Development of NFIQ 2.0

Evaluation of Potential Image Features for Quality Assessment
Version 0.5
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1 Introduction

According to ISO /IEC 29794-1 [1], the quality score output by a biometric quality assessment algorithm should convey a predicted utility of the biometric sample, where the utility of the biometric sample reflects its impact on the recognition performance of the biometric system. This relationship between quality and system performance is depicted in Figure 1.

In accordance with these requirements, the approach taken for the development of the NFIQ and the NFIQ2.0 algorithm is to train a machine learning algorithm (e.g. a neural network) to predict the utility of fingerprints from global and local structures of the fingerprint image, henceforth referred to as quality features. The potential to predict the utility heavily depends on the significance of the quality features for the image properties influencing its utility, i.e. the more indicative the quality features are for the expected biometric performance of the fingerprint, the better can an algorithm predict the utility.

Figure 1: Relationship between quality and system performance (taken from [1])
Several quality features have been proposed in the literature, in particular in ISO/IEC 29794-4 [6], [12] and the NIST report on the development of the NFIQ algorithm [12], but also in other publications, e.g. [1], [2], [3], [4], [7], [10], [11] and [13].

In this document, we report on the implementation and systematic evaluation of a large number of features, including all features proposed in [6], [12] and [12], with respect to their eligibility for predicting fingerprint utility.
2 Features and Feature Extraction Methods

2.1 NFIQ1 Features
The NFIQ1 features are implemented by the NBIS package and have been used in the training of the NFIQ algorithm [12]. They are based on the minutiae output by MINDTCT and a quality map [13]. The quality map is computed on segmentation of the image into 8x8 pixel blocks. This quality map and the local image contrast are used by MINDTCT to compute a quality value for each minutia.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>foreground</td>
<td>number of blocks that are quality 1 or better</td>
</tr>
<tr>
<td>total #of minutia</td>
<td>number of total minutiae found in the fingerprint (using)</td>
</tr>
<tr>
<td>min05</td>
<td>number of minutiae that have quality 0.5 or better</td>
</tr>
<tr>
<td>min06</td>
<td>number of minutiae that have quality 0.6 or better</td>
</tr>
<tr>
<td>min075</td>
<td>number of minutiae that have quality 0.75 or better</td>
</tr>
<tr>
<td>min08</td>
<td>number of minutiae that have quality 0.8 or better</td>
</tr>
<tr>
<td>min09</td>
<td>number of minutiae that have quality 0.9 or better</td>
</tr>
<tr>
<td>quality zone 1</td>
<td>percentage of the foreground blocks of quality map with quality =1</td>
</tr>
<tr>
<td>quality zone 2</td>
<td>percentage of the foreground blocks of quality map with quality =2</td>
</tr>
<tr>
<td>quality zone 3</td>
<td>percentage of the foreground blocks of quality map with quality =3</td>
</tr>
<tr>
<td>quality zone 4</td>
<td>percentage of the foreground blocks of quality map with quality =4</td>
</tr>
</tbody>
</table>

Table 1: Description of NFIQ1 Features.

2.2 FingerJet FX Features

2.2.1 Number of Minutiae

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeCount</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeCount</td>
</tr>
</tbody>
</table>

Description
This value expresses the number of minutia extracted by the open source edition of DigitalPersona’s FingerJetFX algorithm.

2.2.2 Fingerprint Quality

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_FingerprintQuality</td>
</tr>
<tr>
<td>Also known as</td>
<td>FingerprintQuality</td>
</tr>
</tbody>
</table>

Description
This value expresses the quality of the fingerprint image returned by the open source edition of DigitalPersona’s FingerJetFX algorithm.

Notes
The FingerJetFX algorithm constantly returns the value 86. Hence, this feature can be considered irrelevant.
2.2.3 Average Minutiae Quality

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_AverageMinutiaeQuality</td>
</tr>
<tr>
<td>Also known as</td>
<td>AverageMinutiaeQuality</td>
</tr>
</tbody>
</table>

Description
This value expresses the average (arithmetic mean) quality of all returned minutiae by the open source edition of DigitalPersona’s FingerJetFX algorithm.

2.2.4 Minutiae Quality 0

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_0</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 0</td>
</tr>
</tbody>
</table>

Description
This value expresses the percentage of all detected minutiae quality values that have a value of 0 are greater than 100. (Absolute number of minutiae quality values that are 0 or >100 divided by the absolute number of detected minutiae).

2.2.5 Minutiae Quality 1

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_1</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 1</td>
</tr>
</tbody>
</table>

Description
This value expresses the percentage of all detected minutiae quality values that are in the range from 1 until 10 (Absolute number of minutiae quality values that are >= 1 and <= 10 divided by the absolute number of detected minutiae).

2.2.6 Minutiae Quality 2

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_2</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 2</td>
</tr>
</tbody>
</table>

Description
This value expresses the percentage of all detected minutiae quality values that are in the range from 11 until 20 (Absolute number of minutiae quality values that are >= 11 and <= 20 divided by the absolute number of detected minutiae).

2.2.7 Minutiae Quality 3

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
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</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_3</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 3</td>
</tr>
</tbody>
</table>

Description
This value expresses the percentage of all detected minutiae quality values that are in the range from 21 until 30 (Absolute number of minutiae quality values that are >= 21 and <= 30 divided by the absolute number of detected minutiae).
### 2.2.8 Minutiae Quality 4

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
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<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_4</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 4</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 31 until 40 (Absolute number of minutiae quality values that are >= 31 and <= 40 divided by the absolute number of detected minutiae).

### 2.2.9 Minutiae Quality 5

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_5</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 5</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 41 until 50 (Absolute number of minutiae quality values that are >= 41 and <= 50 divided by the absolute number of detected minutiae).

### 2.2.10 Minutiae Quality 6

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
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</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_6</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 6</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 51 until 60 (Absolute number of minutiae quality values that are >= 51 and <= 60 divided by the absolute number of detected minutiae).

### 2.2.11 Minutiae Quality 7

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_7</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 7</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 61 until 70 (Absolute number of minutiae quality values that are >= 61 and <= 70 divided by the absolute number of detected minutiae).

### 2.2.12 Minutiae Quality 8

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
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</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_8</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 8</td>
</tr>
</tbody>
</table>

**Description**

...
This value expresses the percentage of all detected minutiae quality values that are in the range from 71 until 80 (Absolute number of minutiae quality values that are $\geq 71$ and $\leq 80$ divided by the absolute number of detected minutiae).

### 2.2.13 Minutiae Quality 9

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_9</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 9</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 81 until 90 (Absolute number of minutiae quality values that are $\geq 81$ and $\leq 90$ divided by the absolute number of detected minutiae).

### 2.2.14 Minutiae Quality 10

<table>
<thead>
<tr>
<th>Origin</th>
<th>DigitalPersona FingerJetFX OSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>FingerJetFX_MinutiaeQuality_10</td>
</tr>
<tr>
<td>Also known as</td>
<td>MinutiaeQuality 10</td>
</tr>
</tbody>
</table>

**Description**

This value expresses the percentage of all detected minutiae quality values that are in the range from 91 until 100 (Absolute number of minutiae quality values that are $\geq 91$ and $\leq 100$ divided by the absolute number of detected minutiae).

### 2.3 hda Features

#### 2.3.1 Notation

- $w$: Image width in pixels (horizontal)
- $h$: Image height in pixels (vertical)
- $(x, y)$: Image location where $(1, 1)$ denotes the pixel in the upper left corner
- $m$: Number of blocks horizontally
- $n$: Number of blocks vertically
- $V_{(i, j)}$: Image block where $V_{(1, 1)}$ denotes the block in the upper left corner

#### 2.3.2 Frequency Domain Analysis

**Origin**


**NFIQ2.0 identifier**

FDA_#

**Short acronym**

FDA

**Description**

The Frequency Domain Analysis algorithm operates in a block-wise manner. A signature of the ridge-valley structure is extracted and the DFT is computed to determine the frequency of the sinusoid following the ridge-valley structure.

**Extracting the ridge-valley signature**

$$T(x) = \frac{1}{2w + 1} \sum_{k=-r}^{r} I(x, k)$$

**Computing the Frequency Domain Analysis score**

$$Q_{FDA} = \frac{A(F_{\text{max}}) + 0.3(A(F_{\text{max}} - 1) + A(F_{\text{max}} + 1))}{\sum_{F=1}^{N/2} A(F)}$$

**Algorithm**
1. For each block determine the dominant ridge flow orientation
2. Rotate the block such that the dominant ridge flow is perpendicular to the x-axis
3. Crop regions of block such that no invalid regions are included in the block
4. Calculate the mean pixel intensity value $T(x)$ for the block to extract the ridge-valley structure
5. Calculate the Fourier spectrum of $T(x)$
6. Discard the DC component of $T(x)$ and determine the term $F_{max}$ with the highest magnitude

$$A(F_{max})$$

7. The final Frequency Domain Analysis score is the mean of scores assigned to foreground blocks.

**Notes**

The value of $Q_{FDA}$ is undefined if $F_{max} = 1$ or $F_{max} = A(\text{null})$ as $A(0)$ is not a valid index. Workaround in that case is to set $Q_{FDA} = 1$. 

**Processing**

<table>
<thead>
<tr>
<th>Image Description</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td><img src="image" alt="Input" /></td>
</tr>
<tr>
<td>Input with block grid and current block marked in blue</td>
<td><img src="image" alt="Input with grid and current block" /></td>
</tr>
<tr>
<td>Zoomed view of current block</td>
<td><img src="image" alt="Zoomed view" /></td>
</tr>
<tr>
<td>Block rotated</td>
<td><img src="image" alt="Block rotated" /></td>
</tr>
</tbody>
</table>
2.3.3 Gabor

<table>
<thead>
<tr>
<th>Origin</th>
<th>Olsen, Xu, Busch, Gabor Filters as Candidate Quality Measure for NFIQ 2.0 in ICB 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>GABOR_#</td>
</tr>
<tr>
<td>Short acronym</td>
<td>GAB</td>
</tr>
</tbody>
</table>

**Description**

The Gabor quality metric operates on a per-pixel basis by calculating the standard deviation of the Gabor filter bank responses. The size of the filter bank is used to determine a number of filters oriented evenly across the half circle. The strength of the response at a given location corresponds agreement between filter orientation and frequency in the location neighborhood. For areas in the fingerprint image with a regular ridge-valley pattern there will be a high response from one or a few filter orientations. In areas containing background or unclear ridge-valley structure the Gabor response of all orientations will be low and constant.

**Variables**
For a block $v_T$ there are $v_T$ pixels in the valley region and $v_B$ pixels in the valley region with intensity lower than a threshold $DT$. Similarly there are $v_T$ pixels in the ridge region and $v_R$ pixels in the ridge region with intensity lower than a threshold $DT$. $\alpha$ and $\beta$ are expressions of these ratios.

\[ \alpha = \frac{v_B}{v_T}, \quad \beta = \frac{v_B}{v_R} \]

The normalized valley width $\bar{W}_v$ and the normalized ridge width $\bar{W}_r$ are determined

\[ \bar{W}_v = \frac{W_v}{(S/125) W^{max}_v}, \quad \bar{W}_r = \frac{W_r}{(S/125) W^{max}_r} \]

where $S$ is the scanner resolution in dpi, $W^{max}_v$ is the estimated ridge or valley width for an image with 125 dpi resolution, and $W_v$ and $W_r$ are the observed valley and ridge widths. According to [1] $W^{max}_v = S$ is reasonable for 125 dpi resolution.

Computing the Local Clarity Score
The final quality score is computed using the average value of $\alpha$ and $\beta$ in valid ridge and valley regions:

\[ Q_{LC} = \left\{ \begin{array}{ll}
1 - \left( \frac{\alpha + \beta}{2} \right), & (W_v^{min} \leq \bar{W}_v \leq W_v^{max}) \land (W_r^{min} \leq \bar{W}_r \leq W_r^{max}) \\
0, & \text{otherwise}
\end{array} \right. \]

where $W_v^{min}$ and $W_v^{max}$ are the minimum values for the normalized ridge and valley width, and $W_r^{min}$ and $W_r^{max}$ are the maximum values for the normalized ridge and valley width.

Algorithm
1. For each block $v_B$ in the image determine the dominant ridge flow orientation to create an orientation line which is perpendicular to the ridge flow
2. Align $v_B$ such that the orientation line is horizontal to create $v_2$
3. From $v_2$ extract a block $v_2$ which is centered around the orientation line
4. Compute the average profile $v_3$ of $v_2$
5. Determine a threshold $DT$ by applying linear regression on $v_3$
6. Determine the proportion of misclassified pixels $\beta$ and $\alpha$ in the ridge and valley regions
7. Determine the normalized ridge width and valley width $W_r$ and $W_v$.
8. Compute the final quality score $Q_{LC}$.

Further Comments
Particular regions inherent in a fingerprint will negatively affect $Q_{LC}$. For example, ridge endings and bifurcations or areas with high curvature such as those commonly found in core and delta points.

Processing
Input (FVC2000 Db1A 1_1.bmp)

Subtraction of image convolved with Gaussian.

Gabor response for filtered image at orientation 0

Gabor response for filtered image at orientation 1/4

Gabor response for filtered image at orientation 2/4
2.3.4 Gabor Segment

<table>
<thead>
<tr>
<th>Origin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>GS_#</td>
</tr>
<tr>
<td>Short acronym and alternate identifier</td>
<td>GSG, GaborSeg</td>
</tr>
</tbody>
</table>

**Description**

Same as Gabor with the exception that the image is initially convolved with a 2D Gaussian kernel with $\sigma = 6$ instead of $\sigma = 1$. Additionally a segmentation to 2 levels is applied before computing the final quality score.

**Segment to two levels**

Segmenting the map of standard deviations into two levels is done by first determining the cumulative distribution function for pixel intensity values. Next a threshold is determined such that the probability of a pixel belonging to background is the same as that for belonging to the foreground.

**Algorithm**

1. Convolve input image with a 2D Gaussian kernel with $\sigma = 6$
2. Compute the Gabor response of the image for each orientation
3. Convolve the magnitude (complex modulus) of each Gabor response with a 2D Gaussian kernel with $\sigma = 4$
4. Compute the standard deviation of the Gabor magnitude response values at each location yielding a map of standard deviations.
5. Segment the standard deviation map into two levels.
The general form of the complex 2D Gabor (Daugman, 1985) filter $g_{h_k}$ in the spatial domain is given by:

$$h_{h_k}(x,y) = g(x,y) = \frac{1}{\sqrt{2\pi \sigma_x \sigma_y}} \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) \exp(j2\pi f x y)$$

where

$$x_h = x \sin \theta + y \cos \theta$$
$$y_h = x \cos \theta - y \sin \theta$$

and $f$ is the frequency (cycles/pixel) of the sinusoidal plane wave along the orientation $\theta$. The size of the Gaussian smoothing window is determined by $\sigma_x, \sigma_y$.

The filter bank size $n$ is used to compute the differently oriented Gabor filters composing the filter bank. The computation of $\theta$ given $n$ is as follows:

$$\theta = \frac{k-1}{n}, \quad k = 1, \ldots, n$$

For 500 ppi images the following settings are reasonable:

$\sigma_x = \sigma_y = 6$

$f' = 0.1$

$n = 4$

<table>
<thead>
<tr>
<th>$\sigma_x$</th>
<th>2D Gaussian standard deviation in x-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$</td>
<td>2D Gaussian standard deviation in y-direction</td>
</tr>
<tr>
<td>$n$</td>
<td>Size of filter bank, orientations of the gabor wave</td>
</tr>
<tr>
<td>$f_D$</td>
<td>Gabor filter frequency</td>
</tr>
<tr>
<td>Orientation</td>
<td>Image</td>
</tr>
<tr>
<td>-------------</td>
<td>-------</td>
</tr>
<tr>
<td>0</td>
<td><img src="image1" alt="Gabor response at orientation 0" /></td>
</tr>
<tr>
<td>1/4</td>
<td><img src="image2" alt="Gabor response at orientation 1/4" /></td>
</tr>
<tr>
<td>2/4</td>
<td><img src="image3" alt="Gabor response at orientation 2/4" /></td>
</tr>
<tr>
<td>3/4</td>
<td><img src="image4" alt="Gabor response at orientation 3/4" /></td>
</tr>
</tbody>
</table>
2.3.6 Local Clarity Score

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>LCS #</td>
</tr>
<tr>
<td>Short acronym and alternate identifier</td>
<td>LCS, Ridge-valley Structure</td>
</tr>
</tbody>
</table>

**Description**

Local Clarity Score (LCS) computes the block wise clarity of ridge and valleys by applying linear regression to determine a gray-level threshold, classifying pixels as ridge or valley. A ratio of misclassified pixels is determined by comparing with the normalized ridge and valley width of that block.

**Computing the average profile of a block**

Given the block $V_2$, the average profile is obtained by

$$V_3(x) = \frac{\sum_{y=1}^{M} V_2(x,y)}{M}$$

where $M$ is the height of the block.

**Determining the proportion of misclassified pixels**
For a block \( v_2 \) there are \( v_T \) pixels in the valley region and \( v_B \) pixels in the valley region with intensity lower than a threshold \( DT \). Similarly there are \( v_T \) pixels in the ridge region and \( v_B \) pixels in the ridge region with intensity lower than a threshold \( DT \). \( \alpha \) and \( \beta \) are expressions of these ratios.

\[
\alpha = \frac{v_B}{v_T}, \quad \beta = \frac{v_B}{v_T}
\]

**Determining the normalized ridge and valley width**

The normalized valley width \( \overline{W_v} \) and the normalized ridge width \( \overline{W_r} \) are determined

\[
\overline{W_v} = \frac{W_v}{S_{\text{dpi}}} W_{v_{\text{max}}},
\]

\[
\overline{W_r} = \frac{W_r}{S_{\text{dpi}}} W_{r_{\text{max}}},
\]

where \( S \) is the scanner resolution in dpi, \( W_{v_{\text{max}}} \) is the estimated ridge or valley width for an image with 125 dpi resolution, and \( W_v \) and \( W_r \) are the observed valley and ridge widths. According to \( \) \( W_{v_{\text{max}}} \) is reasonable for 125 dpi resolution.

**Computing the Local Clarity Score**

The final quality score is computed using the average value of \( \alpha \) and \( \beta \) in valid ridge and valley regions:

\[
Q_{LCS} = \begin{cases} 
100, & (W_v^{\text{min}} < \overline{W_v} < W_v^{\text{max}}) \land (W_r^{\text{min}} < \overline{W_r} < W_r^{\text{max}}) \\
0, & \text{otherwise}
\end{cases}
\]

where \( W_v^{\text{min}} \) and \( W_r^{\text{min}} \) are the minimum values for the normalized ridge and valley width, and \( W_v^{\text{max}} \) and \( W_r^{\text{max}} \) are the maximum values for the normalized ridge and valley width.

**Algorithm**

1. For each block \( v_2 \) in the image determine the dominant ridge flow orientation to create an orientation line which is perpendicular to the ridge flow
2. Align \( v_2 \) such that the orientation line is horizontal to create \( v_2 \)
3. From \( v_2 \) extract a block \( v_2 \) which is centered around the orientation line
4. Compute the average profile \( v_2 \) of \( v_2 \)
5. Determine a threshold \( DT \) by applying linear regression on \( v_2 \)
6. Determine the proportion of misclassified pixels \( \beta \) and \( \alpha \) in the ridge and valley regions
7. Determine the normalized ridge width and valley width \( \overline{W_r} \) and \( \overline{W_v} \)
8. Compute the final quality score \( Q_{LCS} \)

**Further Comments**

Particular regions inherent in a fingerprint will negatively affect \( Q_{LCS} \). For example, ridge endings and bifurcations or areas with high curvature such as those commonly found in core and delta points.

**Processing**
NFIQ 2.0: Evaluation of Potential Image Features for Quality Assessment

Input with grid and block marked in blue

Zoomed view of block

Block rotated to align ridgelines vertically

Extracted section of the block

Projected mean gray intensity values
2.3.7 Mu

<table>
<thead>
<tr>
<th>Origin</th>
<th>NFIQ2.0 identifier</th>
<th>Short acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mu_#</td>
<td>MUQ</td>
<td></td>
</tr>
</tbody>
</table>

Ridge-valley profile as found by mean values. Red line indicates the threshold for ridge-valley separation.

Ridge-valley segmentation. Ridges shown in black, valleys in white. The mean intensity values are shown above for comparison.

Ridge areas composed into one block.

Shown in white are the parts of the fingerprint which were determined to be ridge but do not belong to ridge as defined by the threshold.

Valley areas composed into one block.

Shown in white are the parts of the fingerprint which were determined to be valley but do not belong to valley as defined by the threshold.

Map of local clarity scores. High intensity corresponds to high local clarity.
Mu is the mean pixel intensity value in the input image.

Algorithm

\[ q_{\text{MU}} = \frac{1}{X \times Y} \sum_{x=1}^{X} \sum_{y=1}^{Y} I(x,y) \]

2.3.8 Mu Mu Block

<table>
<thead>
<tr>
<th>Origin</th>
<th>NFIQ2.0 identifier</th>
<th>MMB #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short acronym</td>
<td>MMB</td>
<td></td>
</tr>
</tbody>
</table>

Description
Mu Mu Block is the mean of the block wise mean pixel intensity value in the input image.

2.3.9 Mu Mu Sigma Block

<table>
<thead>
<tr>
<th>Origin</th>
<th>NFIQ2.0 identifier</th>
<th>MMSB #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short acronym</td>
<td>MMSB</td>
<td></td>
</tr>
</tbody>
</table>

Description
Mu Mu Sigma Block is the mean of the block wise standard deviation pixel intensity value in the input image subtracted the block wise standard deviation.

2.3.10 Mu Sigma Block

<table>
<thead>
<tr>
<th>Origin</th>
<th>NFIQ2.0 identifier</th>
<th>MSB #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short acronym</td>
<td>MSB</td>
<td></td>
</tr>
</tbody>
</table>

Description
Mu Sigma Block is the mean of the block wise standard deviation pixel intensity value in the input image.

2.3.11 Orientation Certainty Level

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>OCL #</td>
</tr>
<tr>
<td>Short acronym</td>
<td>OCL</td>
</tr>
</tbody>
</table>

Description
Orientation Certainty Level is a measure of the strength of the energy concentration along the dominant ridge flow orientation. The metric operates in a block-wise manner.

Computing the covariance matrix
The covariance matrix \( \mathbf{C} \) is computed as:

\[
\mathbf{C} = \frac{1}{N} \sum_{i=1}^{N} \begin{bmatrix} dx \, dx^T \\ dy \, dy^T \end{bmatrix}
\]

where \( dx \) and \( dy \) represent the intensity gradient at that pixel.

Computing the eigenvalues and the final quality score
From the covariance matrix \( \mathbf{C} \) the eigenvalues \( \lambda_{\text{min}} \) and \( \lambda_{\text{max}} \) are computed as:

\[
\lambda_{\text{min}} = \frac{a + b - \sqrt{(a-b)^2 + 4c^2}}{2}
\]

\[
\lambda_{\text{max}} = \frac{a + b + \sqrt{(a-b)^2 + 4c^2}}{2}
\]
this yields an orientation certainty level OCL:

$$OCL = 1 - \frac{\lambda_{\text{min}}}{\lambda_{\text{max}}}$$

which is a ratio in the interval $[0,1]$ where 1 is highest certainty level and 0 is lowest.

**Algorithm**

For each block $b_i$

1. Compute the intensity gradient by applying the 3x3 Sobel operators
2. Compute the covariance matrix
3. Compute the eigenvalues to obtain $OCL$

Finally compute the quality measure $Q_{OCL}$ as:

$$Q_{OCL} = \frac{1}{B} \sum_{i=1}^{B} b_i$$

**Processing**

<table>
<thead>
<tr>
<th>Image</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Input" /></td>
<td>Input</td>
</tr>
<tr>
<td><img src="image2.png" alt="Input with current block marked" /></td>
<td>Input with current block marked</td>
</tr>
<tr>
<td><img src="image3.png" alt="Zoomed view of block" /></td>
<td>Zoomed view of block</td>
</tr>
<tr>
<td><img src="image4.png" alt="Ridge orientation indicated as an ellipse. The eccentricity of the ellipse corresponds to the orientation certainty." /></td>
<td>Ridge orientation indicated as an ellipse. The eccentricity of the ellipse corresponds to the orientation certainty.</td>
</tr>
</tbody>
</table>
2.3.12 Orientation Flow

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>OF #</td>
</tr>
<tr>
<td>Short acronym</td>
<td>OF</td>
</tr>
</tbody>
</table>

### Description

Orientation Flow is a measure of ridge flow continuity which is based on the absolute orientation difference between a block and its neighboring blocks.

#### Block-wise absolute orientation difference

The ridge flow is determined as a measure of the absolute difference between a block and its neighboring blocks. The absolute difference for block $V(i,j)$ is:

$$D(i,j) = \frac{\sum_{m=-1}^{1} \sum_{n=-1}^{1} |V(i,j) - V(i-m,j-n)|}{\theta}$$

#### Local orientation quality score

The local orientation quality score $Q_{loc}(i,j)$ for the block orientation difference $D(i,j)$ is determined as:

$$Q_{loc}(i,j) = \begin{cases} 100, & D(i,j) < \theta_{min} \\ \left( 1 - \frac{D(i,j) - \theta}{\theta_{max} - \theta} \right) \times 100, & D(i,j) > \theta_{min} \end{cases}$$

where $\theta_{min}$ is a threshold for minimum angle difference to consider.

#### Global orientation quality score

With $N \times M$ local orientation quality score blocks the global orientation quality score is computed as:

$$Q_{GF} = \frac{1}{N \times M} \sum_{i=1}^{N} \sum_{j=1}^{M} Q_{loc}(i,j)$$

### Algorithm

1. Compute the absolute orientation difference $D(i,j)$ for each block $V(i,j)$
2. Compute the local orientation quality score $Q_{loc}(i,j)$ for $D(i,j)$
3. Compute the global orientation flow quality score $Q_{GF}$

### Processing
<table>
<thead>
<tr>
<th><img src="image1" alt="input" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current block marked</td>
</tr>
<tr>
<td><img src="image2" alt="Zoomed view of current block" /></td>
</tr>
<tr>
<td>Orientation line shown perpendicular to ridges.</td>
</tr>
<tr>
<td><img src="image3" alt="Block orientations" /></td>
</tr>
<tr>
<td>Map of differences between a block orientation and its 8-neighborhood</td>
</tr>
</tbody>
</table>
2.3.13 Radial Power Spectrum

### Description

The Radial Power Spectrum is a measure of maximal signal power in a defined frequency band of the global radial Fourier spectrum. Ridges can be locally approximated by means of a single sine wave, hence high energy concentration in a narrow frequency band corresponds to consistent ridge structures.

### Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower bound of frequency band</td>
<td>$f_{\text{lower}}$</td>
</tr>
<tr>
<td>Upper bound of frequency band</td>
<td>$f_{\text{upper}}$</td>
</tr>
<tr>
<td>Frequency bin width</td>
<td>$\Delta_f$</td>
</tr>
</tbody>
</table>

### The 2D Discrete Fourier Transform

The 2D discrete Fourier transform $f(x,y)$ of $I(x,y)$ is:

$$f(x,y) = \frac{1}{MN} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} I(x,y) \exp \left( -j2\pi \left( \frac{mx}{M} + \frac{ny}{N} \right) \right)$$

and the magnitude of $f(x,y)$ is:

$$|F(x,y)| = |f(x,y)|^2$$

### Magnitude of frequency bands polar coordinates

The magnitude of the annular band between $r$ and $\Delta_r$ in the polar Fourier spectrum $F(\alpha,r)$ is computed as:

$$J(r) = \frac{\sum_{\theta=0}^{\theta_{\text{upper}}} \sum_{\alpha=0}^{\alpha_{\text{upper}}} F(\alpha,r)}{\sum_{\theta=0}^{\theta_{\text{lower}}} \sum_{\alpha=\alpha_{\text{min}}}^{\alpha_{\text{max}}} F(\alpha,r)}$$

where $\theta$ is the angle and $r$ is the radius.

### Determine quality score from energy distribution

The quality metric $Q_{\text{POW}}$ is found as:

$$Q_{\text{POW}} = \max_{r_{\text{min}},r_{\text{max}}} J(r)$$

### Algorithm

1. Compute the magnitude of the 2D-DFT $F(x,y)$
2. Transform $F(x,y)$ into polar coordinates and normalize to the range of $[0,1]$
3. Determine the maximum energy to compute $Q_{\text{POW}}$

### Process
2.3.14 Ridge Valley Uniformity

<table>
<thead>
<tr>
<th>Origin</th>
<th>ISO/IEC TR 29794-4:2010 (ISO/IEC, 2010) - Clause 6.2.2.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ2.0 identifier</td>
<td>RVU_#</td>
</tr>
<tr>
<td>Short acronym</td>
<td>RVU</td>
</tr>
</tbody>
</table>

**Description**

Ridge Valley Uniformity is a measure of the consistency of the ridge and valley widths.

**Algorithm**

1. For each block $V_0$ in the image determine the dominant ridge flow orientation to create an orientation line which is perpendicular to the ridge flow
2. Align $V_0$ such that the orientation line is horizontal to create $V_1$
3. From $V_3$ extract a block $V_4$ which is centered around the orientation line.
4. Compute the average profile $V_5$ of $V_4$ to produce a vector.
5. Determine a threshold $DT$ by applying linear regression on $V_5$.
6. Segment $V_5$ into two levels based on the threshold $DT$.
7. Determine the indexes in $V_5$ where a change from background to foreground or foreground to background occurs. If no changes are found then return an empty ratio for that block.
8. Remove the first and last parts of $V_5$ to remove incomplete ridge/valleys occurring at the border of the original block. Likewise remove the corresponding changes from the change index vector.
9. If there are no changes after step 8, return an empty ratio for that block.
10. Calculate the ratios between the width of ridges and valleys for the block.
11. Obtain the final quality score as the standard deviation of all ratios.

**Process**

| Input | Input with block grid and current block marked | Current block | Current block with overlap |
2.3.15 Sigma

**Origin**
- NFIQ2.0 identifier: Sigma_
- Short acronym: SIG

**Description**
Sigma is the standard deviation of pixel intensity values in the input image.

**Algorithm**

\[
Q_{\text{SIG}} = \left( \frac{1}{X \times Y - 1} \sum_{y=1}^{Y} \sum_{x=1}^{X} (I(x,y) - I)^2 \right)^{\frac{1}{2}}
\]

where \( I \) is the mean pixel intensity of \( I \).

2.3.16 Sigma Mu Block

**Origin**
- NFIQ2.0 identifier: SMB_
- Short acronym: SMB

**Description**
Sigma Mu Block is the standard deviation of the block wise mean pixel intensity value in the input image.
3 Evaluation Approach

3.1 Methodology

The following methods were used to evaluate the features:

- Determination of spearman correlation among the features and with a utility measure determined from a large number of biometric comparisons.
- Visual inspection of scatter plots.
- Computation of ROC curves resulting from a biometric application simulation, where the feature values are used to select the best fingerprint during enrolment. Details are described in Section 3.1.1.
- Computation of ERC showing the dependence of the FNMR from filtering the genuine scores by the feature values of both reference and probe images (see Section 3.1.3).

3.1.1 Spearman Correlation and Scatter Plots

We compute the spearman correlation, i.e. rank correlation, of the feature values with both the utility values and with values of other features. The utility values are computed according to ISO/IEC 29794-1 for providers 28, 63 and 83, and are used as “ground truth” metric for quality, i.e. the correlation coefficients of the feature values with utility are supposed to indicate their dependency on quality and vice-versa. The correlation coefficients with other feature’s values indicate the potential redundancy among the different features.

For the ease of reading, the correlation matrices are colored according to the absolute value of the correlation coefficient (darker color for higher absolute values) and the coefficients are shown multiplied by 100 and rounded.

In addition to correlation, scatter plots are computed with both the utility values and with values of other features. The scatter plots allow detection of more complex dependencies than the (one dimensional) correlation.

3.1.2 Evaluation by ROC Curves

In order to evaluate how indicative a feature is for biometric performance, we simulate a biometric application using the feature values as quality assessment
criteria. In particular, we perform the following steps on a large database of fingerprints with several impressions per finger:

1. For each fingerprint, we compute a large number of genuine and impostor comparison scores.

2. For each finger, we select the impression having the highest feature value as reference fingerprint.

3. For the selected reference fingerprints, average error rates are computed from their similarity scores. In particular, from the comparison scores of the selected fingerprints accumulated genuine and impostor score distributions are computed and ROC curves are determined. The smaller the error rates are, the more eligible the utility function is to perform quality assurance with the deployed filter method and threshold. The probe fingerprints are not filtered by the feature values.

4. Steps 2 and 3 are repeated but this time, in step 2, the impression having the lowest feature value is chosen as reference image.

5. The better of the two resulting ROC curves, i.e. the ROC curve with lowest error rates is chosen as a measure for the feature.

These steps simulate an evaluation of biometric performance of a biometric system which deploys the utility function for quality assessment during enrolment.

The ROC curves were computed from the comparison scores of several providers. For comparison, ROC curves were also computed for the case where always the first of the three impressions (with respect to their acquisition numbers) is chosen as reference fingerprint. Since the acquisition number is assumed to be unrelated to image quality, this selection criterion simulates a scenario where no quality filtering is applied at all.

3.1.3 ERC Evaluation

An error reject curve (ERC) shows the dependence of the FNMR at a fixed comparison score threshold on the extent of filtering the genuine scores by feature value of both reference and probe image. First, a comparison score threshold \( t \) is selected which results in a fixed FNMR (e.g. 10\%), e.g. for which a fraction of FNMR genuine scores are equal or larger than \( t \). Then for each feature threshold \( 0 \leq q \leq 1 \),
all genuine scores are neglected for which the feature value of the reference image or the feature value of the probe image is below the threshold $q$. For the remaining genuine scores, the fraction of genuine scores equal or larger than $t$ is determined, e.g. the FNMR resulting from filtering a $q$ fraction of the genuine scores. The resulting ERC can vary for different FNMR. Thus, we compute ERC for FNMR of 3% and FNMTR of 10%.

### 3.2 Data basis

For our experiments we use the FingerQS database of BSI, which contains 9 impressions (taken with 3 sensors) of 8784 fingers from 1098 individuals (all fingers except little fingers). In order to amplify differences between tested utility functions in the resulting error rates, we split each user-ID into 3 pseudo-IDs and assign for each finger code 3 fingerprints of this user-ID (taken by the same sensor) to each pseudo-ID. Thus, we treat the impressions of each finger as impressions of 3 different fingers. By this re-labeling, the number of user-IDs is increased by a factor of three and, at the same time, the number of fingerprints per finger is reduced by a factor of three; the reduction of impressions per finger increases the impact of variations in the utility function to the selection of the best fingerprint per finger.

The utility values are computed for three different providers (SDKs), having identifiers 28, 63 and 83. For each fingerprint and each provider, 8 genuine scores and, on average, 57.5 impostor scores are used to compute the utility values. ROC curves are also computed for all three providers. In contrast, we restrict our evaluation with ERC computed from the comparison scores of one provider (28).

### 3.3 Limitations

Both the correlation coefficients and the ROC curves measure to what extend the utility increases or decreases with feature values. Any non-monotonic dependency of feature values from utility is not captured. However, such monotonic dependency can be visible in the ERC and in the scatter plots.

Furthermore, since in the ROC curve method the filtering of fingerprints is performed per finger but not between impressions of different fingers, only intra-finger dependencies of feature values from utility are measured. Therefore, only influences of the quality aspect “fidelity” as defined in ISO/IEC 29794-1 [6], [12], i.e. the quality of the image with respect to the original characteristic, on the feature are captured,
and the impact of the quality aspect “character”, i.e. the eligibility of the character for biometric applications, can not be determined from the ROC curves.
4 Evaluation Results

4.1 Evaluation of the NFIQ1-Features

4.1.1.1 Correlation and Scatter Plots

The spearman correlation coefficients of the 11 NFIQ1 features are given in the following table.

<table>
<thead>
<tr>
<th></th>
<th>foreground</th>
<th>NoMinutiae</th>
<th>min05</th>
<th>min06</th>
<th>min075</th>
<th>min08</th>
<th>min09</th>
<th>QualZone1</th>
<th>QualZone2</th>
<th>QualZone3</th>
<th>QualZone4</th>
<th>util28</th>
<th>util63</th>
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</thead>
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<td>47</td>
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<td>34</td>
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<td>-4</td>
<td>25</td>
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<td>2</td>
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<tr>
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<td>83</td>
<td>82</td>
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</tr>
</tbody>
</table>

Table 2: Spearman correlation coefficients for NFIQ1 features

The highest correlation with utility are observed for (in that order)

1. Quality Zone 4,
2. Quality Zone 3,
3. Quality Zone 1,
4. min05 and min06,
5. min075.

Scatter plots of the features with provider 63 utility according to ISO 28784-1 [5] and density plots of the empirical feature distributions are shown in Appendix A.1.

4.1.1.2 ROC curve evaluation
The following table shows for each NFIQ1 feature, which selection criterion, i.e. choosing the impression with highest feature value or selecting the one with lowest feature value, results in better a ROC curve.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Abbr.</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>foreground</td>
<td>FG</td>
<td>lowest</td>
</tr>
<tr>
<td>total # of minutiae</td>
<td>NoMin</td>
<td>lowest</td>
</tr>
<tr>
<td>min05</td>
<td>Min05</td>
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<td>min06</td>
<td>Min06</td>
<td>highest</td>
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<tr>
<td>min075</td>
<td>Min075</td>
<td>highest</td>
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<tr>
<td>min08</td>
<td>Min08</td>
<td>highest</td>
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<td>min09</td>
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<td>lowest</td>
</tr>
<tr>
<td>quality zone 2</td>
<td>QZ2</td>
<td>lowest</td>
</tr>
<tr>
<td>quality zone 3</td>
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<td>lowest</td>
</tr>
<tr>
<td>quality zone 4</td>
<td>QZ4</td>
<td>highest</td>
</tr>
</tbody>
</table>

Table 3: Optimal selection criteria for ROC curves

For these criteria, the ROC curves are shown in Figure 2, Figure 3 and Figure 4
Figure 2: ROC curves of NFIQ1 features for provider 28

Figure 3: ROC curves of NFIQ1 features for provider 63
The following observations were made:

- Consistently, quality zone 4 performed best, followed by quality zone 3, total # of minutiae and foreground.

- Although feature min08 is positively correlated with utility, the ROC curves for both selection criteria were worse than that of a random selection (NULL feature). This finding indicates, that good quality fingerprint neither have particularly high nor particularly low feature values.

- For provider 83, feature quality zone 1 also performed worse than no quality filtering, but still choosing the impression with lowest value gave better results than selecting the one with the highest value.

Scatter plots of the features with provider 63 utility according to ISO 28784-1 [5] and density plots of the empirical feature distributions are shown in Appendix A.1.

4.1.1.3 ERC Evaluation

For the NFIQ1 features the following ERC curves were obtained. The dotted diagonal line from (0.1, 0) to (0, 0.1) for 10% FNMR and from (0.03,0) to (0.03,0) for 3% FNMR shows the ideal (and hypothetical) ERC in case of a perfect quality filtering, where scores are rejected according to their quality, starting with the lowest quality value.
4.2 Evaluation of the FingerJetFX Features

It turned out that some of the FingerJetFX features always returned the same value:

- The fingerprint quality is hard coded in the source code to the value 86.
- No minutiae with quality value between 0 and 0.4 were detected.

The spearman correlation matrix is shown below.
Table 4: Spearman correlation coefficients for NFIQ1 features

The highest correlation with utility was observed (in that order) for

1. Minutiae Quality 9
2. Minutiae Quality 10
3. Minutiae Quality 7
4. Average Minutiae Quality

Scatter plots of the features with provider 63 utility according to ISO 28784-1 [5] and density plots of the empirical feature distributions are shown in Appendix A.1.
4.2.1.1 ROC Curve Evaluation

The following table shows for the remaining FingerJetFX features, which selection criterion, i.e. choosing the impression with highest feature value or selecting the one with lowest feature value, results in better a ROC curve.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Abbr.</th>
<th>Criterion</th>
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<td>MinutiaeQuality_6</td>
<td>MQ6</td>
<td>highest</td>
</tr>
<tr>
<td>MinutiaeQuality_7</td>
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<td>MinutiaeQuality_10</td>
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</tbody>
</table>

Table 5: Optimal selection criteria for ROC curves

For these criteria, the ROC curves are shown in Figures.

![ROC curves of FingerJet FX features for provider 28](image)
The following observations were made:

- Minutiae Quality 7 took ranked first for all providers.
- For provider 63 and 83, Minutiae Quality 9 and Minutiae Quality 6 took the second and third place, for provider 28 these ranks were exchanged.
- Consistently, Minutiae Count, Minutiae Quality 4, and Minutiae Quality 8 showed very poor performance.

### 4.2.1.2 ERC Evaluation

For the FingerJet FX features the following ERC curves were obtained for FNMR of 3% and 10%. Again, the dotted diagonal line from (0.1, 0) to (0, 0.1) for 10% FNMR and from (0.03,0) to (0.03,0) for 3% FNMR shows the ideal (and hypothetical) ERC in case of a perfect quality filtering, where scores are rejected according to their quality, starting with the lowest quality value.

![Figure 10: ERC of FingerJetFX features at 3% FNMR for provider 28](image1)

![Figure 11: ERC of FingerJetFX features at 10% FNMR for provider 28](image2)
4.3 **Evaluation of the Features Implemented by hda**

For each of the features implemented by hda (see Section 2.3), 13 configurations were tested, resulting in 208 different feature instances. The following Table shows the configurations used.
Table 6: Configurations used for feature computation

<table>
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<tr>
<th>Feature</th>
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Table 6: Configurations used for feature computation

It turned out, that many configurations of a feature gave equivalent values, i.e. with spearman correlation of 1, or almost identical values resulting in a very high correlation. Furthermore, for all configurations, sigmaMuBlock and SigmaMuSigmaBlock gave almost equivalent values to MuMuSigmaBlock (correlation coefficient of -0.99). As a consequence, only 59 distinct instances (feature + configuration) remained.

Table 7: Equivalent, almost identical or constant values of the feature configurations
Furthermore, we did not consider configurations of a feature that exhibited high correlations (greater than 0.875) with other configurations of the same feature. Of the remaining, i.e. the non-redundant, feature configurations, the following showed relatively (for the feature) good biometric performance in the ROC curve evaluation.

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</tbody>
</table>

Table 8: Non-redundant configurations giving relatively good performance for the feature

4.3.1.1 Correlation and scatter plots

For these feature, the correlation coefficients are given in the following table.
Table 9: Spearman correlation coefficients for hda features

The highest correlation with utility was observed (in that order) for

1. Gabor Shen
2. Ridge Valley Uniformity (config 0)
3. Power Spectrum
4. Orientation Certainty Level
5. Ridge Valley Uniformity (config 1)
6. Local Clarity Score (config 7)

Scatter plots of the features with provider 63 utility according to ISO 28784-1 [5] and density plots of the empirical feature distributions are shown in Appendix A.1.
4.3.1.2 ROC Curve Evaluation

For some features, the optimal selection criterion, i.e. if choosing the impression with highest feature value or selecting the one with lowest feature value, results in better ROC curves, varied among the configurations. However, for the better performing configurations of each feature, the criterion was consistent. The following table shows the optimal selection criterion for the hda features.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Abbr.</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
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<td>gabor</td>
<td>Highest</td>
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</tr>
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<td>Gabor Segment 9</td>
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<td>Lowest</td>
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<td>Gabor Shen</td>
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<td>Highest</td>
</tr>
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<td>Local Clarity Score 7</td>
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<tr>
<td>Mu Sigma Block</td>
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<td>Lowest</td>
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<td>Highest</td>
</tr>
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<tr>
<td>Sigma Sigma Block</td>
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</tr>
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</table>

Table 10: Optimal selection criteria for hda features

The ROC curves of the best configurations are shown below. Where several configurations of a feature are included, they are indicated by the number following the feature name.
Figure 12: Provider 28 ROC curves for hda features
Figure 13: Provider 63 ROC curves for hda features

Figure 14: ROC curves for hda features for Provider 63 (top line) and provider 83
The best features are compared in the following ROC curve. Only the best configuration per feature is shown.

Figure 15: Provider 28 ROC curves of best had features

Figure 16: Provider 63 ROC curves of best features
The following observations were made on the ROC curves:

- For provider 28 and 63, Local Clarity Score and Orientation Certainty Level gave best performance, LCS being slightly better for provider 28.
- LCS was top performing for configurations 1 and 7. Although the values computed with these configurations have a spearman correlation coefficient of only 0.57, the scatter plot in Appendix A3 shows that for most fingerprints they are very close.
- For provider 28 and 63, Gabor Shen was clearly at the third rank.
- For provider 83, LCS and OCL were also top ranked but slightly beaten by Gabor Shen for FMR below 0.01%.
- For provider 28, Mu Mu Sigma Block was on rank four, while for providers 63 nd 83, the fourth rank was shared by Orientation Flow and Ridge Vally Uniformity.
- For provider 28, the fifth rank was shared by Mu Mu Block and Ridge Valley Uniformity, while for providers 63 and 83, it was taken by Power Spectrum.
- For all providers, Sigma gave poor performance.

Overall, the results of the ROC curve evaluation were quite consistent among the providers. The top ranking had features are shown in the following Table
<table>
<thead>
<tr>
<th>Provider 28</th>
<th>Provider 63</th>
<th>Provider 83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Clarity Score (1&amp;7)</td>
<td>Local Clarity Score (1&amp;7)</td>
<td>Local Clarity Score (1&amp;7)</td>
</tr>
<tr>
<td>Orientation Certainty Level</td>
<td>Orientation Certainty Level</td>
<td>Orientation Certainty Level</td>
</tr>
<tr>
<td>Gabor Shen</td>
<td>Gabor Shen</td>
<td>Gabor Shen (low FMR)</td>
</tr>
<tr>
<td>Mu Mu Sigma Block</td>
<td>Ridge Valley Uniformity 0</td>
<td>Ridge Valley Uniformity 0</td>
</tr>
<tr>
<td></td>
<td>Orientation Flow</td>
<td>Orientation Flow</td>
</tr>
<tr>
<td>Mu Mu Block</td>
<td>Power Spectrum</td>
<td>Power Spectrum</td>
</tr>
<tr>
<td>Ridge Valley Uniformity 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Spectrum</td>
<td>Mu Mu Block</td>
<td>Mu Mu Block</td>
</tr>
<tr>
<td>Orientation Flow</td>
<td>Mu Mu Sigma Block</td>
<td>Mu Mu Sigma Block</td>
</tr>
</tbody>
</table>

Table 11: Top ranks of ROC evaluation for hda features

### 4.3.1.3 ERC Evaluation

For the features developed by hda the following ERC curves at 3% FNMR and 10% FNMR were obtained. Again, the dotted diagonal line from (0.1, 0) to (0, 0.1) for 10% FNMR and from (0.03, 0) to (0, 0.03) for 3% FNMR shows the ideal (and hypothetical) ERC in case of a perfect quality filtering, where scores are rejected according to their quality, starting with the lowest quality value.
Figure 18: ERC for hda features at 3% FNMR (top line) and 10% FNMR (bottom line) for provider 28
It turned out than some features, namely Gabor Segment 9, Mu Mu Sigma Block, Mu Sigma Block, Mu and Sigma Sigma Block, resulted in similar ERC where the FNMR rapidly decreases for the first 2.5 -3% but from that point on shows only moderate reduction. This phenomenon can be explained as follows: approximately 4-5% of the genuine comparisons for provider 28 give extremely low comparison scores, which is clearly visible in the density function plot below.

![Density function of genuine scores for provider 28](image)

**Figure 19: Density function of genuine scores for provider 28**

Approximately 3% of these “bad genuine scores” seem to be caused by fingerprints with extreme (highest or lowest) feature values for these features, which implies that filtering by these feature values filters very well these 3% of the bad genuine scores. At least for Mu Mu Sigma Block, Mu Sigma Block, Mu and Sigma Sigma Block, this explanation is supported by the scatter plots of genuine scores (for provider 28) and minimum (or maximum, depending on the sign of correlation between feature values and genuine scores) quality values of sample and probe fingerprint: for each of these features, in the very bottom of the scatter plot there is a strong accumulation or a wedge either in the very left (in case where the genuine scores correlate positively with feature values) or in the very right (in case of negative correlation).
Figure 20: Scatter plot of genuine scores and Mu Mu Sigma Block

Figure 21: Scatter plot of genuine scores and Mu Sigma Block
Furthermore, the ERC indicate that the filtering effect by these features is quite similar. This hypothesis is supported by the well-separated accumulations in the corners of the scatter plots among these features, showing that the subsets of genuine scores filtered by these features strongly overlap. This effect is particularly strong for Mu Sigma Block and Sigma Sigma Block.
Figure 24: Scatter plot of Mu Sigma Block and Mu Mu Sigma Block

Figure 25: Scatter plot of Mu Sigma Block and Mu

Figure 26: Scatter plot of Mu Sigma Block and Sigma Sigma Block

Due to the strong initial reduction of the FNMR down to 1% in the ERC for 3% FNMR, the features Gabor Segment 9, Mu Mu Sigma Block, Mu Sigma Block, Mu
and Sigma Sigma Block resulted in the lowest error rates up to 30% rejection rate. For this reason these features were top among the best in the ERC at 3% FNMR while only being mediocre performers in the ERC at 10% FNMR and rejection rate greater than 15%. This phenomenon resulted in different rankings for 3% FNMR and 10% FNMR.

<table>
<thead>
<tr>
<th>FNMR = 3%</th>
<th>FNMR = 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu Mu Sigma Block</td>
<td>Ridge Valley Uniformity 0</td>
</tr>
<tr>
<td>Gabor Segment (config 9)</td>
<td>Orientation Certainty Level</td>
</tr>
<tr>
<td>Mu Mu Sigma Block</td>
<td>Gabor Shen</td>
</tr>
<tr>
<td>Mu Mu Sigma Block</td>
<td>Orientation Flow</td>
</tr>
<tr>
<td>Sigma Sigma Block</td>
<td>Local Clarity Score 7</td>
</tr>
<tr>
<td>Ridge Valley Uniformity 0</td>
<td>Power Spectrum</td>
</tr>
<tr>
<td>Orientation Certainty Level</td>
<td>Gabor</td>
</tr>
<tr>
<td>Ridge Valley Uniformity 1</td>
<td>Ridge Valley Uniformity 1</td>
</tr>
</tbody>
</table>

Table 12: Top ranks of ERC evaluation for hda features

4.4 Overall Comparison

4.4.1 Correlation

The following Table shows the spearman correlation coefficients for the hda features with the top performing features of NFIQ1 (including Foreground) and FingerJet FX.
An interesting observation is that high correlations (> 0.5) occur among the features implemented by hda as well as among FJFX and NFIQ1 features, but not between these two groups. This indicates that features from these two groups may well complement each other with respect to information content.

### 4.4.2 ROC Curve Evaluation

The following figures show the ROC curves of the top performing features.
NFIQ 2.0: Evaluation of Potential Image Features for Quality Assessment

Figure 27: Provider 28 ROC curves of top performing features

Figure 28: Provider 63 ROC curves of top performing features
Following these top performers we found the following features giving next best results.

Figure 29: Provider 83 ROC curves of top performing features

Figure 30: Provider 28 ROC curves of next best performing features
Figure 31: Provider 63 ROC curves of next best performing features

Figure 32: Provider 83 ROC curves of next best performing features

4.4.3 ERC evaluation

The following ERC curves show the best performing features at FNMR of 3% and FNMR at 10%.
Figure 33: Best features in ERC at 3% FNMR for provider 28

Figure 34: Best features in ERC at 10% FNMR for provider 28

4.4.4 Summary

We obtain the following rankings.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>ROC (28)</th>
<th>ROC (63, 83)</th>
<th>FNMR = 3%</th>
<th>FNMR = 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>NFIQ1 QZ4</td>
<td>LCS1</td>
<td>LCS1</td>
<td>MMSB</td>
<td>NFIQ1 QZ4</td>
</tr>
<tr>
<td>GSh</td>
<td>LCS7</td>
<td>LCS7</td>
<td>NFIQ NoMin</td>
<td>FJFX MinQual7</td>
</tr>
<tr>
<td>NFIQ1 QZ3</td>
<td>OCL</td>
<td>OCL</td>
<td>GS9</td>
<td>RVU0</td>
</tr>
<tr>
<td>RVU0</td>
<td>GSh</td>
<td>GSh</td>
<td>Mu</td>
<td>OCL</td>
</tr>
<tr>
<td>OCL</td>
<td>FJFX MinQual7</td>
<td>NFIQ1 QZ4</td>
<td>MSB</td>
<td>NFIQ1 NoMin</td>
</tr>
<tr>
<td>PS</td>
<td>NFIQ1 QZ4</td>
<td>RVU0</td>
<td>SSB</td>
<td>GSh</td>
</tr>
</tbody>
</table>
From the various evaluation methods, we (subjectively) derive a rough ranking of the features (with configuration number indicated) which reflects their priority for consideration in the NFIQ2 training process:

1. NFIQ1 Quality Zone 4
2. FingerJetFX Minutiae Quality 7
3. Orientation Certainty Level 0
4. Ridge Valley Uniformity 0
5. Gabor Shen 10
6. NFIQ1 Total # Minutiae
7. Ridge Valley Uniformity 1
8. Mu Mu Sigma Block 0
9. Local Clarity Score 7
10. NFIQ1 Quality Zone 3
11. FingerJetFX Minutiae Quality 9
12. Power Spectrum 0
13. Sigma Sigma Block 0
14. Gabor Segement 9
15. Mu Sigma Block 0
16. Local Clarity Score 1
17. FingerJetFX Minutiae Quality 10
18. FingerJetFX Minutiae Quality 6
19. Orientation Flow 2
20. Mu Mu Block
21. NFIQ1 Foreground
22. Gabor 0
23. FingerJetFX Minutiae Quality 8
24. Frequency Domain Analysis 1
5 References


