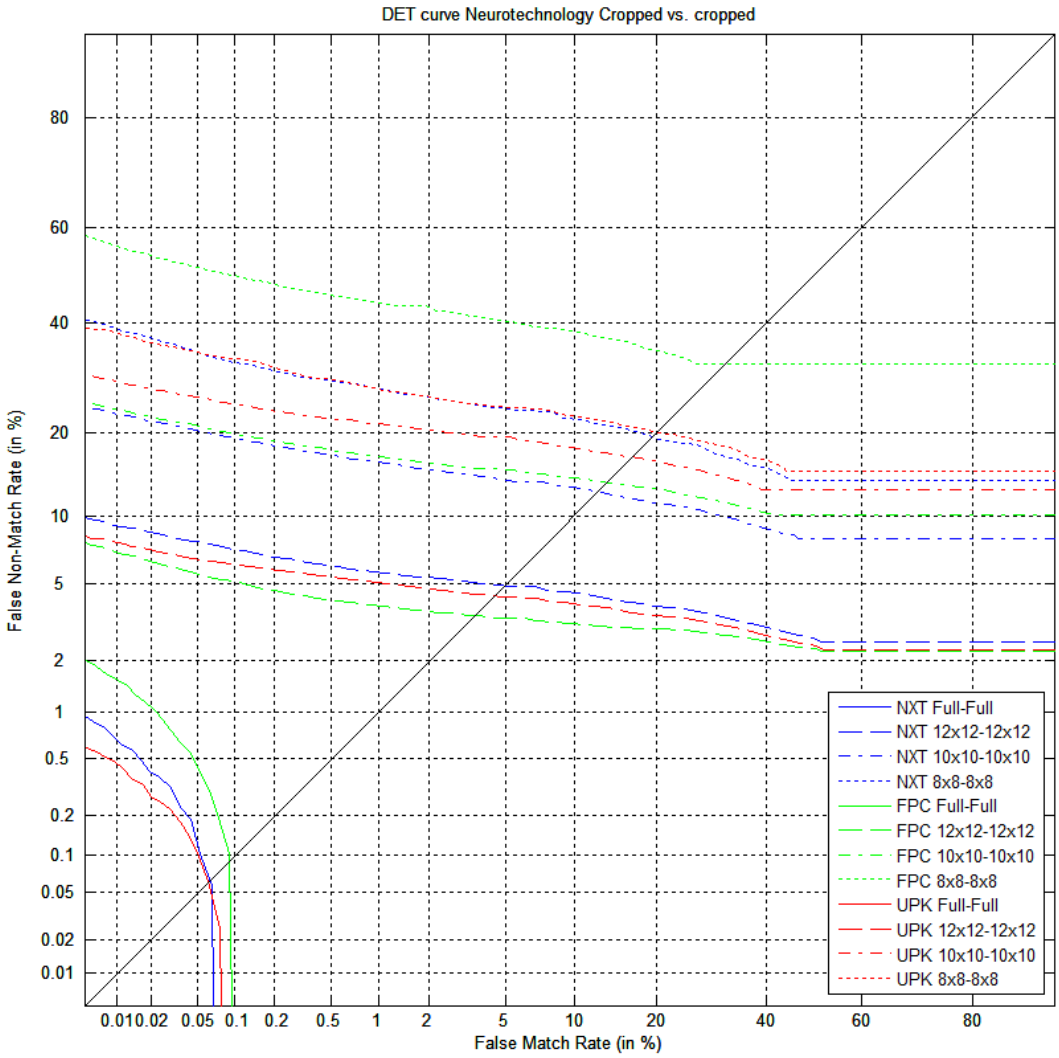


**Figure 66. DET curve using Neurotechnology**

## D.2. Roc curve including all cropped sizes

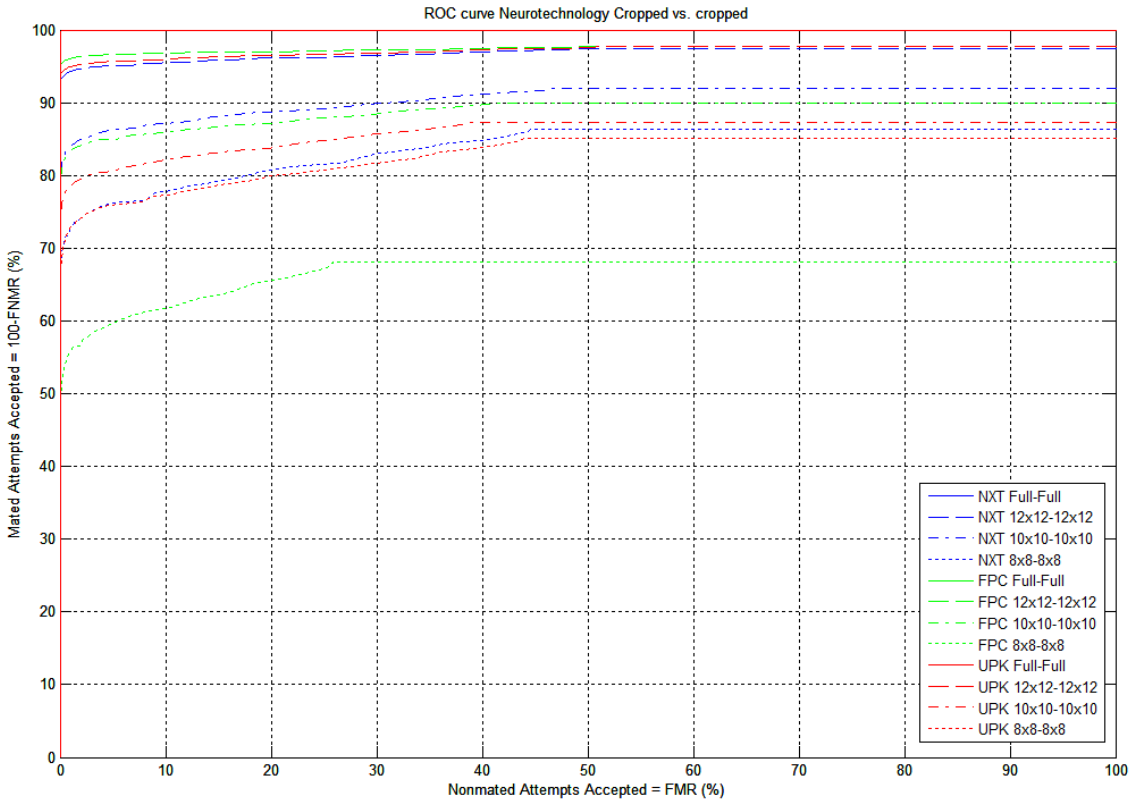


**Figure 67. ROC curve using Neurotechnology**